The Proceedings of the International
Conference on Creationism

Volume 8 Article 30

2018

The Coconino Sandstone (Permian, Arizona, USA): Implications for the origin of ancient cross-bedded sandstones

DOI: https://doi.org/10.15385/jpicc.2018.8.1.42

John H. Whitmore
Cedarville University

Paul A. Garner
Biblical Creation Trust

Recommended Citation

Whitmore, J.H., and P.A. Garner. 2018. The Coconino Sandstone (Permian, Arizona, USA): Implications for the origin of ancient cross-bedded Sandstones. In Proceedings of the Eighth International Conference on Creationism, ed. J.H. Whitmore, pp. 581–627. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Whitmore, J.H., and P.A. Garner. 2018. The Coconino Sandstone (Permian, Arizona, USA): Implications for the origin of ancient cross-bedded sandstones. In *Proceedings of the Eighth International Conference on Creationism*, ed. J.H. Whitmore, pp. 581–627. Pittsburgh, Pennsylvania: Creation Science Fellowship.

THE COCONINO SANDSTONE (PERMIAN, ARIZONA, USA): IMPLICATIONS FOR THE ORIGIN OF ANCIENT CROSS-BEDDED SANDSTONES

John H. Whitmore, Cedarville University, 251 N. Main St., Cedarville, OH USA 45314 johnwhitmore@cedarville.edu
Paul A. Garner, Biblical Creation Trust, P.O. Box 325, Ely, CB7 5YH United Kingdom paul@biblicalcreationtrust.org

ABSTRACT

The Permian Coconino Sandstone is one of the most prominent layers of rock in the Grand Canyon and is important to creationists because it has often been used by conventional scientists to discredit the Bible since it is a supposed wind-blown (eolian) deposit. Their argument is that deposits like this would be impossible to form in the midst of a global flood as described in Genesis. Over the past forty years, new data has been collected by us and others that we believe indisputably identifies the Coconino as a subaqueous sandstone--data that will be difficult for our critics to counter. These data include evidence from petrology, fossil footprint studies, sedimentology, regional stratigraphy and soft sediment deformation features. In our studies we found that there are many misconceptions or "urban myths" about the Coconino Sandstone including its grain roundness, grain sorting, grain frosting and angle of cross-bed dips. There are no modern analogs that match the precise sedimentology of the Coconino, but we believe that subaqueous sand waves may be a start in the right direction to understand how the Coconino was deposited. Instead of the Coconino being a problem for creationists, it can be one of our most powerful arguments in support of the biblical account of the Flood. There are many other similar cross-bedded sandstones around the world; the Coconino may be the key to unlocking their origin as well.

KEY WORDS

Coconino Sandstone, Permian sandstones, vertebrate trackways, cross-bedded sandstones, sand waves

INTRODUCTION

The Coconino Sandstone (Permian, Arizona, USA) has been something of a "type" example for the conventional geological community for what eolian sandstones should look like (Figs. 1 and 2). The eminent Grand Canyon geologist Edwin McKee published the first and, until our studies, the only comprehensive study of the sandstone in 1934. He concluded then and in his later works (1979) that the Coconino was wind-blown. Many Pennsylvanian and Permian sandstones very similar to the Coconino occur around the world and this fact is often used as compelling evidence that Pangea was a subaerial supercontinent. At various times for about the last forty years some significant new discoveries have been made about the Coconino. This report is a summary of that work and what we currently understand about the Coconino. Even though more work remains to be done and all of the answers are not yet clear, we believe the evidence now undeniably suggests a subaqueous origin for this important sandstone. Hence, we believe that some of the same features that are found in the Coconino may be useful for reinterpreting other sandstones with large cross-beds, of course after careful study.

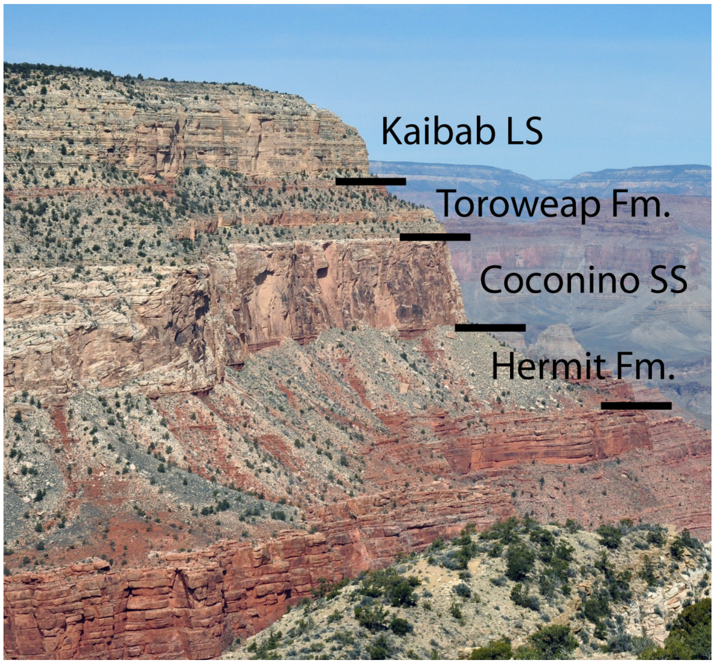


Figure 1. The Coconino Sandstone as viewed from the Hermit Trail, Grand Canyon, Arizona. JHW photo 8131-2013.

The primary features that many have claimed support the eolian origin of the Coconino are its large cross-beds, steep cross-bed dips, well-rounded and well-sorted quartz sand grains, vertebrate and invertebrate trackways and raindrop prints. We have found evidence that some of these claims are simply not true or that they do not support an eolian origin for the sandstone. We have found other features that seem to have no explanation besides a subaqueous depositional environment. Examples include extensive mica and dolomite, parabolic recumbent folds, extensive current lineation, planar beds, poor sorting and rounding of grains, cross-bed dips averaging about 20 degrees, similarity of vertebrate trackways to those made underwater, sand injectites and other features.

The Coconino Sandstone has been important in the discussion as to whether the Genesis Flood actually happened as described in Scripture, or not at all. For example, speaking specifically about the Coconino Sandstone and eolian deposits in general, Strahler (1999, p. 217) states:

> "The evidence of subaerial origin of the dune-sand formations is undisputed as to its significance by mainstream geology; in itself is sufficiently weighty to discredit the biblical story of the Flood of Noah as a naturalistic phenomenon occurring in one year."

The Coconino is thought to have been deposited during Noah's Flood by most Flood geologists because it is bounded by widespread Paleozoic marine deposits, which occur both below, and above the Coconino; and of course you cannot have major windblown dune sands in the middle of worldwide Flood deposits. A wide variety of other skeptics, some theistic, have come to similar conclusions about the sandstone. Examples include Helble (2011), Hill et al. (2016), Ranney (2001), Weber (1980) and Young and Stearley (2008).

PREVIOUS WORK

Darton (1910) originally named the Coconino Sandstone after outcrops in Coconino County, Arizona. However, the sandstone is best known for its outcrops near the rim of Grand Canyon and along the Mogollon Rim south of Flagstaff. McKee (1934) published the first comprehensive study of the Coconino and followed it with other minor papers throughout his long career (1944, 1945, 1979). Gilmore published several papers regarding the vertebrate tracks in the sandstone obtained for the Smithsonian Institution (1926, 1927a, 1927b, 1928). Other short papers on the sparse paleontology of the Coconino have been published since then. Several theses on various aspects of the sandstone include those by Elcock (1993), Fisher (1961), Lundy (1973), Millhouse (2009) and Sumner (1999). Reiche (1938) published data on cross-bed dips within the Coconino. Blakey has published numerous papers regarding the stratigraphy of Pennsylvanian and Permian rocks of the Colorado Plateau, which include the Coconino (Blakey 1990, 1996; Blakey and Knepp 1989; Blakey et al., 1988). Middleton et al. (2003) published the most often cited technical summary of the Coconino.

As far as creationist and ichnology work in the Coconino, Leonard Brand's experiments and publications stand above all the rest; they include Brand (1978, 1979, 1996), Brand and Kramer (1996), and Brand and Tang (1991). He and some of his students have also published a number of short abstracts that have appeared in the *Geological Society of America Abstracts with Programs*, for example. John Whitmore informally began his studies on the Coconino in 1998 when as a graduate student he began field work on the sandstone (Whitmore and Peters 1999). His first formal publication was in 2005. The Institute for Creation Research sponsored the present authors, Raymond Strom and some others as part of the multi-year "FAST" project (approximately 2006-2012) to study the Coconino. A number of short abstracts, magazine articles and publications (including this one) were the direct result of many of those studies; technical works include Maithel et al. (2015), Whitmore and Strom (2010), Whitmore et al. (2014) and Whitmore et al. (2015). A number of Whitmore's students have also published abstracts related to the Coconino during this period (too numerous to mention). As a result of all this work, Whitmore et al. submitted a lengthy unpublished report to ICR in 2012. A few formal papers remain to be published which were side projects of the main Coconino FAST project. Sarah Maithel (student of Whitmore and later Brand) is currently doing active research on

Figure 2. Typical cross-bedding in the Coconino near Holbrook, Arizona. Most is planar tabular-shaped or planar wedge-shaped (after McKee and Weir, 1953). Vertical scale bar on left is approximately 1 m long. JHW photo 5430-2009.

the sandstone at the PhD and post-doctoral levels.

GENERAL METHODS

The present authors, Raymond Strom and a few others visited a significant number of Coconino Sandstone outcrops beginning in 1998. These included sites along every trail in Grand Canyon where a trail crosses the Coconino and many other locations throughout northern and central Arizona. Samples were collected at many of the sites for thin section, scanning electron microscopy (SEM) and X-ray diffraction (XRD) work. Permits were obtained for collection in the National Park. General field notes, rock characteristics and cross-bed dips were measured at most sites. Measured sections were made at some sites. Laboratory work was primarily completed at Calgary Rock and Materials Services Inc. in Calgary, Alberta. Microscope work was done in Calgary and at Cedarville University, Ohio. Other Pennsylvanian and Permian sandstones that were similar to the Coconino were also studied, but not as extensively. These included sandstones in the western United States such as the Tensleep, Lyons, Glorieta, Cedar Mesa, White Rim, Weber, Schnebly Hill, Casper and De Chelly. In Great Britain our examination included sandstones such as the Hopeman, Bridgnorth, Penrith and Dawlish. Detailed petrographic studies and point counting was completed on many samples to determine sorting, rounding and percent composition of minerals and porosity. More detailed methods can be found for this work in literature that has already been published (Maithel et al. 2015; Whitmore et al. 2014; Whitmore et al. 2015).

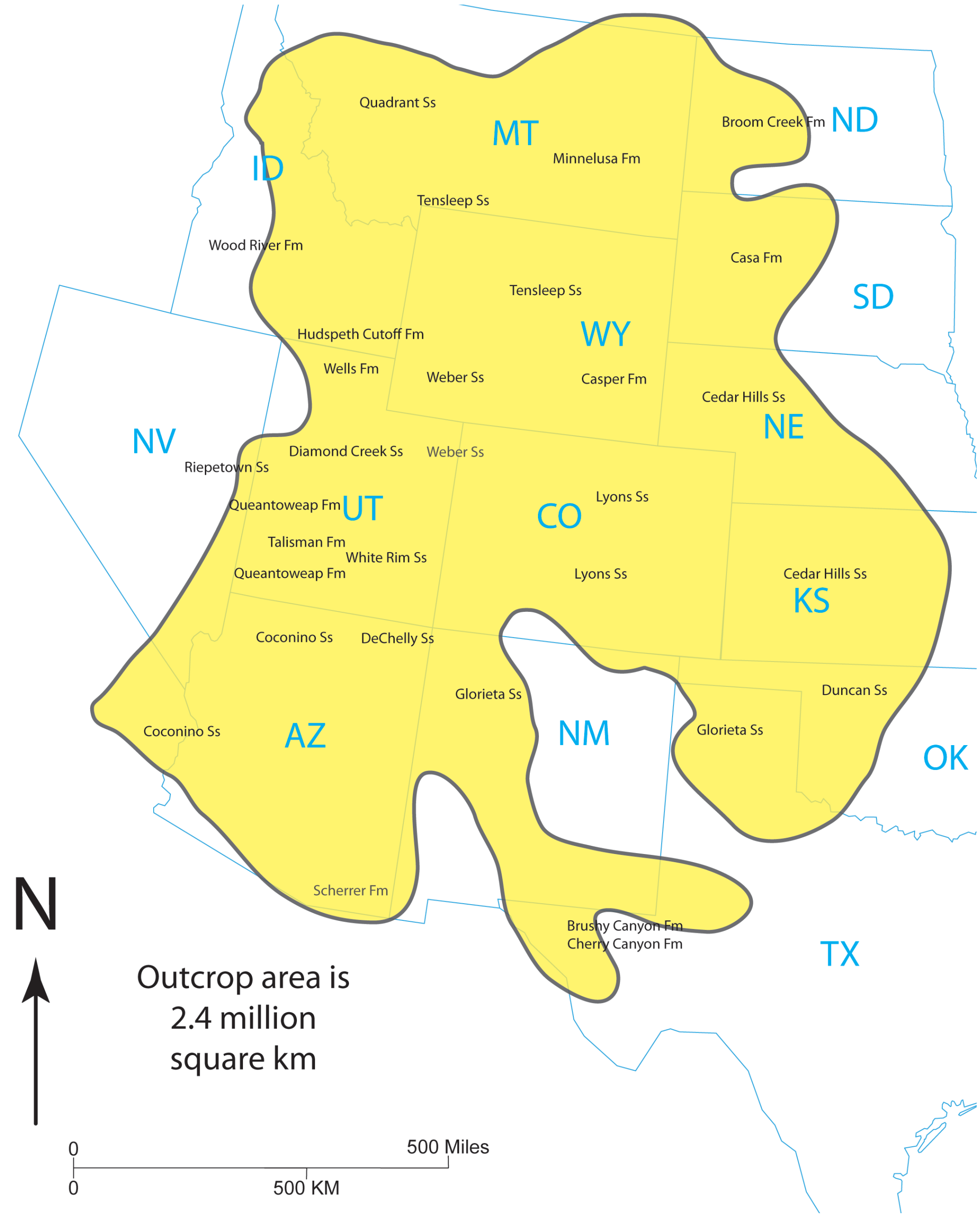


Figure 3. Areal extent of the Pennsylvanian-Permian sandstone sheet that can be correlated as a more or less continuous unit in the western United States that includes the Coconino Sandstone (in Arizona). In general, formations to the north are Pennsylvanian and those to the south are Permian. Preliminary work by Whitmore (2016).

An effort was made to locate all of the pertinent literature on the Coconino and its possible correlatives. This included papers, abstracts, geological maps, stratigraphic columns, charts and electronic data sheets, especially from the data compiled for the COSUNA project by the American Association of Petroleum Geologists (AAPG) in the 1980s. COSUNA is an acronym for Correlation of Stratigraphic Units of North America. These materials and a few other sources were used to compile stratigraphic correlations and thicknesses of the Coconino and similar formations from Arizona to surrounding states (Whitmore 2016).

DESCRIPTION OF THE CONONINO SANDSTONE

1. Areal extent and thickness

The Coconino Sandstone occurs in northern and central Arizona (Fig. 3). Its maximum thickness is about 300 m along the Mogollon Rim near Pine, Arizona. To the north, it thins and is absent near the Arizona/Utah border. In the main part of the Grand Canyon it is about 100 m thick. As with most formations in the United States, names change as state lines are crossed. However, the "Coconino" is still recognized by some authors just across the Arizona state line in parts of Nevada, California and southwestern Utah (Baltz 1982; Beard et al. 2007; Billingsley and Workman 2000; Castor et al. 2000; Stone et al. 1983). A small isolated pocket of metamorphosed Coconino occurs in southwestern Arizona near Quartzite (Miller and McKee 1971).

Some preliminary and ongoing work of this project is to correlate the Coconino beyond the borders of Arizona (Whitmore 2016). Figs. 3 and 4 show our preliminary map of the areal extent and thickness of units that are very close in age and character to the Coconino.

2. Petrology

A. General petrology

In most locations the Coconino is a fine-grained quartz arenite, containing about 90% quartz/chert and 10% orthoclase and other accessory and trace minerals. Mean grain size ranges from about 3.45 ϕ in northern Arizona to about 2.75 ϕ in central Arizona (Figs. 5 and 6). The sandstone is more poorly sorted in northern Arizona compared to central Arizona (Figs. 7 and 8). The sandstone in Whitmore Canyon (WC) is very poorly sorted (standard deviation = 0.94) compared to the sandstone at Cave Spring Campground (CSC) which is well sorted (standard deviation = 0.50). We found that the Coconino is sub-angular in northern Arizona and sub-rounded in central Arizona (Figs. 9 and 10). Whitmore et al. (2014) discusses the petrology and mineralogy of the Coconino in greater detail.

B. Dolomite

Dolomite occurs in four different modes in the Coconino over a relatively large area (Fig. 11). It occurs as beds (Fig. 12), as ooids (Fig. 13), as cement and rhombs (Fig. 14) and as large clasts, often orders of magnitude larger than the surrounding quartz grains (Figs. 14 and 15).

C. Muscovite

In nearly every thin section of the hundreds of thin sections we cut of the Coconino, we found muscovite mica as a trace mineral (Fig. 16). Also see Borch et al. (2018).

D. Orthoclase

Orthoclase (K-feldspar) usually comprised about 10% of the sandstone (Fig. 17). Surprisingly, it is often more angular than the harder quartz sand (orthoclase = Mohs 6, quartz = Mohs 7). Alos see Whitmore and Strom (2018).

E. Zircons

Analysis of zircons contained within the Coconino Sandstone indicates that many of them were probably derived from the mid-Proterozoic rocks of eastern North America (Gehrels et al. 2011).

F. Frosting

In the few samples that we examined with the SEM, we found that quartz grains exhibited "frosting" (Fig. 18).

G. Compaction

Typical thin sections of the Coconino show little or no evidence of compaction (Fig. 19), except in sand injectites and a roughly 0.5 m-thick

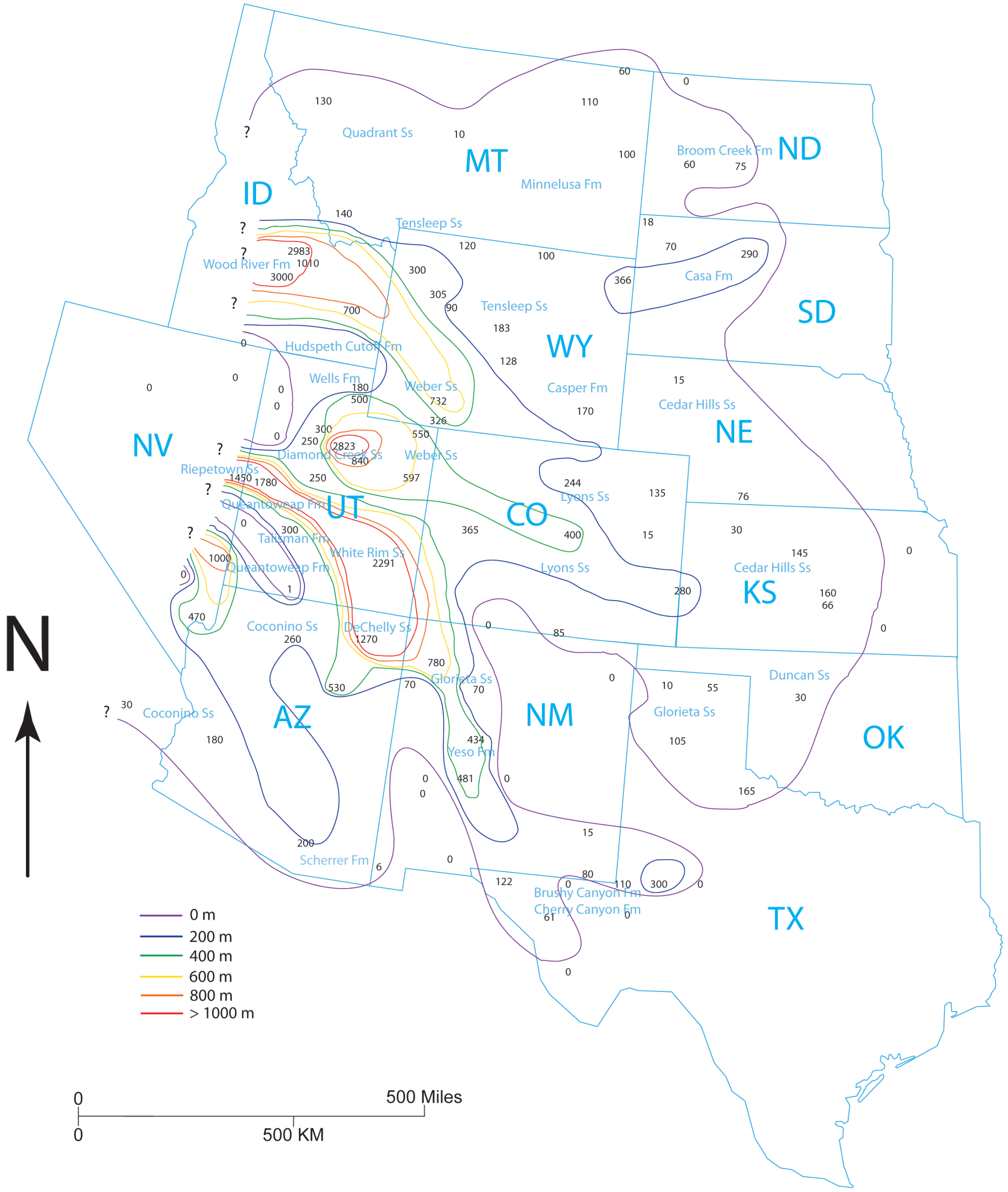


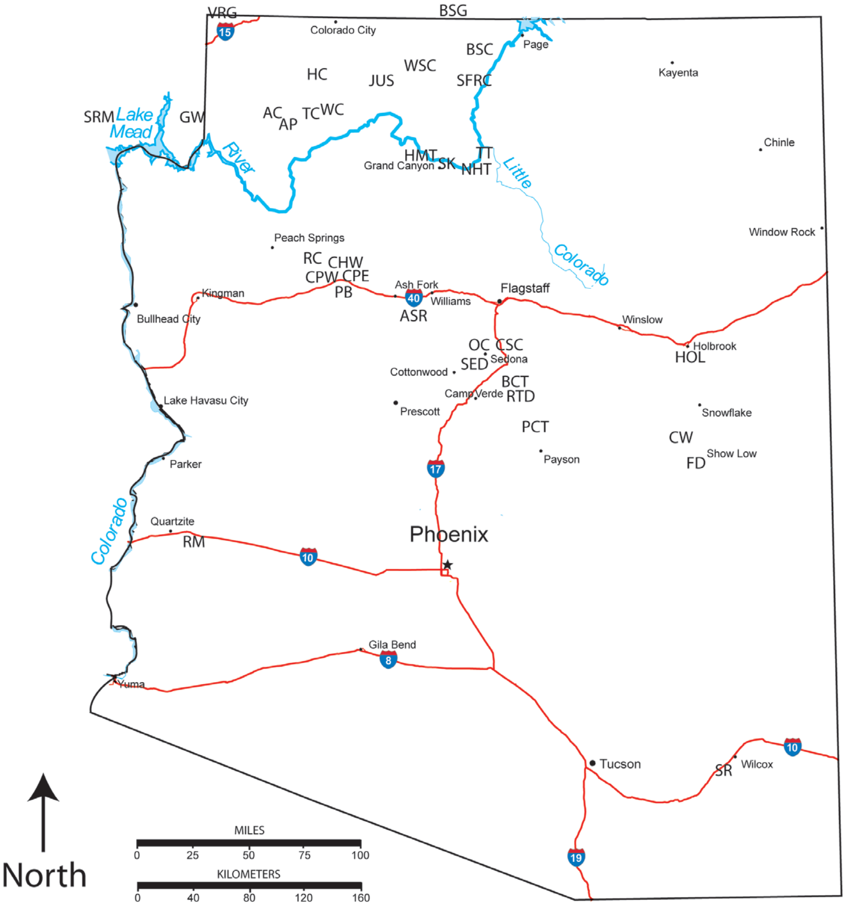
Figure 4. Thickness of the Pennsylvanian-Permian sandstone sheet that can be correlated as more or less continuous in the western United States that includes the Coconino Sandstone (in Arizona). Preliminary work by Whitmore (2016). Not all units are shown on the map.

"homogenized" zone at the base of the Coconino which is intimately associated with sand injectites. Here porosities are only a few percent compared to about 17 percent average porosity in most of the rest of the Coconino. Typical indicators of compaction in thin section are fractured grains, contorted ooids and mica flakes, extensive stylolites and relatively low porosities. These features are not widespread or common in the sandstone.

3. Sedimentology

A. General appearance

The most conspicuous feature of the Coconino is large-scale planar-tabular and planar-wedge cross-bedding in sets up to 20 m thick, separated by extensive bounding surfaces (Figs. 2 and 20). Some small-scale sets of trough cross-bedding (<1 m thick) are rarely present. Most of the cross-bedded units consist of thin, laterally continuous parallel laminae (2mm to 15cm in thickness) that can be traced for many meters along strike (Fig. 21). Along-strike cross-sections do not show any hint of concave avalanche beds that are typical on the slip faces of desert dunes (Fig. 22). The sandstone often breaks into slabs about 10-15 cm thick, which makes it ideal for flagstone quarrying operations, especially in the Ash Fork, Arizona area. Large-scale contorted bedding is observed in some localities, notably near Doney Crater in Arizona (McKee and Bigarella 1979a, p. 202) and in the Sedona area (Whitmore et al. 2015). Other occasional features include low-amplitude ripples with crests parallel to dip slopes (Fig. 23), small features within beds that have the appearance of slumps (Fig. 24) and small pits on bedding surfaces (Fig. 25) interpreted by some as raindrop impressions. Detailed work on the sedimentology of the Coconino is in the process of completion by Maithel who has published a number of abstracts (Maithel et al. 2013, 2014, 2015, 2016, 2017). Her work will not be commented on here as it was in the process of completion as this manuscript was being compiled.



AC-Andrus Canyon
AP-Andrus Point
ASR-American Sandstone Ridge
BCT- Bell Canyon Trail
BSC- Burro Springs Canyon
BSG- Buckskin Gulch
CHW- Chino Wash
CPE-Chino Point East
CPW- Chino Point West
CSC- Cave Spring Campground
CW- Cottonwood Wash
FD- Forestdale
GW- Garden Wash
HC-Hurricane Cliffs
HMT- Hermit Trail
HOL- Holbrook
JUS-Jumpup Spring
NHT-New Hance Trail
OC- Oak Creek Canyon
PB-Picacho Butte
PCT- Pine Creek Trail
RC- Rhodes Canyon
RM- Ramsey Mine
RTD-Red Tanks Draw
SED- Sedona (includes SBR)
SFRC- South Fork Rock Creek
SK-South Kaibab
SRM-Sunrise Mountain
SR-Scherrer Ridge
TC-Trail Canyon
TT-Tanner Trail
VRG-Virgin River Gorge
WC- Whitmore Canyon
WSC-Warm Springs Canyon

Figure 5. A map showing location information for the Coconino sites used in this study (from Whitmore et al. 2014).

B. Cross-beds and cross-bed dips

In our measurements of over 200 cross-bed dips from widespread locations in the Coconino, we found that the mean dip was about 20º (Fig. 26). This is at odds with some who say the dips are much steeper, closer to the angle of repose (Hill et al. 2016, p. 70), but almost identical with Reiche's data (1938) who also measured large numbers of dips (Fig. 27). On large exposed foreset beds, cross-bed dip often remains fairly constant down-dip (Fig. 28). Dip only rapidly decreases at the bottom of foresets, less than a meter from the bounding surface. Our data confirmed Reiche's data showing that the primary dip direction in the Coconino is to the south and southeast.

C. Laminae

The Coconino laminae are usually 1-2 mm thick and often graded both in outcrop and in thin section, but it is difficult to tell if they are normally or inversely graded because of the lack of clear erosional truncations from one lamina to the next (Fig. 29). In some cases, the rock appears to be laminated in outcrop, but under the microscope the grading is often difficult to find. Preliminary work by Rouse (2017) shows that thin sections that show macroscopic laminae are more poorly sorted than those that do not have visible laminae. She identified laminae as being present by 1) grain size differences, 2) changes in minerals and 3) the presence of stylolites (dissolution features). Some laminae in the Coconino are more massive in nature and occur as thicker, 2-5 cm beds. She also found that most laminae are difficult to trace under the microscope, even over the 5 cm or so length of a thin section.

D. Planar and massive beds

The most common bedding style by far in the Coconino is small- to large-scale (up to 20 m thick) planar-tabular and planar-wedge cross-stratification (Middleton et al. 2003). It is unusual to find other bedding styles in the Coconino, but when they occur they have been found to be associated with some special features. Whitmore and Strom (2010) reported massive beds (up to 1.0 m thick) at several locations just above sand injectites at the base of the Coconino (Fig. 30). Planar beds have been found in several locations. Some, in Sedona, are associated with parabolic recumbent folds (Whitmore et al. 2015) and others contain dolomite (Andrus Point) or calcite (Kaibab-Buckskin Gulch) as documented by Whitmore et al. (2014).

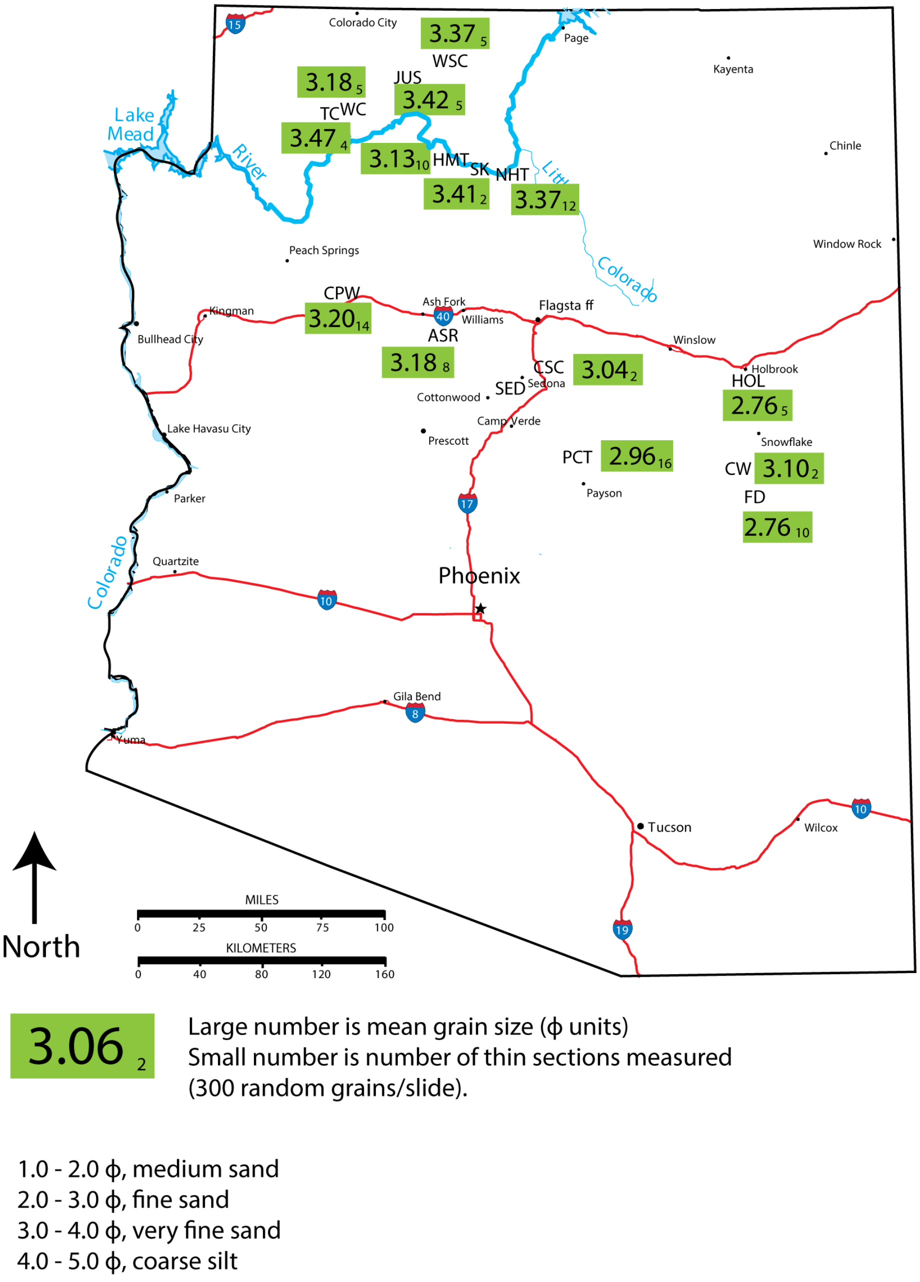


Figure 6. Grain size variation within the Coconino Sandstone (from Whitmore et al. 2014).

E. Parting lineation features

Relief on most flat Coconino foreset surfaces closely resembles “current lineation” or “parting lineation” (Fig. 31). The lineated pattern is always parallel with dip.

F. “Raindrop” prints

Small pits or crater-like features are rarely found at various Coconino localities (Fig. 25) and have been called “raindrop” prints by some (Hill et al. 2016). In Ash Fork and Seligman, Arizona the features often occur in rows and are parallel to dip instead of being randomly distributed on the rock surface as in some other areas. Sometimes the “pit” extends a centimeter or more through the rock and similar deformation patterns can be found on both sides of thin cm-thick beds (Fig. 32). Small pea-sized nodules (possibly siderite) can fall out of the rock surface to create some pits (Fig. 33). Other features that appear to be raindrop prints when initially observed may be entry/exit points of some small organism that burrowed horizontally in the sediment (Fig. 34); the lateral burrows are not always seen below the surface as in Fig. 34B. The “pits” and “crater-like” features have little resemblance to raindrop prints commonly found in sand (Fig. 35).

G. Ripples

Features that resemble ripples should not be considered common in the Coconino, but occasionally they can be found and are always parallel to dip (Fig. 36). Sometimes they are found associated with the “raindrop” prints mentioned above. They are often difficult to see because they are commonly very low relief features. Sometimes they are not noticed unless the sun is shining at a low angle on the rock face.

H. “Mud cracks”

Some have called polygonal cracks within the Coconino “mud cracks” (Hill et al. 2016, p. 68). The cracks (Fig. 37) are polygonal but they only superficially resemble modern mud cracks. They have only been found on bounding surfaces and their origin is still enigmatic (Brand 2018 personal communication; Peters and Brand 1999). The cracks penetrate *both downward and upward* about 15 cm from bounding surfaces. Laminations continue horizontally through the “cracks” demonstrating that they were never open as true desiccation cracks.

I. Sand injectites

Large sand-filled cracks, some >15 m deep, occur at some locations at the base of the Coconino Sandstone and penetrate into the underlying Hermit Formation (Fig. 38). The sediment within them is usually massive in nature with some cracks exhibiting vertical “layers” but not horizontal ones. Most have identified the cracks as "mud cracks" or "playa cracks" (Abbott and Cook 2004; McKee 1934; White 1929). The cracks are deepest near the greatest displacement of the Bright Angel Fault (near Grand Canyon Village), become shallower with distance away from the fault and decreased displacement of the fault. They have a statistically significant preferred orientation with a directional mean of about 143º (Fig. 39) and have been interpreted as sand injectites by Whitmore and Strom (2010).

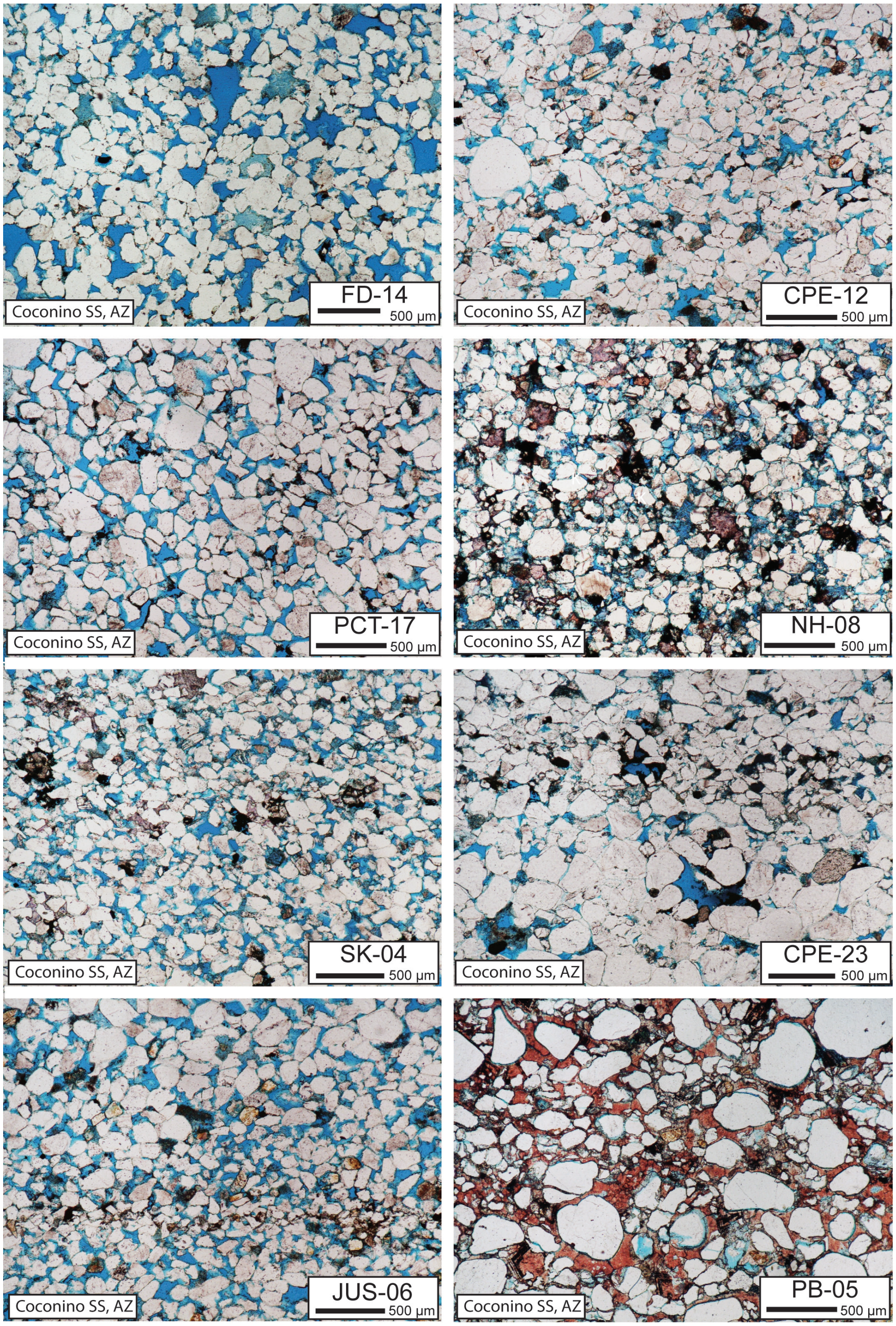


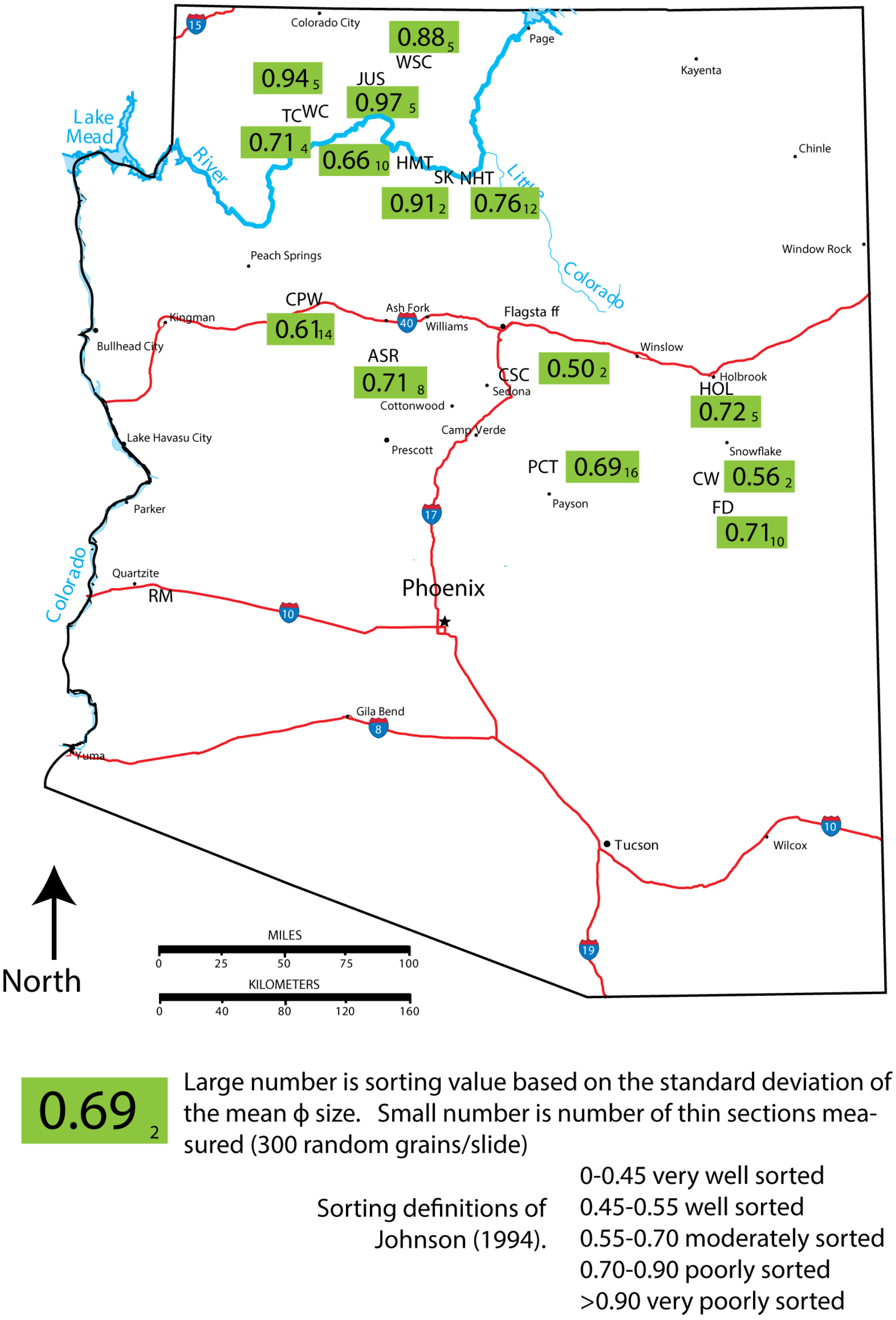
Figure 7. Thin sections showing grain size and sorting within the Coconino Sandstone (from Whitmore et al 2014).

J. Parabolic recumbent folds

Large parabolic recumbent folds (Fig. 40) have been found in several places around the Sedona, Arizona area and near Doney Crater (Whitmore et al. 2015). In Sedona, the fold on "Lizard Head" is nearly 7 m thick and extends for at least 50 m along the face of the outcrop. Several sets of folds occur along Brins Ridge. They are 1-2 m thick and extend over a distance of 400 m before the outcrop disappears on one end and is eroded away on the other. It is likely they originally extended over a much greater distance.

K. Marine interfingering

The Coconino interfingers with a number of aqueous deposits, both laterally and vertically around its margins. Below the Coconino, Blakey (1984) has reported marine sand waves within the Schnebly Hill Formation that in turn grade into typical Coconino lithologies. In the Grand Canyon region, a transitional contact between the water-laid Hermit and the Coconino occurs along Tanner Trail (McKee, 1934) and in some places in Parashant Canyon (Fisher 1961). We located this transitional contact along the Tanner Trail (Fig. 41). Within the Coconino, Fisher (1961) reported tongues of fossiliferous marine limestone. We located dolomite beds at Andrus Point which are probably equivalent to Fisher's limestone beds (Fig. 12). Laterally, the Coconino grades into water-deposited sediments. Peirce et al. (1977) describe what they think is a west to east transition of mostly eolian to mostly water-deposited Coconino along the Mogollon Rim. They report that nearly all of the 90 m of Coconino exposed near Show Low, in east central Arizona, was water deposited. West of a line from about Sedona to Page, the Coconino "intertongues with and is overlain by the Toroweap" (Blakey and Knepp 1989, p. 336). Some authors also report that cross-bedding style, dip direction and grain size in the Toroweap is indistinguishable from the Coconino in the Oak Creek Canyon area, causing them to think part of the Toroweap is eolian (Rawson and Turner-Peterson 1980). Blakey (1990) names the upper part of the Coconino the "Cave Spring Member" and claims that it grades laterally into the Toroweap according to data from Rawson and Turner-Peterson (1980). The Coconino also grades into Toroweap at locations above the Coconino. In northern Arizona, Billingsley and Dyer (2003) report that the Coconino occurs as a thin and discontinuous cross-bedded unit incorporated within the base of the Toroweap. Fisher (1961) reported a transitional contact within Parashant and Andrus Canyons. Additionally, Cheevers and Rawson (1979) presented evidence that the Coconino even grades into the Kaibab Limestone (where the Toroweap is absent) in eastern Arizona. We located the northern margin of the Coconino in Kaibab-Buckskin Gulch area in Utah. At this location, the Coconino was sandwiched between the Hermit and Toroweap, but it consisted of planar-bedded sandstones, carbonate beds and only some meter-thick cross-bed sets (Fig. 42). Sumner (1999) visited Kaibab Gulch, but apparently did not recognize the change in the lithology of the Coconino or thought it was part of the Toroweap (see pp. 109-110). Doelling et al. (2003) recognized about 19.6 m of Coconino in this area. They interpreted it as a near-shore deposit grading southward into its typical lithologies (p. 205). The Coconino probably correlates with the Scherrer Formation, which is a marine sandstone, in southeastern Arizona (Blakey 1990, p. 1216) and transitions eastwards into the Glorieta Sandstone of New Mexico which is also thought to be marine (Baars 1961, p. 199).



Large number is sorting value based on the standard deviation of the mean ϕ size. Small number is number of thin sections measured (300 random grains/slide)

Sorting definitions of Johnson (1994).

0-0.45 very well sorted
0.45-0.55 well sorted
0.55-0.70 moderately sorted
0.70-0.90 poorly sorted
>0.90 very poorly sorted

Figure 8. Map showing sorting within the Coconino Sandstone (from Whitmore et al. 2014).

L. Flat contacts

Most are familiar with the base of the Coconino as it outcrops along the South Rim trails of the Grand Canyon forming a sharp and flat contact with the Hermit Formation below (Fig. 43). Some recognize an unconformity here as more than 600 m of Schnebly Hill Formation can be found between the Hermit and Coconino from core in the Holbrook area (Blakey and Knepp 1989), probably representing an approximately 10-million-year hiatus in conventional terms.

4. Paleontology

A. Vertebrate trackways

No body fossils have been reported from the Coconino Sandstone, with the possible exception of some unidentified microfossils along the northern margin of the outcrop (Cheung et al. 2009). However, the Coconino is known for the abundance of its ichnofossils (Fig. 44; Baird 1952; Braddy 1995; Gilmore 1926, 1927b, 1928; Lull 1918; Spamer 1984) and has been described as one of the richest and most important Paleozoic track sites known (Kramer et al. 1995).

Descriptions and systematic discussions of the Coconino vertebrate trackways were published by Lull (1918), Gilmore (1926, 1927b, 1928), Baird (1952) and Haubold (1971, 1984). In a major revision of Permian vertebrate ichnotaxonomy, McKeever and Haubold (1996) reclassified vertebrate tracks from the Permian Corncockle and Locharbriggs Sandstones of Dumfries and Galloway, Scotland, giving priority to names first assigned by Owen (1842) and Jardine (1850, 1853). They recognized one ichnogenus, *Chelichnus*, consisting of four ichnospecies distinguished by pes size. The four species were *C. bucklandi* (10-25 mm), *C. duncani* (25-75 mm), *C. gigas* (75-125 mm) and *C. titan* (>125 mm). They extended this new classification to the ichnofaunas of the Coconino and the Cornberger Sandstein of Germany and attributed the Coconino tracks to three of their ichnospecies (*C. bucklandi*, *C. duncani* and *C. gigas*). Ichnospecies previously assigned to *Laoporus* and other ichnogenera were considered synonyms (Table 1). A new type of Coconino vertebrate trackway was described by Hunt and Santucci (2001), larger than average for the Coconino with an L-shaped manus smaller than the pes and exhibiting a prominent tail drag. These characteristics seemed to mark it out as anatomically distinct from *Chelichnus*, but the authors were unsure whether it represented a new ichnotaxon.

Notable field and laboratory investigations of the Coconino vertebrate trackways were conducted by McKee (1944), Brand (1979, 1996), Brand and Tang (1991) and Brand and Kramer (1996). Brand (1979) noted that the Coconino trackways usually consisted of distinct and separate prints, some showing only toe marks, others only sole marks and some showing both toe and sole marks. In some trackways individual prints were oriented in a different direction to the trackway itself. These sideways or oblique trackways often showed clear pes impressions only while manus impressions were indistinct or absent (Brand and Tang 1991). Other trackways began or ended abruptly, without evidence that sediment slumping had disturbed the bedding surfaces (Brand and Tang 1991). Gilmore (1927b), McKee (1944) and Brand (1979) also observed that almost all the Coconino trackways displayed upslope orientations, with “downhill” tracks notable by their near-absence.

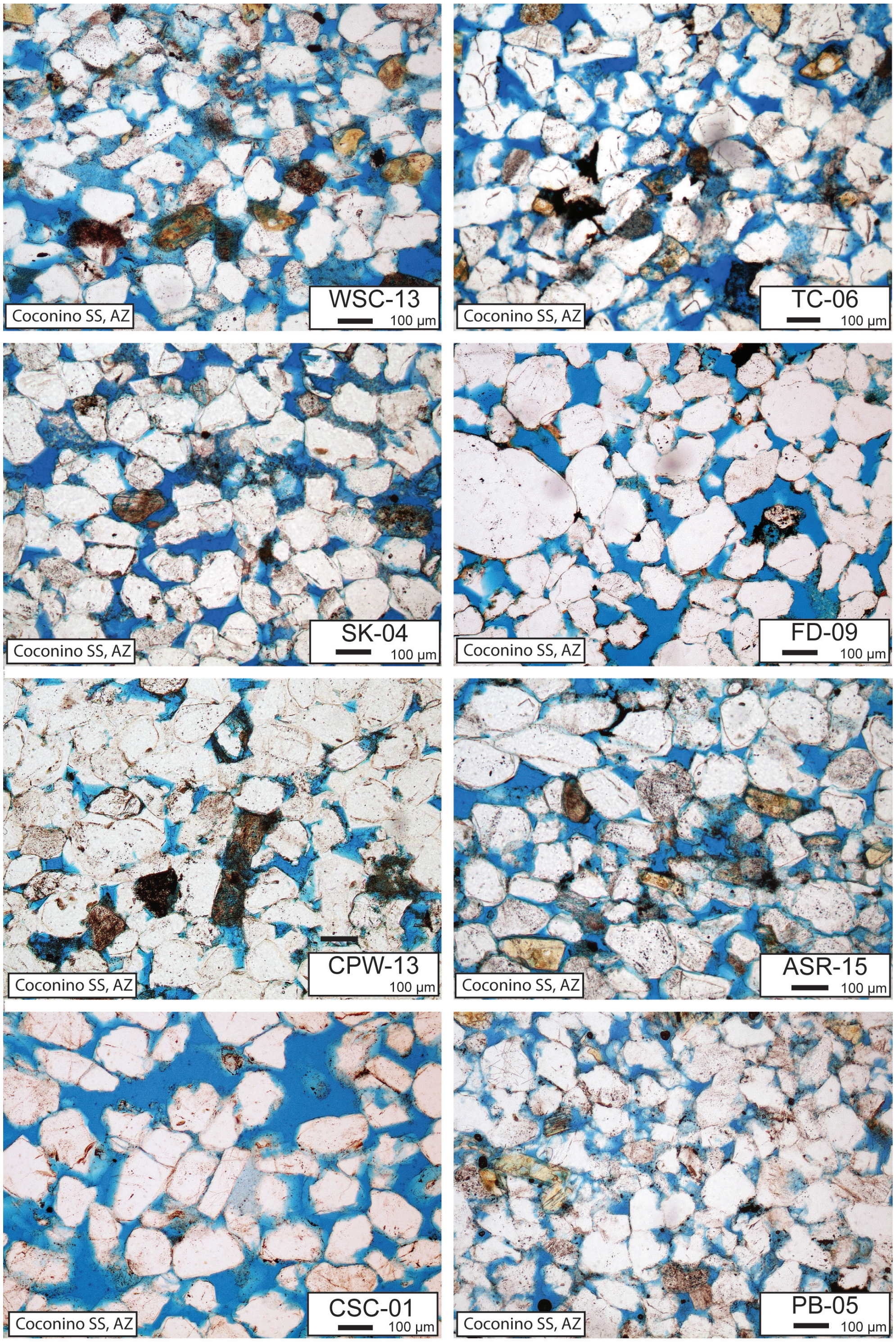


Figure 9. Thin sections showing grain rounding within the Coconino Sandstone (from Whitmore et al. 2014).

The Coconino’s low-diversity vertebrate ichnofauna is now recognized as part of a widely distributed ichnofacies characterizing Permian “eolianites” in Scotland, Germany, Argentina and across the southwestern USA (Haubold 1996; Haubold et al. 1995b; Hunt and Lucas 1998; Hunt and Santucci 1998; Lockley et al. 1995; McKeever and Haubold 1996; Melchor 1997, 2001; Morales and Haubold 1995). This *Chelichnus* ichnofacies contrasts markedly with the *Batrachichnus* ichnofacies described from Permian “redbeds,” also widely distributed across North and South America and throughout Europe (Haubold et al. 1995a; Hunt et al. 1995; Hunt and Lucas 1998, 2005; Schult 1995). Both ichnofacies are stratigraphically persistent through the Paleozoic, encompassing all Carboniferous to Permian vertebrate ichnofaunas (Hunt and Lucas 2005; Olson 1952, 1983).

B. Invertebrate trackways

Invertebrate traces occur rarely in the Coconino (Fig. 45). Early descriptions and systematic discussions of invertebrate ichnofossils in the Coconino were published by Lull (1918), Gilmore (1926, 1927b, 1928), Brady (1939, 1947, 1949, 1961) and Alf (1968). A later review by Braddy (1995) concluded that much unwarranted taxonomic splitting had taken place. He recognized only two ichnogenera in the Coconino, each with two ichnospecies (Table 2): *Paleohelcura* comprising *P. tridactyla* and *P. benjamini* (*Mesichnium benjamini* of Gilmore; see Kozur et al. 1994) and *Octopodichnus* comprising *O. didactylus* and *O. minor*. *P. tridactyla* consists of two parallel rows of imprints in groups of three (or occasionally two), usually with a medial impression interpreted as a tail drag. *P. benjamini* is similar to *P. tridactyla* but with a regularly spaced ovoid medial impression interpreted as a trace left by part of the track-maker's abdomen. *O. didactylus* consists of alternating sets of impressions in groups of four, in which the individual prints are sometimes bifurcated. There is no medial impression. *O. minor* is similar to *O. didactylus* but distinctively smaller. Finally, Kramer et al. (1995) described a new Coconino ichnospecies which they assigned to an existing ichnogenus, *Permichnium coconinensis*. This trace consists of two parallel rows of evenly spaced V-shaped prints and lacks a medial impression.

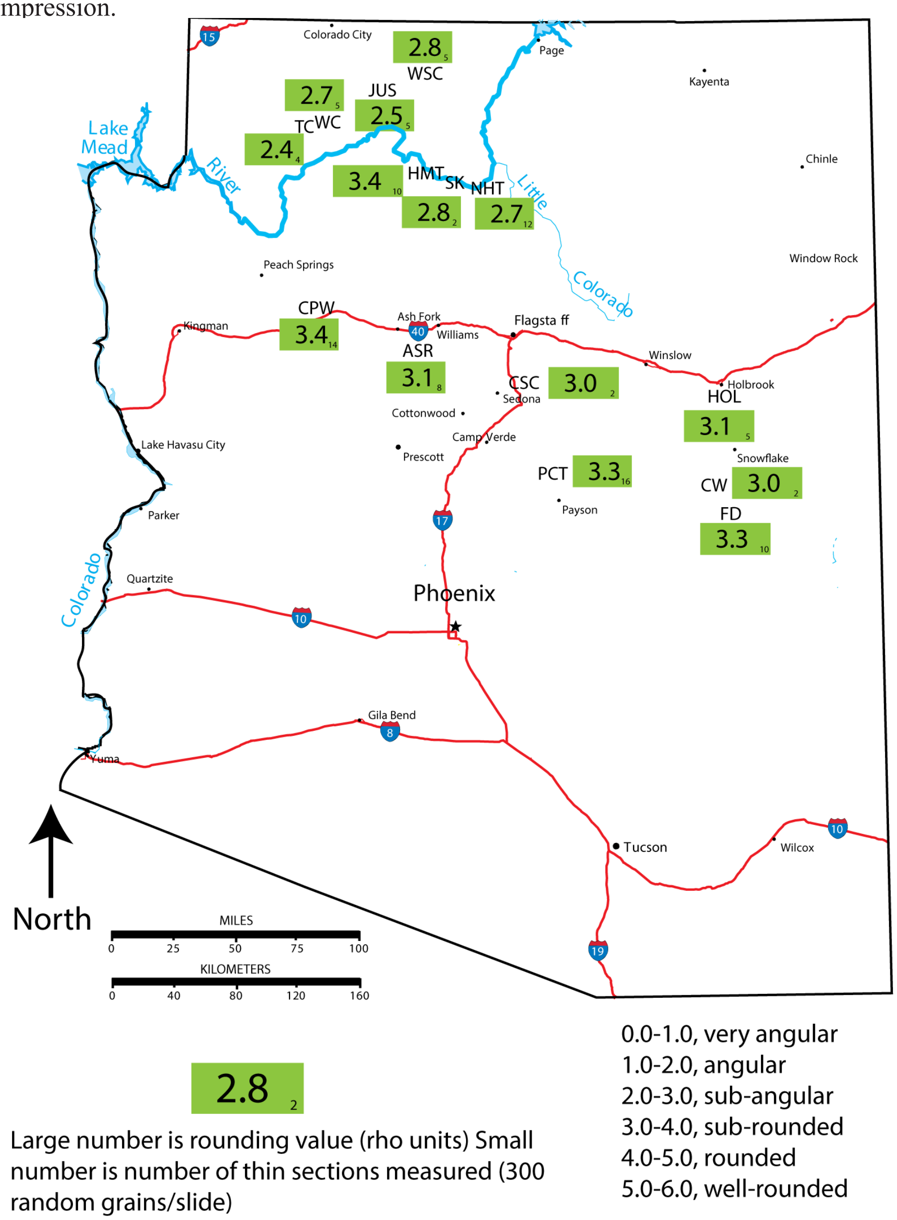


Figure 10. Map showing grain rounding within the Coconino Sandstone (from Whitmore et al. 2014).

OTHER SIMILAR SANDSTONES AROUND THE WORLD

Whitmore and Strom (2018) have published a table summarizing the literature on many of these sandstones (see their Appendix I).

1. North American examples

Sandstones attributed to eolian processes occur throughout the stratigraphic record (from the Precambrian to the Cenozoic) and are widely distributed geographically (in North and South America, Europe, Asia, Africa and Australia) (McKee and Bigarella 1979a, p. 190). They are particularly well developed in the upper Paleozoic to middle Mesozoic of the western and southwestern United States. The Permian and Jurassic systems of the Colorado Plateau include at least ten formations interpreted as erg deposits and many smaller units also considered to be eolian in origin (Blakey 1988, p. 129). Permian sandstones of the western and southwestern USA attributed wholly or in part to eolian deposition, besides the Coconino, include the Cedar Mesa (Utah), De Chelly (Arizona), Glorieta (New Mexico), Lyons (Colorado), Tensleep (Wyoming), Weber (Utah) and White Rim (Utah). Eolianites are also said to occur in the Upper Minnelusa Formation (Wyoming). Some of these units have become classic textbook examples of ancient eolian deposition (e.g., Selley 1985, pp. 82-101).

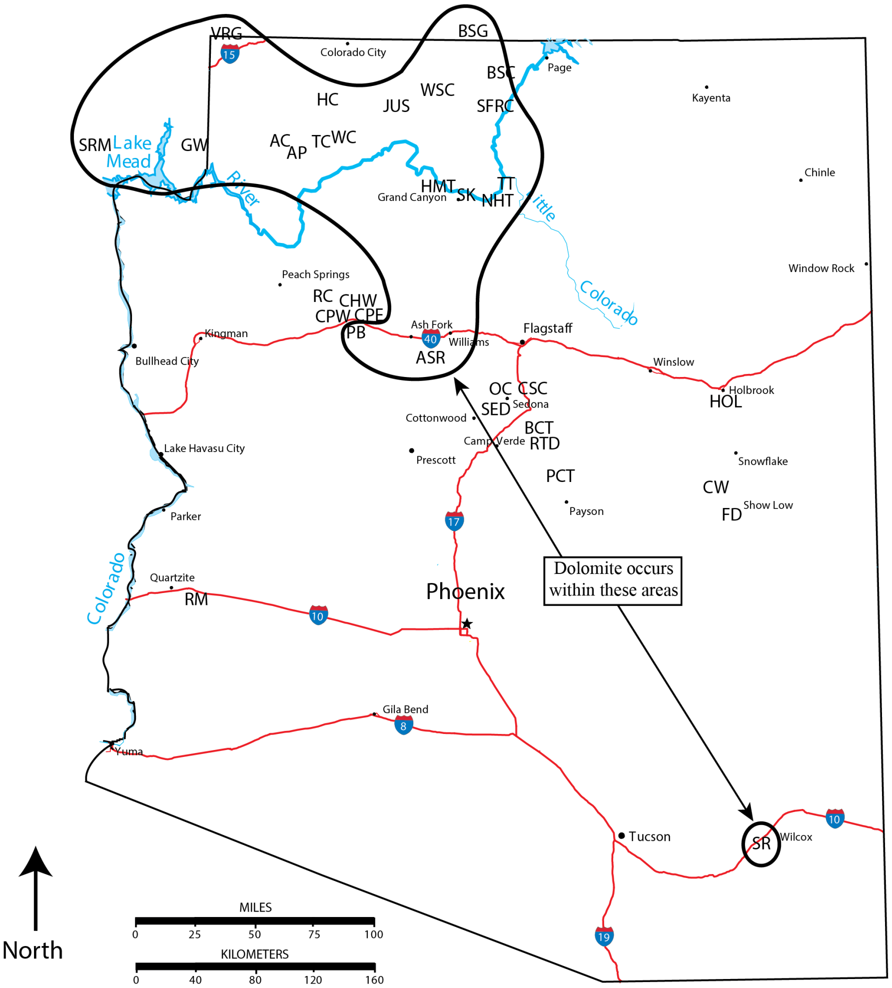
2. European examples

Similar sandstones also occur in Europe. The Lower Permian in the gas and oil fields of the southern North Sea, in Germany and in the Fore-Sudetic Monocline of Poland is characterized by an extensive red sandstone facies (the Rotliegendes) overlain by sandstones that are typically white or grey in color (the Wiessliegendes) (Börmann et al. 2006; Glennie 1972, 1983; Glennie et al. 1978; Stemmerik et al. 2000; Strömback and Howell 2002). Four distinctive facies have been recognized in the Upper Rotliegend, including sandstones with cross-bedded sets around 1-7 m thick and occasionally up to 20 m thick (Glennie 1972, 1983). This facies is usually interpreted as eolian in origin. Permian sandstones in England attributed to eolian deposition include the Bridgnorth Sandstone (Shropshire), the Dawlish Sandstone (Devon), the Penrith Sandstone (Cumbria) and the Yellow Sands (County Durham). Similar units in Scotland include the Hopeman Sandstone (Morayshire), the Corncockle and Locharbriggs Sandstones (Dumfries and Galloway) and the Corrie Sandstone (Isle of Arran). These sandstones and associated sediments are conventionally interpreted as the product of eolian sedimentation in a series of fault-bounded, intermontane basins that developed in the Early Permian (Brookfield 1978, 1980, 2000; Steel 1977).

DISCUSSION: DATA SUGGESTS A SUBAQUEOUS ORIGIN FOR THE COCONINO

1. Areal extent and thickness

The areal extent and thickness of many modern ergs are quite small compared to the Coconino and other ancient cross-bedded sandstones of similar nature (Table 3). Many of the larger ergs, for example those in northern Africa ("the Sahara"), are separated by large swaths of bare rock and sparse vegetation; so, the ergs are not directly continuous with each other. This is not true for the geological record. Sandstones like the Coconino can be traced through outcrops and cores (understanding some has been removed by erosion) for its entire extent. From examining Table 3 it quickly becomes clear that ancient cross-bedded sandstones are orders of magnitude different from modern ergs in areal extent and especially thickness. Pye and Tsoar (2009, p. 155) recognize this and offer three possible explanations for the differences: 1) there has been preferential preservation of ancient sequences because they were deposited in slowly subsiding basins or rift valleys, 2) some thick sequences represent multiple stacked ergs, 3) eolian processes may have been more effective in the past, especially before the development of land plants. Explanation (1) does not seem to apply to the Coconino because it crosses through many ancient basins. It does thicken and thin through these areas, like the Sedona Arch (Blakey and Knepp 1989). Explanation (2) may explain parts of the Coconino, especially in the Sedona area where there appear to be two members of the formation which Blakey (1990) calls the "Cave Springs Member" (upper part) and "Harding Point Member" (lower part). The contact is flat with no relief and forms a "green line" of vegetation about in the middle of the formation. Explanation (3) does not seem plausible because on a conventional time scale plants were around at least 100 million years before the Coconino was formed. These explanations do not seem reasonable for the Coconino or many of the other ancient cross-bedded sandstones. However, marine deposits do have the characteristics of being areally extensive and thick.



Dolomite Ooids and Proto-ooids	Dolomite Cement & Rhombs	Dolomite Clasts	Dolomite Beds
AC	AC AP	AC	AP
AP	TC WC	AP	BSG
HC	JUS HC	TC	SR (Scherrer Fm)
TC	WSC PB	WC	
WC	ASR SK	JUS	
JUS	HMT SFRC	WSC	
SFRC	SRM VRG	NHT	
		SFRC	

Figure 11. Map showing the extent and type of dolomite within the Coconino Sandstone (from Whitmore et al. 2014).

2. Petrology

A. General petrology

There is a great misconception that all desert sand grains become "well-rounded" over time. In a study of nearly 22,000 sand grains from many dunes, Goudie and Watson (1981) found very few "well-rounded" grains. Roundness is typically measured with a scale developed by Powers (1953) and modified by Folk (1955) which is shown in Fig. 46. Goudie and Watson found that sand grains in the 2.5 ϕ range had a mean roundness of 3.19 and in the 3.5 ϕ range had a slightly lower mean roundness of 3.04. Both of these values are on the lower end of the subrounded category. However, it is noteworthy that only negligible rounding takes place during non-eolian transport of sand grains. This has been observed in many experimental and real-world situations (Garzanti et al. 2012, 2015; Kuenen 1960; Russell and Taylor 1937; Twenhofel 1945). In the Garzanti et al. (2012, 2015) studies, sand was traced for hundreds of kilometers along the southwestern shoreline of Africa and no noticeable rounding occurred (despite active tidal and longshore currents) until the sand was picked up by eolian processes and transported to the Namib dunes. Then, "all minerals get rapidly rounded" (2015, p. 971). In considering ancient deposits that consist of nearly pure quartz grains and have abundant rounded and well-rounded grains (like the Ordovician St. Peter Sandstone, midwestern US) the consensus of most authors seems to be that the sand has endured multiple generations of eolian processing and that the "roundness" may not have come from the last depositional event (e.g., Dott 2003). Evidence for this is in the form of multiple "dust rims" around some of the grains. We found that the Coconino sand ranges in rounding from 2.5 to 3.4 (Figs. 9 and 10) Overall, the Coconino is more angular than what Goudie and Watson found for modern ergs. Since many observations have shown that rounding happens quickly in eolian settings, it is difficult to understand why the Coconino is not more rounded if the eolian hypothesis for its formation is correct.

The grain size of the Coconino ranges from about 3.45 ϕ in northern Arizona to about 2.75 ϕ in central Arizona, with a mean of about 3.0 ϕ (Figs. 5 and 6). This is smaller, but not out of, the range of mean grain sizes from modern dunes calculated from the data of Ahlbrandt (1979) and Whitmore et al. (2014), which is about 2.5 ϕ. Although grain size studies of modern marine sand waves are limited, the mean grain size in those is 0.25 to 0.5 mm (2.0-1.0 ϕ; Garner and Whitmore 2011), which is slightly coarser than the range of sand found in the Coconino. It is interesting to note that downwind grain sizes in modern ergs decrease (Crouvi et al. 2008; Jerolmack and Brzinski 2010; Lancaster 1995; Pye and Tsoar 2009; Smalley and Vita-Finzi 1968; Wright 2001). The cross-bedding in the Coconino indicates an increase of grain size with transport to the south.

The Coconino was more poorly sorted in northern Arizona compared to values that we found further to the south (Figs. 7 and 8). When comparing the overall grain size and sorting in the Coconino against modern eolian dunes, the Coconino appears to be somewhat out of range, which may be more consistent with aqueous depositional processes (Fig. 47). Wind tends to sort sand grains much better than water can. We think the grain size sorting in the Coconino is more consistent with an aqueous deposit.

B. Dolomite

Dolomite occurs in the Coconino as beds, ooids, cement and clasts over a relatively large area (Figs. 11-15). It is far from being a "dash of marine sediment" as some have suggested (Hill et al. 2016, p. 203). Although the formation of dolomite is still one of the biggest geological mysteries, its formation must be a wet chemical process (Lippman 1973) that requires special conditions with high temperatures (>100 °C) and/or high pressures (Arvidson and Mackenzie 1999). It also requires constant water circulation and a steady supply of Mg^{2+} and CO_3^{2-} ions (Morrow 1988). These conditions must all be met in order for the mineral to form, and certainly are not going to occur in a desert on any large scale. The presence of dolomite, in four different forms, in the Coconino strongly argues for aqueous deposition.

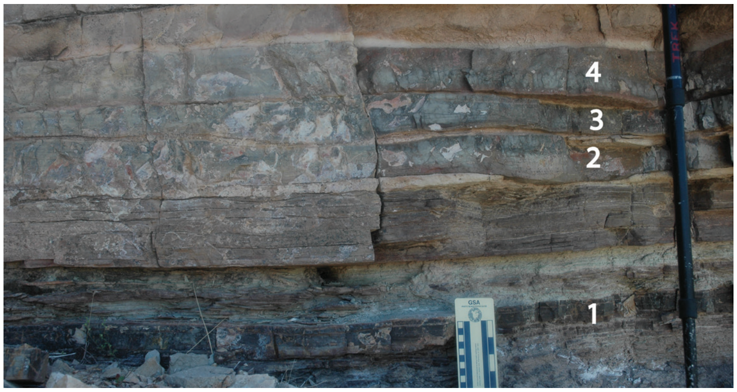


Figure 12. Dolomite beds in the Coconino at Andrus Point, Arizona. JHW photo 9412-2008.

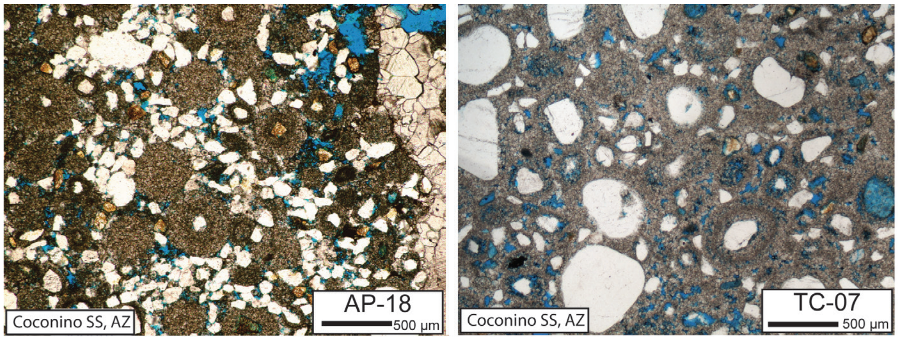


Figure 13. Dolomite ooids contained within the cross-bedded sands of the Coconino.

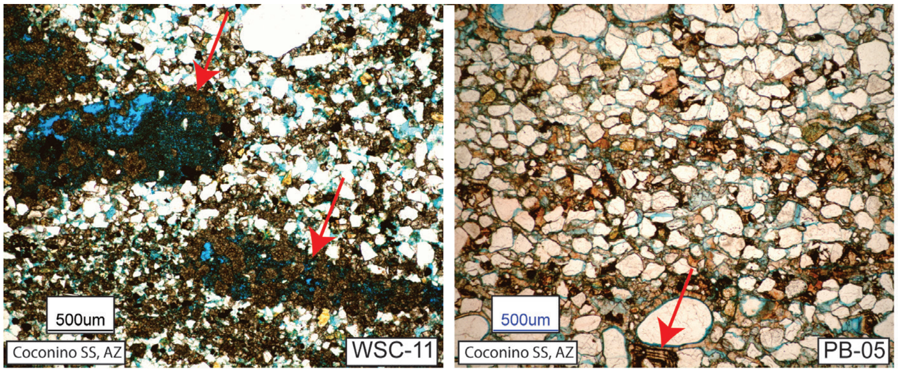


Figure 14. Dolomite cement within the Coconino. WSC-11 has dolomite cement (brown) and several dolomite clasts (two indicated by red arrows). PB-05 has brown dolomite cement, some of which has been replaced with calcite (red). A dolomite rhomb is indicated by the red arrow.

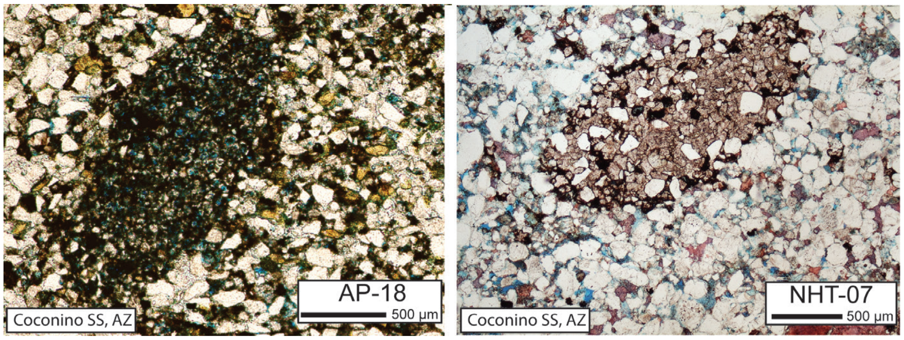


Figure 15. Dolomite clasts within the Coconino Sandstone. Also see Fig. 14. It is important to note that the clasts were transported along with all of the other surrounding grains. The clasts are likely too big to be transported by wind; wind sorts materials better than this.

C. Muscovite

As Anderson et al. (2017) have shown, muscovite flakes rapidly deteriorate (within days) with constant eolian action, but can last more than a year with constant aqueous tumbling. Mica was sparse in our investigations of modern ergs and only occurred when a crystalline rock source was nearby. Garzanti et al. (2012, 2015) confirmed our observations that mica degrades rapidly in eolian settings. In their studies they found mica in the shoreline sediments, but it disappeared as it was transported to the Namib erg. The presence of muscovite flakes in nearly every thin section of Coconino that we studied (Fig. 16) strongly argues for an aqueous origin of the deposit (see Borsch et al. 2018 in these proceedings).

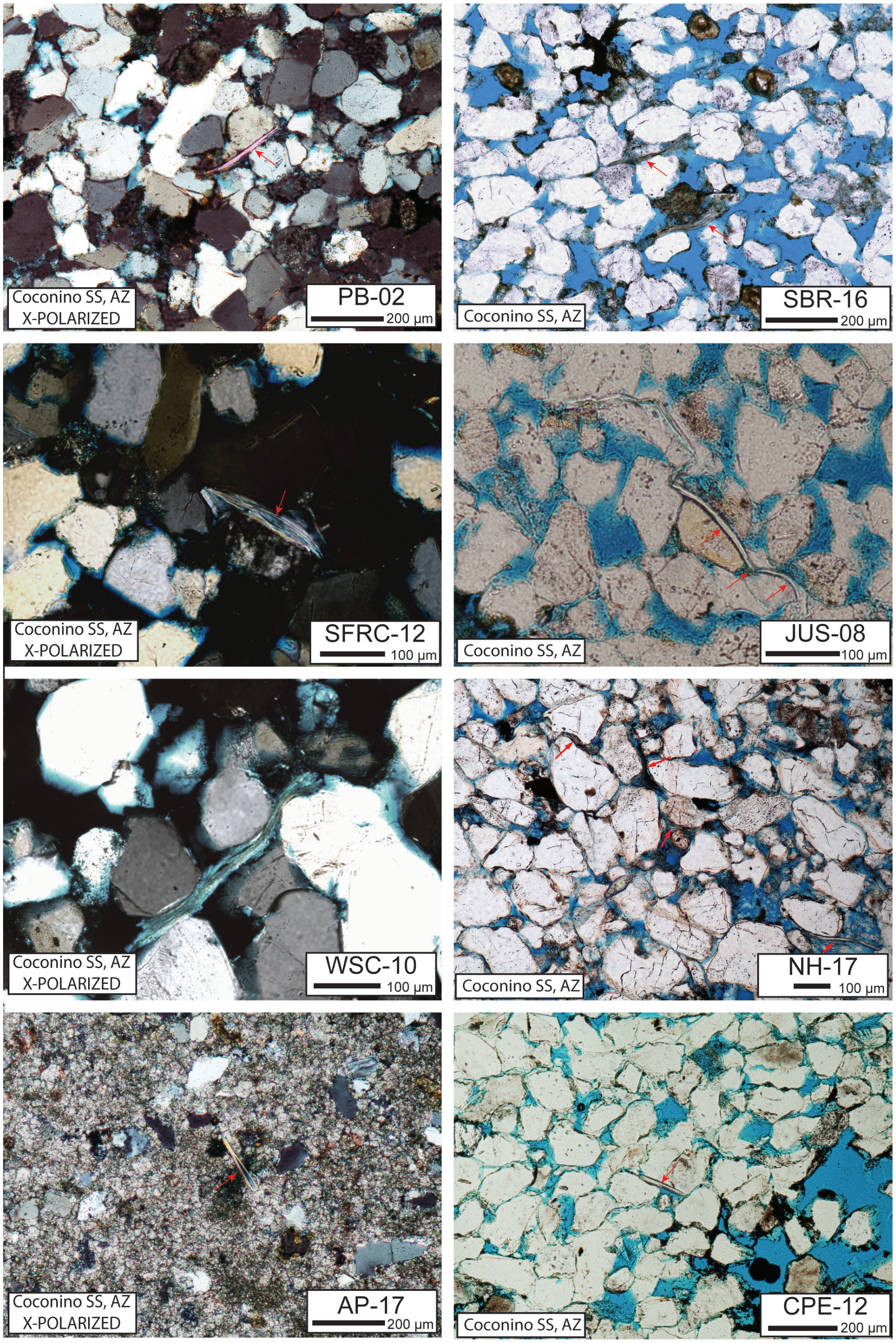


Figure 16. Mica within the Coconino Sandstone (from Whitmore et al. 2014). Most is muscovite, but occasional biotite has been found as well. Small red arrows show the locations of the mica.

D. Orthoclase

Orthoclase, or K-feldspar, is a fairly common mineral in most Coconino thin sections, comprising about 6-10% of the studied samples (Whitmore et al. 2014). Most surprising were angular K-feldspar grains that were sometimes more angular than the quartz grains that surrounded them (Fig. 17). K-feldspar sand remains angular in aqueous settings (Kuenen 1960; Russell and Taylor 1937; Twenhofel 1945) and only becomes rounded when it is transported by wind (Whitmore and Strom 2017; Garzanti et al. 2012, 2015). Garzanti et al. (2015) found the following sequence of mechanical durability of various mineral species in the Namib erg: garnet > quartz > epidote > volcanic rock fragments > feldspars > opaques > pyroxene > amphibole > sedimentary rock fragments. Whitmore and Strom (2018, these proceedings) showed that angular K-feldspars are not only common in the Coconino but in many other supposed eolian sandstones as well. It is difficult to understand how angular K-feldspars could survive in an eolian environment without becoming rapidly rounded unless there was a nearby fluvial or bedrock source. In the absence of a nearby source for the angular K-feldspar, it strongly favors an aqueous origin for the Coconino.

E. Zircons

Gehrels et al.'s (2011, p. 197) analysis of zircons within the Coconino indicates that many of them were probably derived from the mid-Proterozoic rocks of eastern North America, or possibly, but less likely, from the Ouachita orogen. They suggest that large rivers and northeasterly trade winds carried the Coconino sand from these areas to where it formed dunes during the final stages of the collision of North America with the African continent. We think the zircon evidence is compelling and does suggest a distant origin for some of the Coconino sand. However, based on the muscovite and angular K-feldspar that we have documented in the formation, we feel that some type of aqueous transport was primary. Eolian transport would have quickly rounded the K-feldspars and caused the micas to disappear.

F. Frosting

The Coconino sand grains are "frosted" (Fig. 18), but they have not been frosted by ballistic collisions of sand grains in an eolian environment as some have imagined. Our SEM work has shown that the grains have been frosted via chemical means, not mechanical (Whitmore et al. 2014). Marzolf (1976) found the same for the Navajo Sandstone. Grain size plays a large role in mechanical frosting. In modern deserts, only larger grains (> 300 µm, 1.74 ϕ) tend to be mechanically frosted (Pye and Tsoar 2009). Most Coconino grains are quite small, in the range of 90-148 µm (3.47-2.76 ϕ). Kuenen and Perdok (1962) found that frosting becomes less pronounced in a range of grain sizes from 500 to 150 µm (1.00-2.74 ϕ). Almost no grains of the smaller grain size were mechanically frosted. Thus, frosting should not be used as a definitive eolian criterion for the Coconino (or other sandstones) until SEM and grain size studies are completed to confirm whether the frosting is mechanical or chemical.

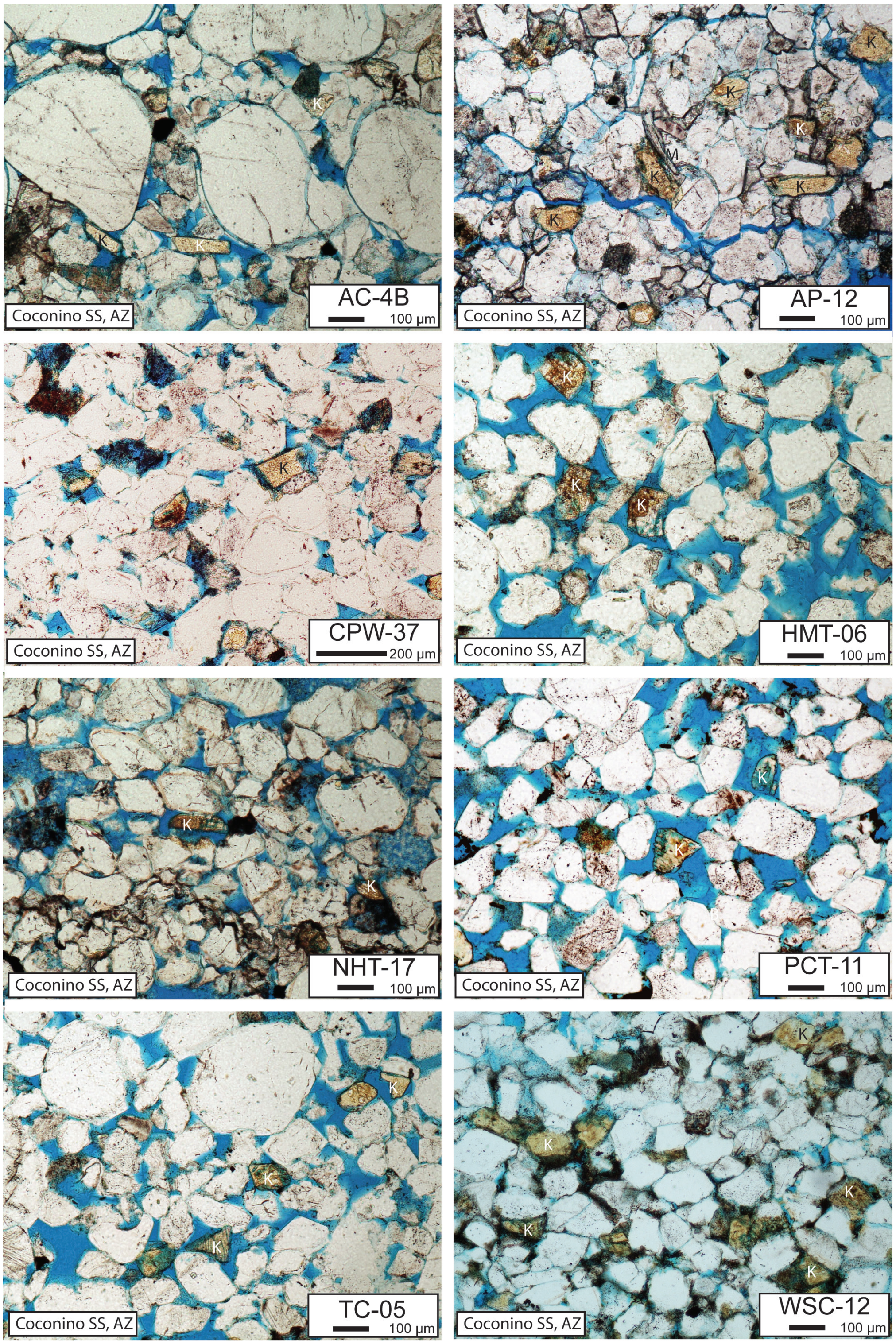


Figure 17. Angular K-feldspar (orthoclase) within the Coconino Sandstone (Whitmore and Strom 2018). Some of the grains are labeled: (K) K-feldspar and (M) muscovite.

G. Compaction

Some have recognized that cross-bed dips in supposedly eolian cross-bedded sandstones are too low and have cited post-depositional compaction as the reason for consistent dips far less than the angle of repose (e.g., Glennie 1972, p. 1058; Hunter 1981, p. 323; Walker and Harms 1972, p. 280). As far as we know, no one has cited compaction as a reason for the low Coconino dips; most (as in Hill et al. 2016) just seem to be ignorant of data that has been in the literature for 80 years (Reiche 1938). Whether or not the Coconino has been compacted from the angle of repose down to an average dip of about 20° is fairly easy to assess in thin sections. Coconino thin sections show high porosities (Fig. 19), an abundance of unfractured grains (Fig. 19) and undeformed ooids (Fig. 13), which would not be present if the rock had been severely compacted. Some theoretical work has been done to see if compaction is a reasonable hypothesis to account for lower than expected cross-bed dips in the Coconino, and it is not (Emery et al. 2011). Compaction can probably account for only a few degrees of dip reduction at the most.

3. Sedimentology

A. General appearance

If the Coconino was truly an eolian sandstone, one of the missing features that should be prominently displayed are avalanche tongues. These are common in modern desert dunes of all types and occur as sand avalanches down the lee slope scooping out and filling a long tongue-like feature on the dune (Fig. 22) which can often extend down the entire length of the lee slope (as seen in Fig. 22). Hunter (1977) illustrates cross-sections of the "tongue-like" features in his paper, which he calls "sand flow cross-strata." Instead of finding these features in the Coconino, the foreset beds seem to be rather continuous beds of either laminated or massive sand (as it appears in the outcrop). The continuous nature of these beds along strike (Fig. 21) makes it appear that these beds may have formed from some type of continuous avalanche process across the entire lee face of the dunes. Maithel et al. (2013, 2014, 2015, 2016, 2017) have been working on an explanation for the sedimentology of the beds, but to date it does not appear that they are similar to any of the types of stratification in dunes outlined by Hunter (1977).

Hunter (1981) reported a number of the features that he identified in modern sand dunes in supposed ancient dunes of the western United States. In his survey of sandstones, he mentions that he was on the Bright Angel Trail and looked at the Toroweap Formation (p. 321), which is just above the Coconino. However, he apparently did not make it down the trail a little further to look at the Coconino (which fails to get mentioned in the paper). However, Hunter recognized that the tongue-like sand flow cross-strata are quite common in modern dunes, but nearly absent in ancient sandstones. He comments (pp. 319-320):

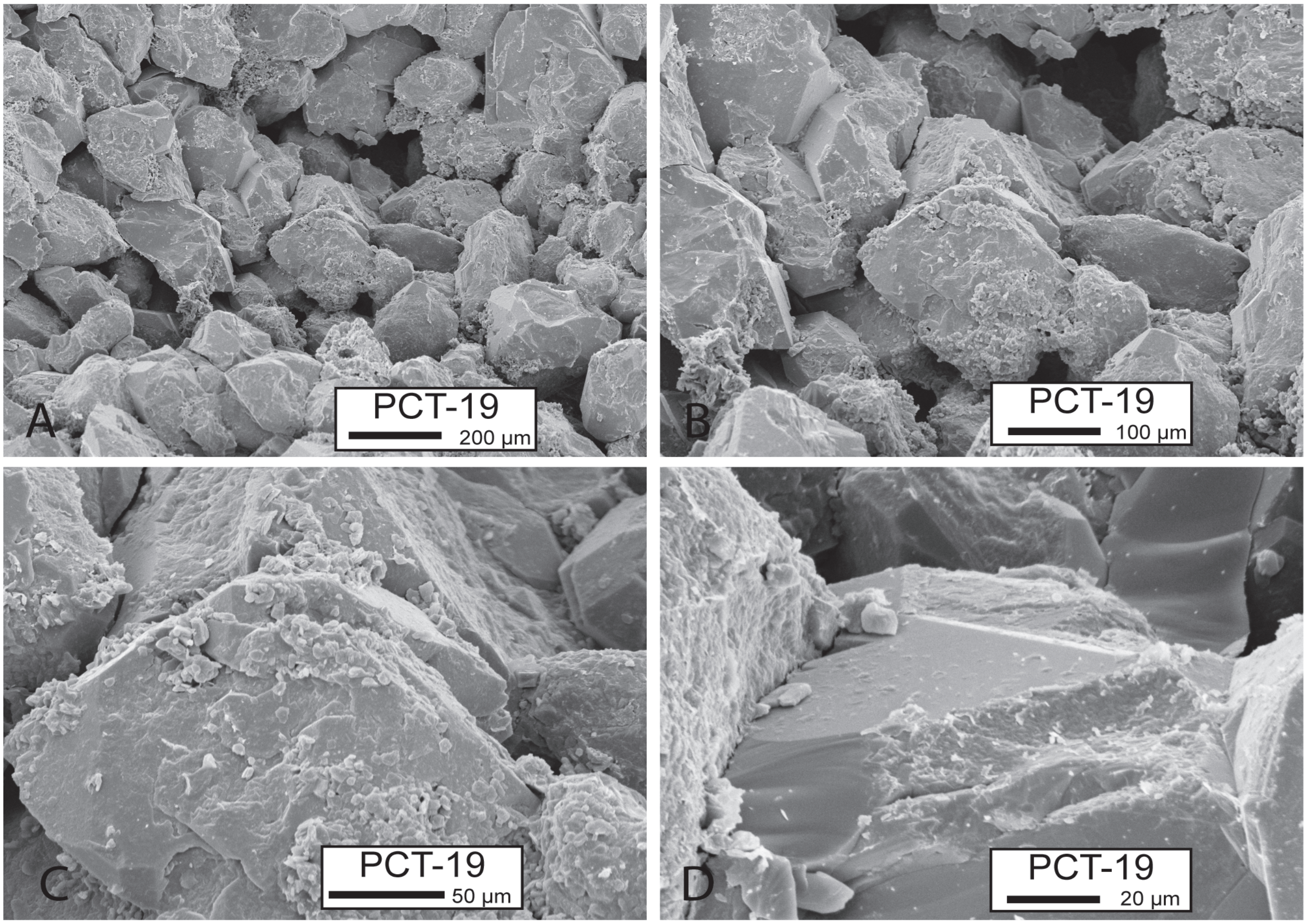


Figure 18. Chemical frosting of the Coconino sand grains (Whitmore et al. 2012).

A. PCT 19 100x-02. A poor to moderately-sorted example of Coconino Sandstone. At this magnification, it is apparent that most of the grains have quartz overgrowths.

B. PCT 19 200x-03. Clean crystal faces delineate growth of quartz into open pore spaces. Very few grains in this view do not have quartz overgrowths or clay coatings (authigenic kaolinite and illite). Dissolution of many feldspar grains provided a source for later quartz and clay precipitation. Large open pores, having roughly the same size as the grains, is a possible indication of almost complete dissolution of some grains with the only parts remaining being the clay rims. Undulose and conchoidal fracture surfaces give a "frosted" appearance.

C. PCT 19 500x-04. A grain surface exhibiting deposits of individual flakes of kaolinite as well as small booklet structures (middle-upper). This grain surface also has quartz overgrowths present as at lower left. Quartz overgrowths (upper right and upper left) provide an interlocking structure providing cohesiveness to the rock.

D. PCT 19 1000x-05. Image of a quartz overgrowth showing conchoidal fracturing (mid lower left), a face with an irregular surface (center) and a highly irregular surface (middle) that is most likely a parted contact between it and an adjacent grain surface. Illite has grown on this surface and is the white, wispy material. The grain surface on the left is highly irregular and is in contact with the quartz cement. This surface appears to be strongly chemically etched rather than abraded. This is not surprising given the degree of dissolution features and precipitation that has occurred in this rock.

> Sand flow cross-strata are quite common in the [ancient] sandstones discussed here. Narrowly lenticular sand flow cross-strata, such as are common in small modern dunes of the Oregon and south Texas coasts (Hunter, 1977) and in some desert dunes (Sharp, 1966), are very rare in the [ancient] sandstones discussed here. Rather, the individual sand flow cross-strata typically extend many meters along the strike of the cross-stratification. In addition, the sand flow cross-strata of the ancient sandstones differ from those of modern small dunes by typically being in contact with other sand flow cross-strata rather than being separated from one another by grainfall deposits. The general absence of fadeout laminae (defined by McKee et al. 1971) within the sand flow cross-strata indicates that the flows became thoroughly mixed before coming to a stop. Structures indicative of slumping down a slipface are very uncommon in the sandstones discussed here (McKee, 1979, p. 192).

We concur with Hunter that these structures are very rare. We did not locate any lenticular-like flows in the Coconino and we think the absence of such features in the Coconino and other sandstones is indicative of aqueous processes. We did find these features preserved in the sediments of numerous modern subaerial dunes that we studied (Fig. 22), but these features have not been identified in subaqueous dunes. Instead, subaqueous dunes tend to have very wide avalanche surfaces (Hunter 1985).

Modern sand dunes that have been excavated have revealed a number of small-scale structures (McKee and Bigarella 1979b). We failed to find many of these features in the Coconino. Things that resemble some of these features are present, like overturned folds, but they are not laminae-scale or cm-scale features as illustrated by McKee and Bigarella 1979b; instead, they are meter-scale (like the parabolic recumbent folds).

We did locate a number of low-amplitude ripples with crests parallel to slopes (Fig. 23) and features that were slump-like (Fig. 24). However, these kinds of ripples are known to occur in similar style on various sand waves and related subaqueous features (Houbolt 1968). The "slumps" may actually be slumps, but they cannot be explained in an eolian environment because the dips

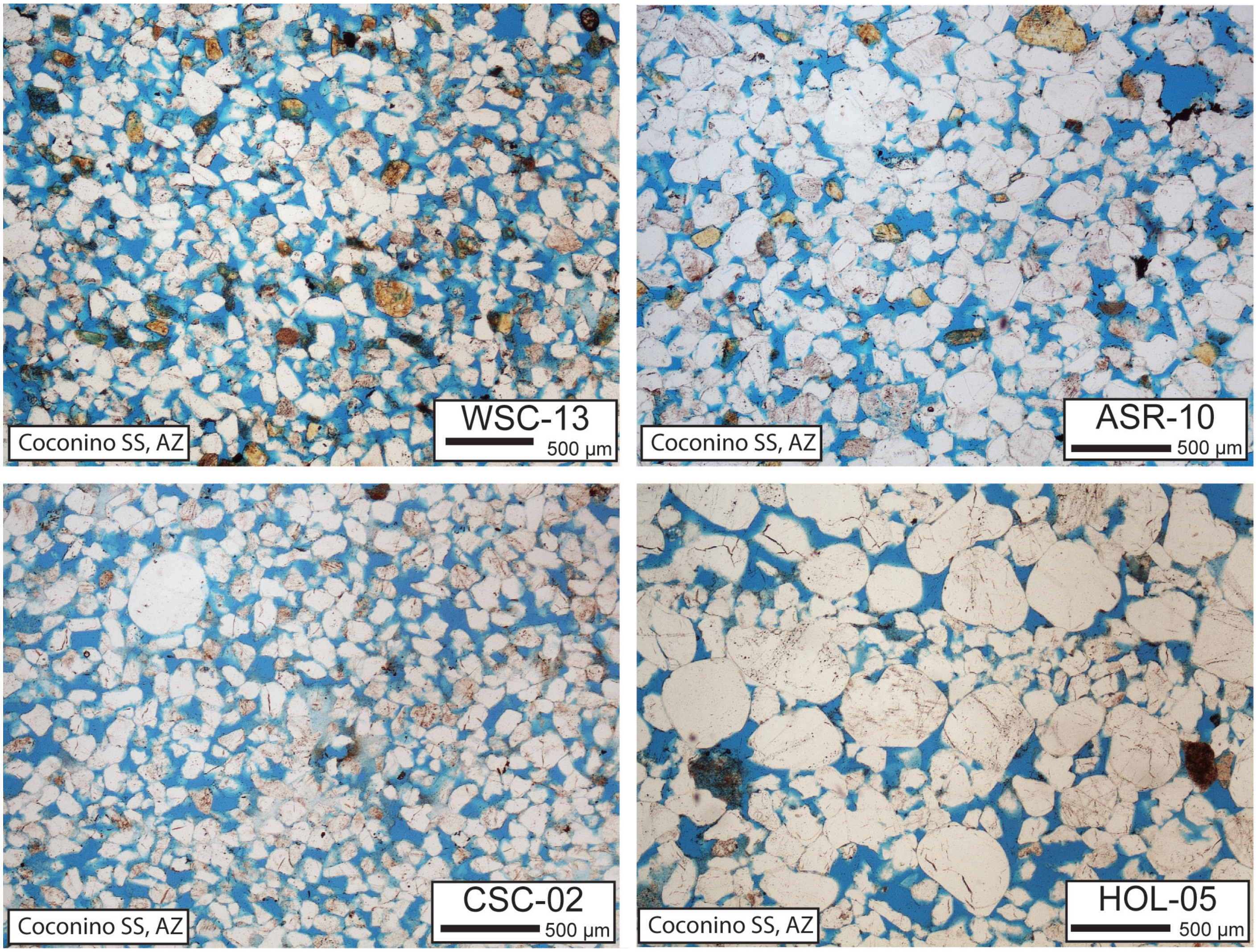


Figure 19. Thin sections show there has been very little compaction within the Coconino Sandstone. This data rejects the hypothesis that the cross-beds of the Coconino have been significantly compacted in order to make the observed dips (averaging about 20º) much less than the angle of repose (about 33-34º). Also see Fig. 13 which shows no compaction of dolomite ooids.

Figure 20. Tabular and wedge cross-bed sets in the Coconino as seen near the bottom of the formation along Hermit Trail in Grand Canyon. Notice how the cross-bed sets have a relatively constant thickness along dip until near the bottom of the set. Sometimes near the bottom they thin and form a "wedge." The set between the two major bounding surfaces is about 8 m thick. JHW photo 8142-2013.

Figure 21. A bounding surface (the horizontal rock surface) within the Coconino has been exposed to reveal the many thin foreset laminae that can be traced for many meters along strike (toward the girls). The beds are dipping to the left. Some gradually pinch out over the length of the outcrop. This is much different than cross-sections of avalanche tongues that can be found in modern dunes (see Fig. 22). This exposure is near Ash Fork, Arizona. One m hiking stike near middle of photo. JHW photo 9391-2013.

are too shallow for the sand to fail in such a way (dips that the structures are contained within are often 20° or less). However, if the slump occurred in a subaqueous setting, it is possible the failure could have occurred on a shallow slope and been driven by a down-slope current.

B. Cross-beds and cross-bed dips

It has been incorrectly stated by some that the Coconino has steep cross-beds which are close to the angle of repose (e.g., Hill et al. 2016, pp. 58, 70, 202). In fact, a whole series of cross-bed dips were published by Reiche (1938) whose mean dip was very close to our mean dip of about 20°. Another misunderstanding that many have is that the angle of repose (about 33°) is less under water than it is in air. This is false. The angle of repose underwater is about the same as that in air (Allen 1970a; Carrigy 1970; Hunter 1985). In aqueous settings a variety of factors (velocity, water depth, amount and type of entrained sediment) control whether cross-beds or plane beds are formed. In general, the faster the current the lower the angle becomes on cross-bed dips until plane beds are formed in the upper flow regime.

A possible explanation for cross-bed dips less than the angle of repose, is that the upper (steeper) parts of the cross-beds have been eroded away by the next migrating set of cross-beds (e.g., Poole 1962, p. 148). We do not know how steep the upper parts of the cross-beds were (or how tall the bedforms were) because we do not have the upper parts of the dune to measure, so this may be a possibility. However, in extremely thick (> 15 m) cross-bed sets that were measured by Maithel (personal communication, 2018) in the Ash Fork area, dips remained fairly constant at about 23° from the top of the set until a meter or two near the bottom of the set where the cross-beds rapidly flattened out (see Fig. 28). This pattern occurs throughout much of the Coconino which may suggest the tops of the dunes were never much steeper than the bottoms.

Sand waves have not been studied extensively because they occur in underwater settings with strong current flows. However, it is interesting that measured cross-bed dips of sand waves are in the range for the dips that we see within the Coconino and other cross-bedded sandstones. The lee slopes of sand waves in marine and estuarine settings typically display angles of less than 20° but have been reported to reach more than 30° (e.g., Aliotta and Perillo 1987, p. 11; Cornish 1901, p. 170; Dalrymple 1984; Elliott and Gardiner 1981, p. 58; Langhorne 1982, p. 580; Ludwick 1970; Salsman et al. 1966, p. 13; Werner 2000, p. 87). In some instances, smaller sand waves were found to be steeper than larger ones (e.g., Dalrymple 1984). However, the opposite trend was reported for the sand waves off the coast of western Australia (Jones et al. 2009). Lee slope angles in sand waves depend on a variety of factors, including tidal current velocity, tidal current asymmetry, bed load versus suspended load transport, grain composition, grain size and textural characteristics, and these relationships warrant further investigation.

C. Laminae

Hunter's types of dune stratification (1977) have been widely cited, but we have had difficulty identifying clear examples in our study as has Maithel et al. (2013, 2014, 2015, 2016, 2017). Hunter

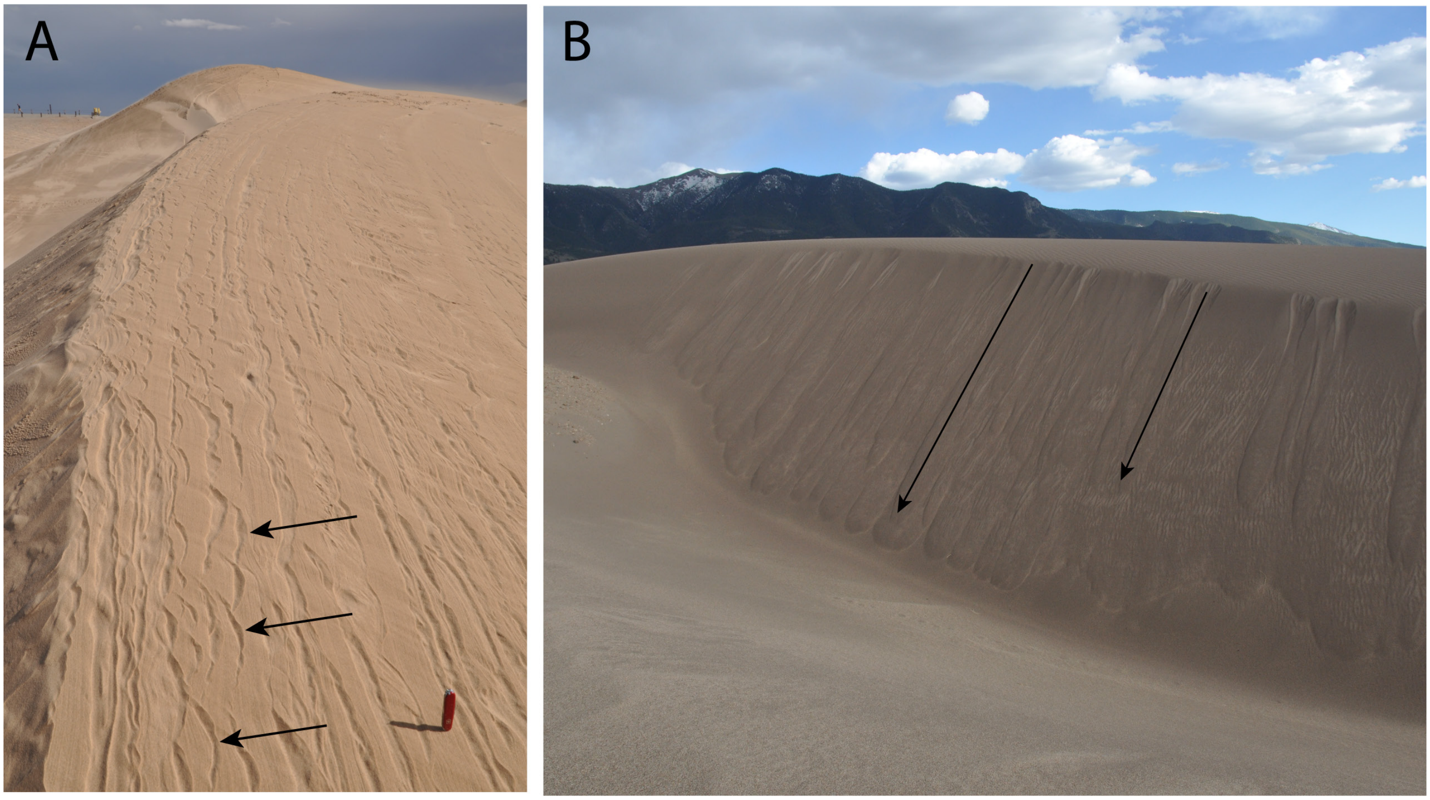


Figure 22. (A) The brink of a modern dune showing multiple crescent-shaped avalanche tongues in cross-section, features that are missing in the Coconino and most other ancient cross-bedded sandstones (see Hunter 1981). This photo was taken at the brink of a dune a day after a heavy rain; the side lee side of the dune is to the left. Wind subsequently polished the stoss slope (to the right) exposing the cross-sections of the avalanche tongues. Red pocketknife for scale. Glamis Dunes, California. JHW photo 0139-2015. **(B)** Multiple avalanche tongues down the lee face of a dune in Great Sand Dunes National Monument, Colorado. Note that some of the avalanche tongues extend all the way to the bottom of the dune. JHW photo 1298-2009.

recognized six types of eolian strata: planebed laminae, rippleform laminae, ripple-foreset cross-laminae, climbing translatent strata, grainfall laminae and sand flow cross-strata. The only authors who have commented as to whether these types of laminae are present in the Coconino or not are Middleton et al. (2003). They suggest that most of the laminae within the Coconino are wind-ripple laminae, sand flow cross-strata and minor grainfall laminae (pp. 171, 174). Although more study needs to be completed in this area, it seems to us that the laminae in the Coconino might be better explained as subaqueous sand flow cross-strata (Hunter 1985) or something similar. These types of strata have similarities to eolian sand flow cross-strata in that the dips are fairly constant from the top to the base of the foresets, the cross-strata are generally straight and can have a slight to moderate concave-upward curvature near their toes (p. 887). Additionally, at least in smaller subaqueous dunes, Hunter states that sand flow cross-strata are very wide and have poorly defined lateral edges, whereas eolian sand flows are narrow and have well-defined lateral edges (p. 890). We think this better matches the thicker laminae we see in the Coconino, although more work needs to be done.

Rouse (2017) did some preliminary work on tracing laminae in thin sections of Coconino. The laminae are very difficult to trace with certainty even over the 5 cm or so length of a thin section. One possibility that might explain discontinuous laminae is spontaneous sorting of grains as they are deposited during grain avalanche events. Makse et al. (1997, 1998) showed that these processes

Figure 23. Low amplitude ripples, parallel to dip, that can occasionally be found in the Coconino. This is a slab of float that was oriented so the sun highlighted the ripples a bit better. West side of Chino Point, Arizona. JHW photo 5797-2007.

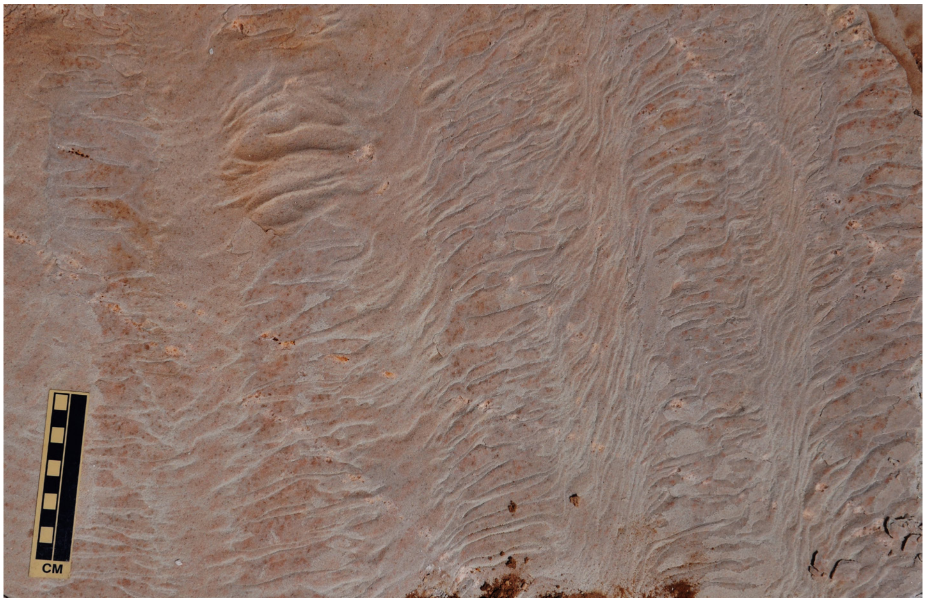


Figure 24. Slump-like features that can occasionally be found in the Coconino. The dip is only 23 degrees on this outcrop—about 10 degrees too shallow for slumping to occur in dry material. We are still not sure what the origin of these features are, but they appear to be more ripple-like than slump-like. Near Ash Fork, Arizona; Maithel's ASF-4 site. JHW photo 0318-2018.

Figure 25. A variety of small pits on bedding surfaces (rather rare) are sometimes interpreted as raindrop prints. They sometimes occur in vertical rows with low-relief ripples and other curious features as seen here; always going down dip. See also figs. 32-36. JHW photo 0331-2018.

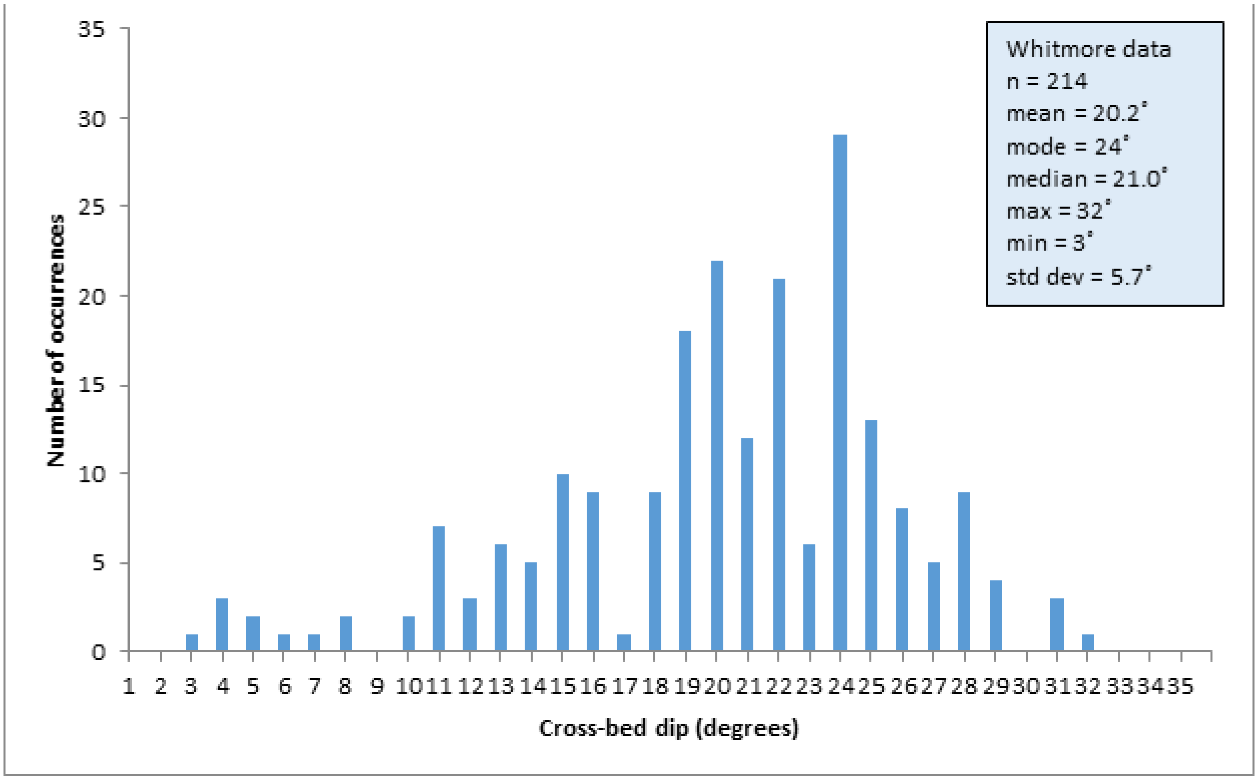


Figure 26. Our data from measured cross-bed dips in the Coconino from many different locations.

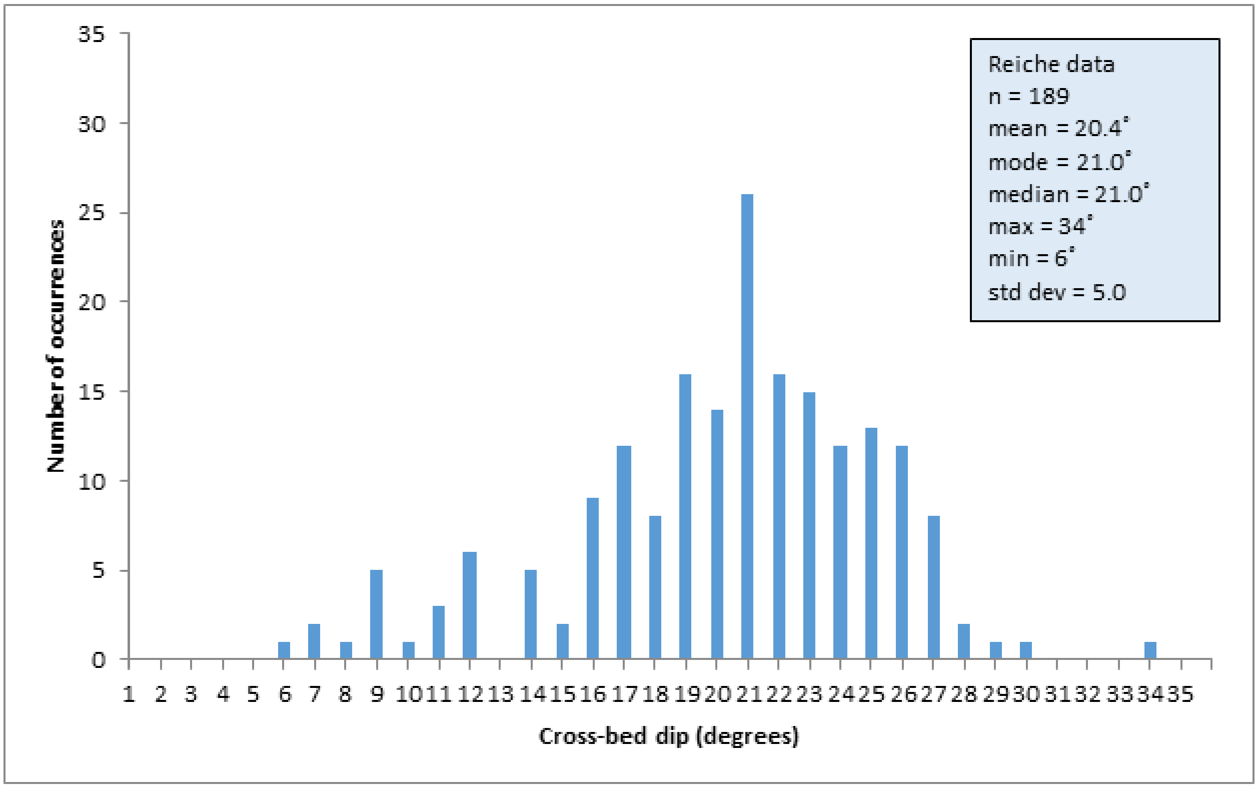


Figure 27. Reiche's (1938, p. 908, 925) data of cross-bed dips in the Coconino from four different localities. The data was gathered from his four plots and then entered into Microsoft Excel so the statistics could be calculated.

happen in air. Creationists have also done some preliminary work in this area and showed that particles can also spontaneously sort in aqueous heterogeneous sand mixtures (Julien et al. 1994). This would be a productive area of continued research with the laminations of cross-bedded sandstones, called "wind ripples" by some, in mind.

There are some other mechanisms that can make graded laminae in subaqueous conditions. Normally graded parallel lamination can be produced by the migration of very low relief ripples during upper flow regime flow (Paola et al. 1989). Cheel and Middleton (1986) found that very thin and extensive graded beds (both normally and reversely graded) can form under conditions of the upper flow regime. They found that "bursts" formed fining upward (FU) sequences and "sweeps" formed very thin coarsening upward (CU) sequences. The FU sequences were thicker than the CU sequences, some of which were very extensive and less than 1.0 mm thick. Sometimes ungraded layers were produced. Kleinhans (2004, p. 77) indicates sweeps are a dominant process on the lee sides of large subaqueous dunes (which form thin CU laminae). In many places, the Coconino is finely laminated with beds that resemble CU sequences on the foresets. One mechanism that could produce these fine laminae on the foresets are these sweeps.

D. Planar and massive beds

Planar beds, which are very unusual in the Coconino, were found at several locations. In Sedona, they were associated with large parabolic recumbent folds (discussed below) which may indicate a flow regime change if the sand was being transported and deposited subaqueously, and would also help explain the folds (Whitmore et al. 2015). Planar beds at Andrus Point were composed of pure dolomite and the cross-beds above contained dolomite ooids which would be very unexpected in an eolian setting, but would be much easier to explain in a marine setting (Whitmore et al. 2014). Planar beds in Kaibab-Buckskin Gulch area had abundant calcite and dolomite cement.

Massive beds that contained bedded clasts of Coconino Sandstone were found at several locations near the base of the Coconino (Fig. 30). Whitmore and Strom (2010) proposed that these beds were a reaction to a seismic shock, likely originating from the Bright Angel Fault during Laramide events in the Grand Canyon region. They argued that the basal Coconino had to be water-saturated and only partially lithified (at most) during the faulting. This caused liquefaction of the basal Coconino which destroyed most laminations and created the massive (unbedded) layer. This layer was then able to flow horizontally and downward into the Hermit Formation, forming the sand-filled cracks (discussed below) that can sometimes be found at the base of the Coconino. This scenario has abundant evidence (Whitmore and Strom 2010) but causes a time problem for the conventional view. Conventionally, the Coconino was deposited about 275 million years ago and the displacement along the Bright Angel Fault occurred about 225 million years later during the Laramide uplift of the Grand Canyon area, about 50 million years ago. The problem for the conventional view is how the Coconino remained unlithified for such a long period. In a young-earth view, there is no problem because the timing of Coconino deposition and regional uplift was probably less than a year and the Coconino would have been still water-saturated due to being deposited during the Flood. Thus, the massive bed and the associated injectites eliminate millions of years of geological time from the strata of the Grand Canyon.

E. Parting lineation features

Parting lineation (also called current lineation, parting-step lineation or sand streaks) is commonly found on most cross-bed surfaces of the Coconino. These features are well known from subaqueous current deposits of various types (Allen 1970b; Cheel 2003; Corbett 1972; Picard and Hulen 1969; Stokes 1947) and have been produced experimentally in the laboratory (Mantz 1978; Weedman and Slingerland 1985). According to Stokes (1968, p. 1419) current

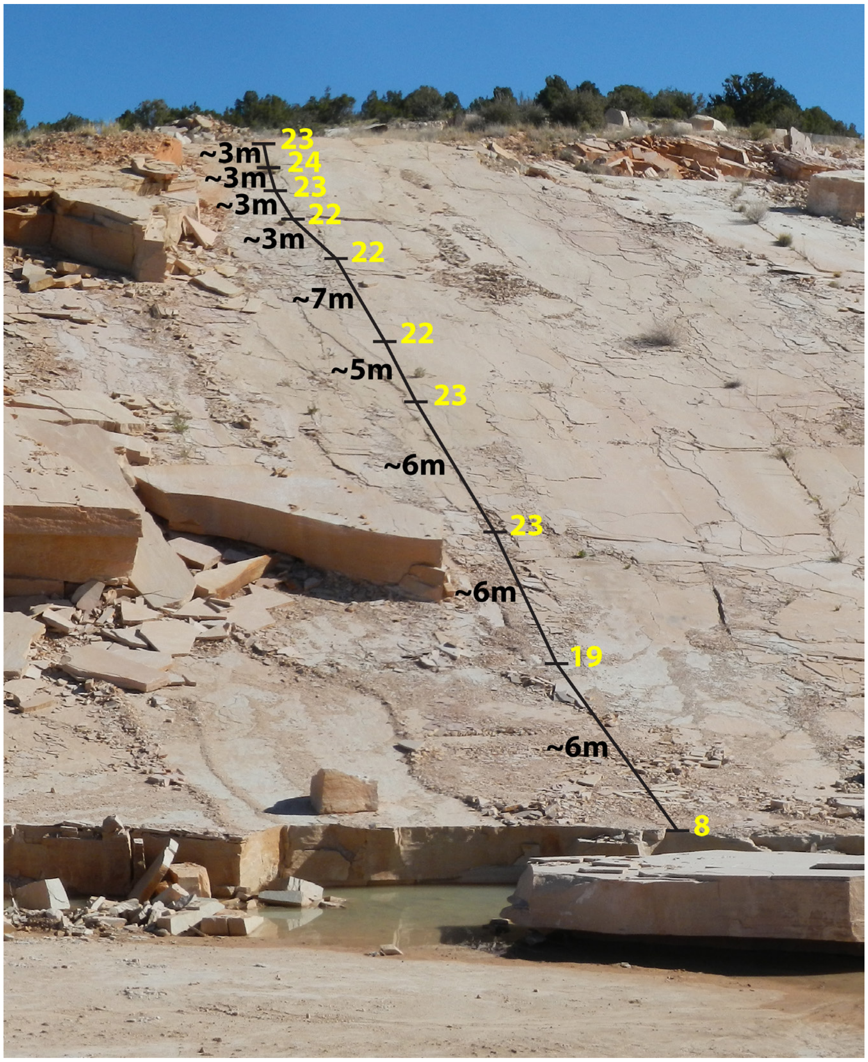


Figure 28. Cross-bed dips vary little on some of the longest-known foresets in the Coconino. The yellow numbers are dip angles and the black numbers show the distance between measurements. The cross-bed set has a vertical thickness of just over 15 meters. Photo and data courtesy of Sarah Maithel. Santa Cruz Quarry near Ash Fork, Arizona.

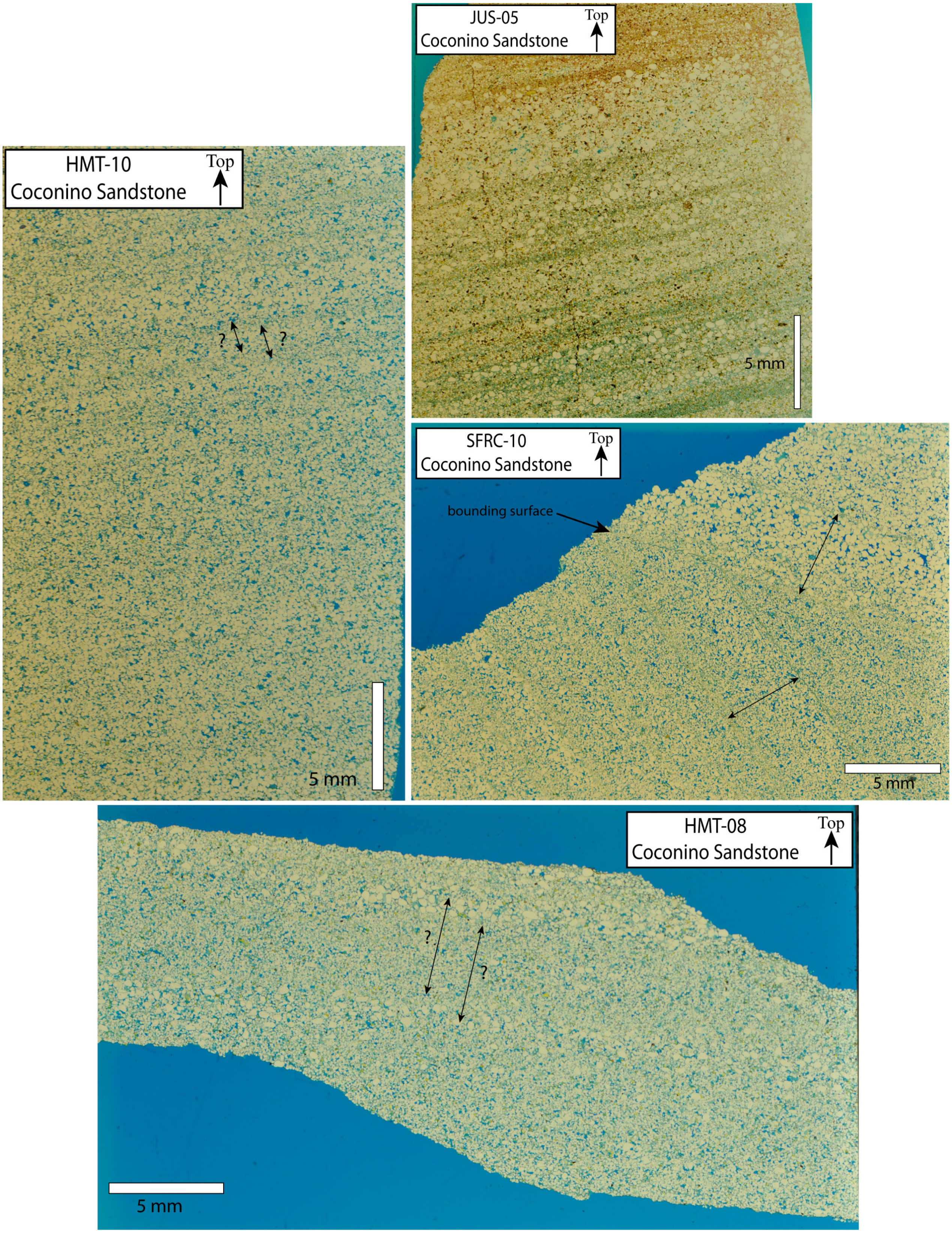


Figure 29. "Laminated" Coconino Sandstone. It is often difficult to tell whether the laminations are normal or inversely graded as in HMT-10 and HMT-08. In other samples, the grading is clearly inverse as in JUS-05 and SFRC-10. Both types of grading can be found in eolian deposits (Hunter 1977). According to Hunter (1985) in subaqueous cross-strata, inverse grading dominates in the upper and middle parts of the dune with sharp contacts between laminae. In the lower part of the set, laminae are less regular and normal grading is more common when laminae are present. It is important to understand that Hunter's studies (1977, 1985) were made on relatively small dunes. More laboratory and field study is needed on large dunes as would have been the case in the Coconino. Note the bounding surface preserved in SFRC-10.

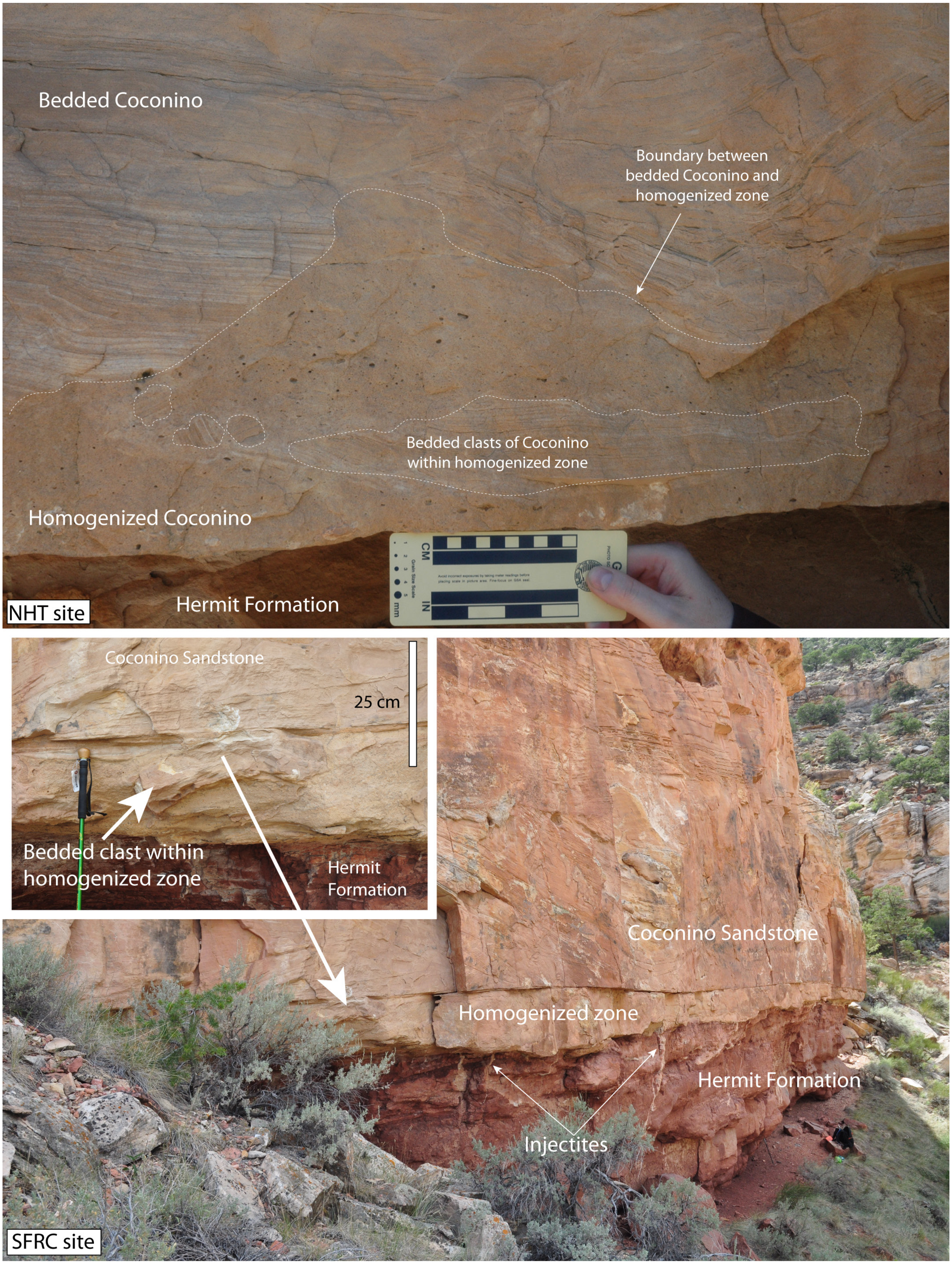


Figure 30. Homogenized (massive with no layering) beds have been found at the base of the Coconino in several locations. Bedded clasts of Coconino can be found within the beds showing that the "homogenization" was an intrastratal process. JHW photos 5946-2007, 5270-2009, 5267-2009.

lineation forms due to a "streamlining effect on loose sand grains parallel with the current direction." Allen (1970b, p. 68) reports them "on the backs of active [subaqueous] sand ripples and dunes, where there is erosion." Allen (1985, p. 111) believes that current lineation can form under a variety of subaqueous conditions probably due to parallel vortices traveling in the boundary layer next to the sediment/water interface. Current lineation is a well-known feature of upper flow regime plane beds (Allen 1984; Fielding 2006; Paola et al. 1989). At least one author has suggested that current lineation is also produced in eolian settings, but this was based on observations of the features in sandstones interpreted to be eolian, not observational evidence in actual eolian environments (Tanner 2001). He thought current lineation would only occur at the base of the dunes where grainfall and wind ripples are the dominant sedimentary processes and structures; we have found them on bedding planes far from the lower bounding surfaces where sand flow would likely be the dominant process. Except for this one instance, as far as we know, the literature has only associated current lineation with aqueous deposits.

Figure 31. Most surfaces of the Coconino foresets are covered with parting lineation features. WSC site. RS photo 0219-2008.

F. "Raindrop" prints

It has often been claimed that raindrop prints are one of the most distinctive characteristics that indicate the Coconino is eolian (McKee 1934; McKee and Bigarella 1979a; Middleton et al. 2003; Ranney 2001). Often the crater-like features can even be found with slight disturbances down-dip, as one might expect from a raindrop impact on a steep sandy slope. However, the "raindrop" prints preserved in the Coconino have different characteristics than raindrop prints found in modern settings. First, when most think of raindrop prints, they usually think of well-defined crater-like depressions in mud. But, raindrop prints in sandy substrates do not typically form well-defined crater-like depressions. Instead, the surface becomes rather mottled and the prints do not form distinct craters (Fig. 35). Second, the "raindrop" prints in the Coconino typically occur in linear zones, not in randomly scattered patterns as one would expect (Fig. 36). Third, some things that look like raindrop prints are probably burrows or some other feature because the structures vertically penetrate the sand, some about 1 cm (Fig. 32).

At this point we do not know for sure what the "raindrop" prints are. It appears that several different features have been referred to "raindrop" prints. At least some of them are closely related with current lineation features. Since they often form in "zones" perhaps they are related to some type of water or gas escape process occurring between the vortices that form current lineation (Allen 1985, p. 111). Others may be related to burrowing activity (Fig. 34). In any case, we do not think the small crater-like features can be raindrop prints, because raindrops make a mottled surface in sand, not well-defined craters (Fig. 35).

G. Ripples

In modern dunes, wind ripples can often be found parallel to dip on the lee slopes of dunes, often interfingering with sand flow avalanches. Lee slopes of modern dunes are almost always either covered with avalanches, wind ripples or both (Fig. 22B). Sometimes grainfall deposits are present resulting in a smooth dune surface, but these surfaces are often quickly modified either by avalanches or wind ripples. Down-dip wind ripples form as vortices travel perpendicular to the lee face of the dune, even when the wind is blowing over the top of the dune in a direction that parallels the ripples. Several authors have reported similar ripples in the Coconino (McKee 1945; McKee and Bigarella 1979a; Middleton et al. 2003) and we have found them as well, but they are not as common as one might expect if this was truly an eolian environment. They

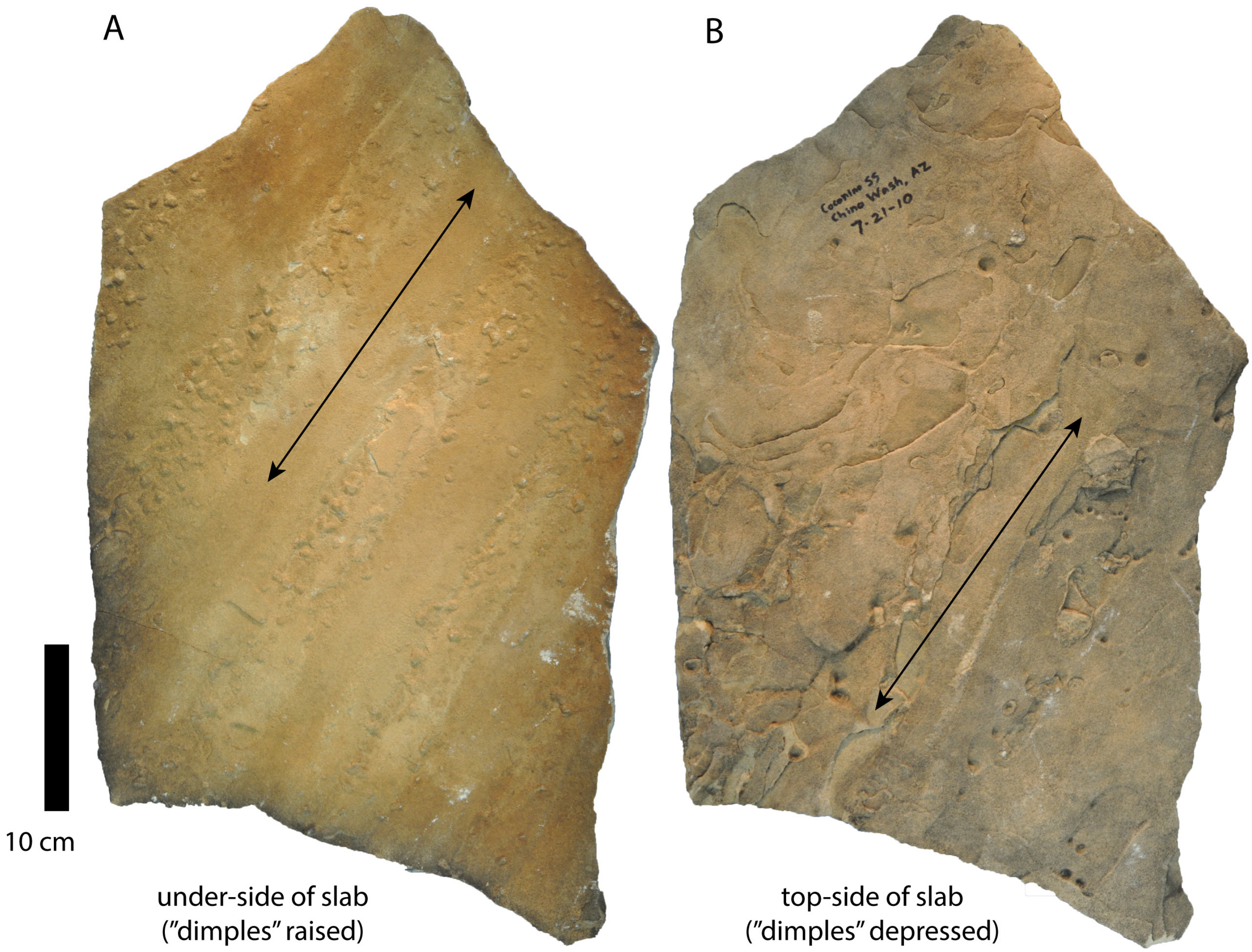


Figure 32. Sometimes "raindrop prints" form deep depressions into cm-thick slabs. This pair of images shows the bottom-side and top-side of the same cm-thick piece of rock. The underside has raised "dimples" that shows the pattern of the surface of the rock that was below this slab. The pattern is similar to the rows of "dimples" that we found on other rocks (see Figs. 25 and 36). The slab was a piece of float, so we only know the dip was in one of the directions of the double-ended arrow. The rows of dimples are associated with very low relief ripples. Some of the dimples on the top-side are about 7 mm deep. The patterns are not as clear, but they are also oriented in the same approximate direction as the layer below. If these were "raindrop prints" it seems the dimples would be in random patterns and not oriented. Furthermore, why would there be similar patterns on two closely-spaced surfaces? We hypothesize the "dimples" may be water or gas escape structures. Chino Wash, Arizona. JHW photos 2506-2018, 255-2018.

are often noticed because they stand out compared to the tabular bedding that is so common. The ripples do resemble wind ripples which tend to have more rounded crests than most ripples found in subaqueous settings.

We find no reason to believe that the ripples found in the Coconino could not have been formed in a subaqueous sand wave environment. Although much is not known about the fine-scale structures from large subaqueous sand waves, some observations have been made using radar and video. Lawrence Poppe of the United States Geological Survey claims that small ripples are present on the backs of megaripples which occur on the backs of larger sand waves in Long Island Sound, near New York City (personal communication, 2011; Poppe et al. 2006). Currents flowing over the tops of sand waves should produce lee vortices in much the same way as they are produced in eolian settings; this could possibly produce subaqueous ripples, depending on current velocity. Houbolt (1968) suggested currents could flow perpendicular to the flanks of large sand ridges on steep foreset slopes. Lundy (1973) used this idea to explain the parallel-to-dip ripples in a subaqueous Coconino model.

H. "Mud cracks"

Some have claimed that the polygonal crack-like patterns (Fig. 37) that can commonly be found on the tops of bounding surfaces are indeed desiccation cracks (Hill et al. 2016, p. 68). However, these cannot possibly be "mud" cracks because these features are in a clay-poor sandstone, not mud. In order for sediment to crack by desiccation it must be dominated by clay-sized particles and must have certain clay minerals. Even the Hermit Formation (which is dominantly a siltstone) does not have the right grain size and mineralogy to crack via desiccation (Whitmore and Strom

Figure 33. Sometimes small brown nodules can “fall out” of the Coconino sand leaving a crater-like pit. These nodules are from Capitol Butte in the Sedona area (photo by Guy Forsythe 0205-2017). The nodules we tested had a significant calcite component (red in the thin section scan, RS 2017). The brown may be siderite or dolomite.

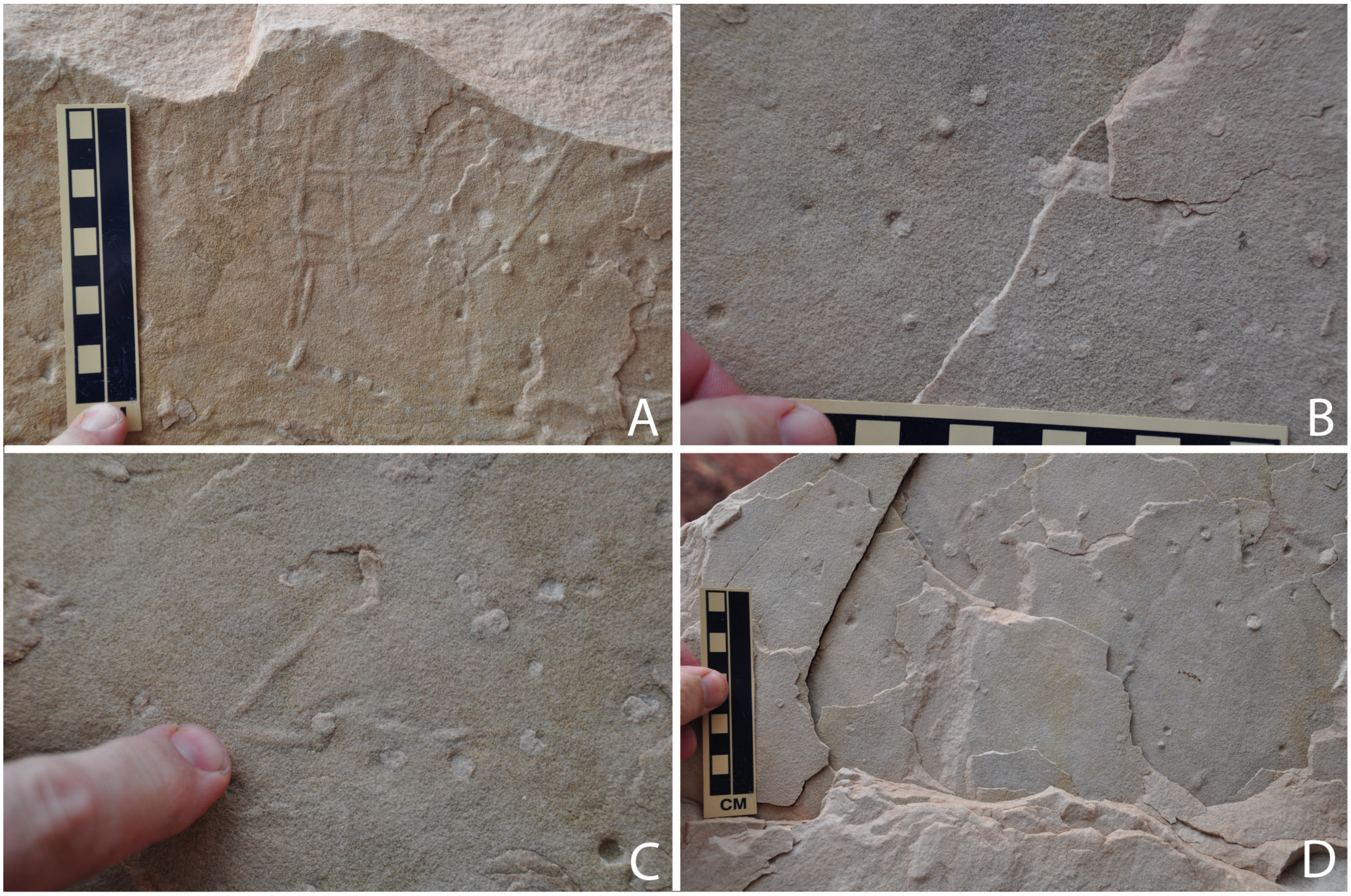


Figure 34. “Raindrop” prints associated with small horizontal burrows. The circular features in this block of Coconino appeared as though they might be exit/entry burrows (notice that some of the burrows terminate at the circular features). Some of the circular features can resemble “raindrop” prints, as in B. They occurred on dozens of thin laminae through about a meter or so of rock. All the photos were taken in a single block of float (with Toroweap Formation on top) at Lone Cedar camp (mile 23.5) along the Colorado River. Photos by JHW 0151-2017, 0141-2017, 0138-2017, 0149-2017.

2010). Sand grains are usually too large and insufficiently cohesive to form cracks during desiccation (Lowe 1975).

In our unpublished XRD studies of the Coconino, both weight and volume fractions of clay minerals were always less than about 2% and were often non-existent in the bulk powder results. The most common clays in the Coconino were kaolinite and illite. Modern soils that crack due to desiccation have significant amounts of clay. Basma et al. (1996), Harianto et al. (2008), Yassoglou et al. (1994) and Yesiller et al. (2000) report cracking in soils with clay contents ranging from 13 to 58.3% and silt contents ranging from 21 to 52%. The Coconino simply does not have the clay minerals necessary for any kind of desiccation to occur. The origin of the polygonal structures in the Coconino is not known; Leonard Brand has been thinking about these for some years (personal communication 2018; Peters and Brand 1999), but their origin is still a mystery.

Figure 35. Raindrop prints in modern sand usually produce a mottled-like surface, not a cratered surface as one would expect. This sand was nearby some dried and cracked mud, which had the more typical raindrop prints in it (inset photo). Pocketknife insignia is about 1 cm long. JHW photo 3229-2010 and 3222-2010 (inset).

I. Sand injectites

Whitmore and Strom (2010) argued that the sand-filled cracks found at the base of the Coconino and penetrating into the Hermit Formation cannot be desiccation cracks or large playa cracks because of the lack of abundance and types of certain clays necessary for desiccation cracks to be produced in the Hermit Formation. They argued the sand-filled cracks are injectites caused by the Laramide movement of the Bright Angel Fault. It is not unusual for clastic dikes, injectites, and sand volcanoes to occur coincident with faulting; fine-grained water-saturated sands are especially mobile (Hurst and Cartwright 2007; Ettensohn et al. 2002). Evidence that the Bright Angel Fault was responsible for the sand-filled cracks includes 1) the deepest sand-filled cracks occur next to the fault (>15 m in depth) and at its greatest offset (61 m, Fig. 43), and 2) the cracks decrease in length away from the fault and get shorter along places where the fault did not have as much displacement. Cracks disappear altogether far away from faults (Fig. 39). If the cracks were truly desiccation cracks we might expect random orientation of crack trends (instead they are oriented) and horizontal layering of crack fill as sand filtered down from above filling the cracks (instead the cracks are mostly massively bedded and some contain vertical “layering”).

Figure 36. Ripples in the Coconino are often associated with parallel rows of crater-like features that some may have identified as “raindrop prints.” As are the ripples, these features are parallel to dip. The underside of this slab has been placed on edge so sunlight could better highlight the features. Ash Fork Area. JHW photo 3434-2014.

J. Parabolic recumbent folds

Whitmore et al. (2015) argued that large deformation features found in the Coconino and Toroweap Formations near Sedona and in the Coconino in Wupatki National Monument are penecontemporaneous parabolic recumbent folds (Fig. 40). If these were slumped eolian dunes as McKee and Bigarella (1979a, pp. 201-202) argued, or groundwater deformation features as commonly found in the Navajo Sandstone (Bryant and Miall 2010) the deformation would cross through bounding surfaces and have limited horizontal extent. Instead, the folding we found in Sedona is confined to individual cross-bed sets (proving its penecontemporaneous nature with the cross-beds) and extends for at least 400 m on Brins Ridge and for at least 50 m on Lizard Head in a regular pattern (showing that these features are not slumped eolian dunes). The mechanism of parabolic recumbent fold formation may be one or a combination of four causes (Whitmore et al. 2015), all of which take place during active

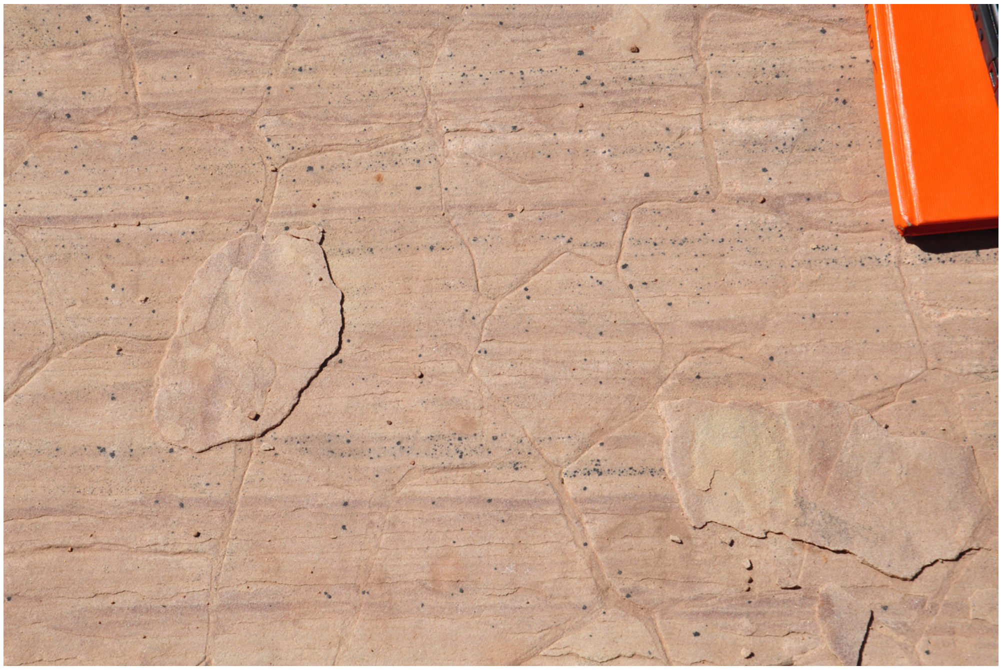


Figure 37. This image is looking downward at polygonal "cracks" on a bounding surface (note multiple beds running from left to right) in the Ash Fork area. These features are sometimes referred to as "mud cracks" by some workers (Hill et al. 2016, p. 68). It is important to note that the Coconino is a sandstone with very little clay content, and not a mudstone. These "cracks" often occur on bounding surfaces and extend both upward and downward from the bounding surface. Looking at the rock from the vertical dimension, laminae extend through the "cracks" so the features were never open, as in mud cracks. As far as we know, Leonard Brand (Peters and Brand 1999; personal communication with Brand 2018) has been the only person who has extensively studied these enigmatic features. The photo is about 50 cm wide. JHW photo 3410-2014.

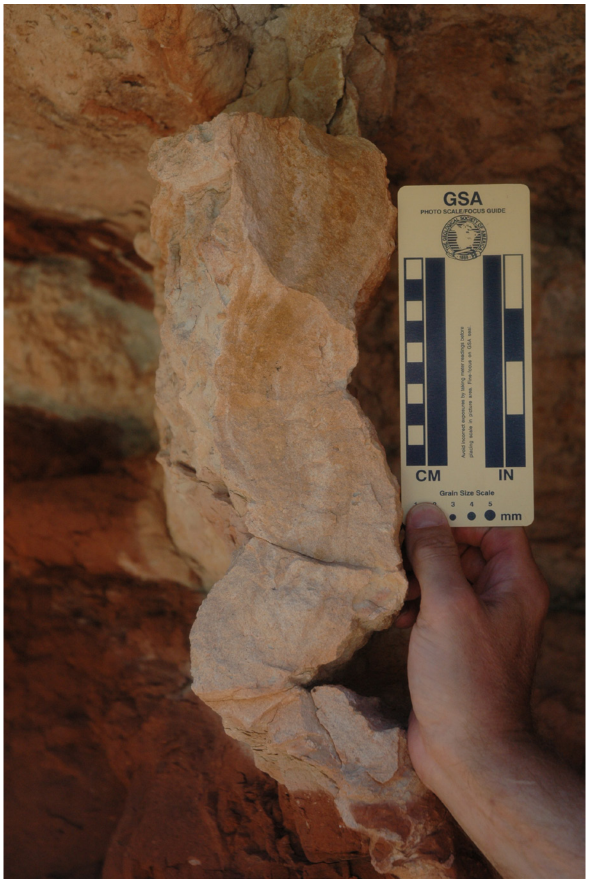


Figure 38. Sand-filled cracks that can often be found at the base of the Coconino Sandstone. Also see figure 30. Whitmore and Strom (2010) interpreted these as sand injectites. The Hermit Formation has been weathered away from the sandstone crack fill. New Hance Trail, Grand Canyon. Figure 42 illustrates a larger injectite. JHW photo 5919-2007.

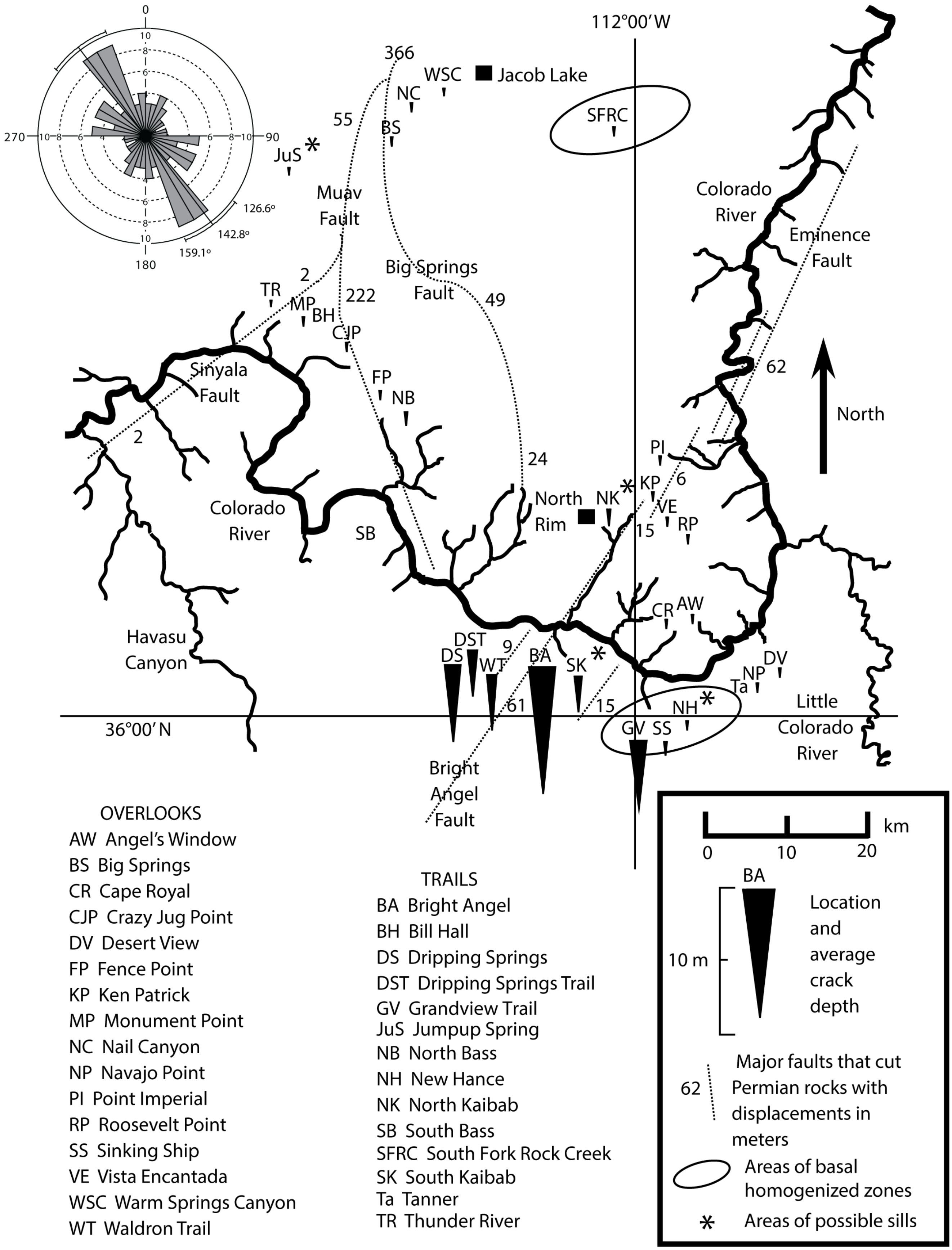


Figure 39. Sand-filled crack occurrence and depth into the Hermit Formation (modified from Whitmore and Strom 2010). The inset shows crack orientation, which is statistically significant.

Figure 40. Parabolic recumbent folds in the Coconino Sandstone (see Whitmore et al. 2015). (A) is from Lizard Head, a landmark in Sedona. The fold is about 7 m thick and extends to the right another 50 m. (B) is from Brins Ridge, also in Sedona. Here, the folded rock extends for about 400 m to right of this photo. If these were slumped dunes we would not expect the folds to extend such great distances or to be contained between bounding surfaces. JHW photos 8032-2013, 1956-2011.

Figure 41. A transitional contact between the Hermit Formation (Ph) and the Coconino Sandstone (Pc) along Tanner Trail in the Grand Canyon. JHW photo 2164-2006. Leonard Brand is the geologist closest to the center of the photo. Inset photo shows telephoto shot of transitional contact between the Hermit and Coconino in the North Canyon area of Grand Canyon (about mile 21, river right, on the Colorado River). JHW photo 0716-2018.

deposition of subaqueous cross-beds: 1) seismic activity leading to temporary liquefaction of the sand grains in the cross-beds, 2) strong sediment-laden currents flipping the cross-beds over, 3) flow regime change causing liquefaction at the subaqueous dune front, or 4) liquefaction of bottom sediments from cyclic loading and unloading due to sudden changes in water depth from passing waves. At this time, we favor mechanism (3) because two rather uncommon features occur together in the Coconino: the folds and planar beds. Of all the features in the Coconino, we think these folds are one of the best evidences for rapid subaqueous deposition of the cross-beds.

K. Marine interfingering

The Coconino interfingers (or intertongues) with other layers (both horizontally and vertically), many of which have been recognized as marine layers such as the Toroweap Formation, Kaibab Limestone and Glorieta Sandstone. This is important because in areas where this happens there is no real change in "typical" Coconino cross-bedding. If these were coastal dunes marking where the transition takes place, we might expect to find a variety of facies and sedimentary structures that would indicate beach, tidal or offshore sands. Instead, the Coconino always appears as "typical" Coconino even though a single cross-bed layer with only a meter of thickness or less is present (Billingsley and Dyer 2003; Billingsley and Graham 2003; personal observations). These formations (which are clearly marine) intertongue with "typical" Coconino facies with no evidence of intervening coastal depositional environments; contrary to expectations if the Coconino were truly eolian.

L. Flat contacts

One of the features of the Coconino, and indeed many other formations, is that the upper and lower contacts are flat. The Hermit Formation is purported to be a large fluvial floodplain deposit (Blakey 2003), so we might expect at least dips and gullies at the top of the Hermit since it is purported to be a terrestrial deposit. The story is usually told (Abbott and Cook 2004) that the climate dried up toward the end of the Hermit time and, as a result, the Hermit developed deep desiccation cracks, similar to cracks found on large playa surfaces today. Additionally, it is thought the open desiccation cracks filled in from above to form the large sand-filled cracks. The problem with this model is that the Hermit does not have the *right type of clays* for desiccation cracks to develop nor does it have *a sufficient amount of clay-sized particles* (Whitmore and Strom 2010). Desert floors are often either covered with bare bedrock or with desert pavement resulting from alluvial fans and intermittent streams that deposit sediment on the desert floor. We find no traces of such features at the surface of the Hermit. To say that those features were there and then have been eroded

Figure 42. Cross-beds and planar beds within the Coconino in the Kaibab Gulch area. Thick cross-bedded section seen in the middle of the photo is about 7 m above the Hermit Formation. In this area there are a number of thin planar-bedded sandstones and carbonate beds within the Coconino section. This area is described by Doelling et al. (2010, p. 210). JHW photo 3363-2010.

Figure 43. The typical "sharp" contact between the Hermit Formation (bottom) and the Coconino Sandstone in the Grand Canyon along Bright Angel Trail. Note the large sand injectite penetrating into the Hermit just to the right of center. It is about 20 m from the top of the photo to the bottom. Photo by RS 0157-2008.

Table 1. Vertebrate ichnotaxonomy of the Coconino.

Ichnogenus	Ichnospecies	Synomyms	References
Chelichnus	*C. duncani*	*Baropezia arizonae;* *Allopus? arizonae;* *Baropezia eakini;* *Agostopus matheri;* *Agostopus medius;* *Palaeopus regularis;* *Barypodus tridactylus;* *Barypodus metszeri;* *Nanopus maximus;* *Laoporus noblei* of Gilmore (1926)	McKeever and Haubold (1996)
	C. gigas	*Barypodus palmatus;* *Amblyopus pachypodus;* *Baropus coconinoensis*	McKeever and Haubold (1996)
	C. bucklandi	*Dolichopodus tetradactylus;* *Laoporus schucherti;* *Laoporus coloradensis;* *Nanopus merriami;* *Laoporus noblei* of Lull (1918)	McKeever and Haubold (1996)

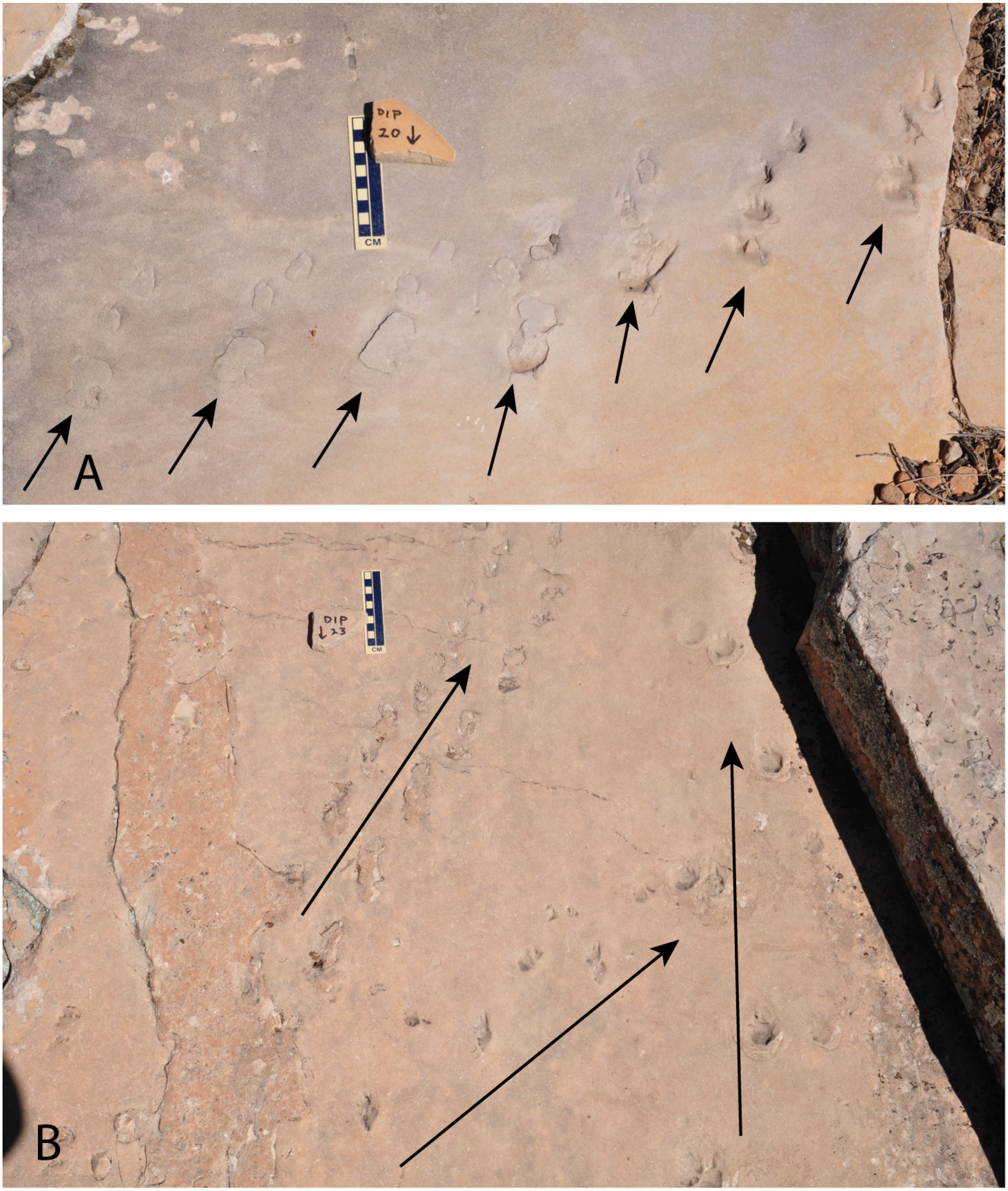


Figure 44. Tracks in the Coconino almost always go up dip as illustrated in these slabs of in situ rock along the Hermit Trail in Grand Canyon where the slope is 20˚ in photo A and 23° in photo B. In (A), tracks on the left side of the photo are still partially filled with rock, while the tracks on the right side are well exposed. Note that the animal is not only going up slope, but also is moving sideways, which is typical of many of the Coconino tracks. Brand and Tang (1991) have hypothesized that these tracks were made underwater and that a water current was pushing the organism from left to right making it partially bouyant as it walked. Photo by JHW 0437-2018. (B) shows at least three trackways, two of which are also traveling at an angle to the dip slope. Photo by JHW 0450-2018. 10 cm scale in each photo.

away is problematic because there are no dips and gullies at the contact between the two formations as might be expected in such a terrestrial deposit. Flat contacts are common between marine deposits as well-documented in the walls of most of the Grand Canyon. Roth (2009) argues that these types of "flat gaps" are a serious challenge to long geological ages.

4. Paleontology

A. Vertebrate trackways

McKee (1944, 1947) reported sand trough experiments with several reptiles including spiny lizards (*Sceloporus*), side-blotched lizards (*Uta*) and chuckwallas (*Sauramalus*). The animals were induced to walk over a ridge of sand with varying slope and moisture content. Small reptiles failed to leave tracks in anything other than dry sand. Only the largest animals (chuckwallas) made tracks in wet or damp sand and even then the tracks were not as clear as in dry sand. McKee concluded that the tracks had formed in loose, dry sand that was subsequently dampened by mist or dew. Since then, most investigators have followed McKee in interpreting the Coconino

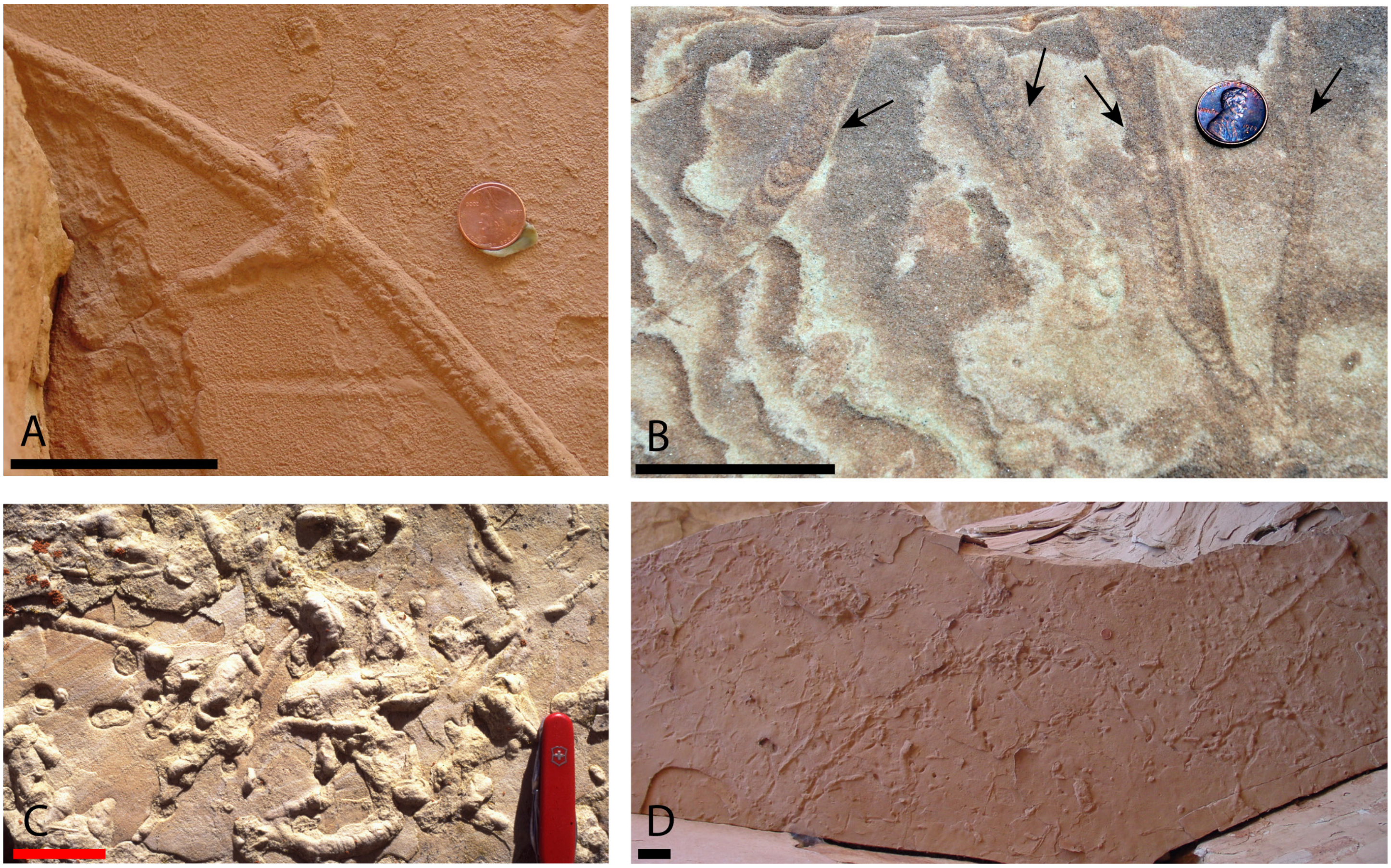


Figure 45. Invertebrate traces in the Coconino Sandstone. A) double-furrowed trace from the underside of cross-bed surface (in situ) near the bottom of the Coconino, Bright Angel Trail (photo by JHW 4866-2004); B) Four traces from near the bottom of the Coconino along a cross-bed surface, South Fork of Rock Canyon (photo by JHW 5255-2009); C) bioturbated cross-bed surface near the bottom of the Coconino, Tanner Trail (photo by JHW 4.19-1999); D) underside of an in situ cross-bed surface along Bright Angel Trial (same area as A), near the bottom of the Coconino (photo by JHW 04850-2004). Scale bar in the bottom left of each photo is 5 cm. For additional invertebrate traces, see Fig. 34.

Table 2. Invertebrate ichnotaxonomy of the Coconino.

Ichnogenus	Ichnospecies	Synomyms	References
Paleohelcura	*P. tridactyla*	*Triavestigia niningeri;* *P. dunbari;* *P. lyonensis*	Braddy (1995)
	P. benjamini	*Mesichnium benjamini*	Kozur et al. (1994); Braddy (1995)
Octopodichnus	*O. didactylus*		Braddy (1995)
	O. minor	*O. raymondi*	Braddy (1995)
Permichnium	*P. coconinensis*		Kramer et al. (1995)

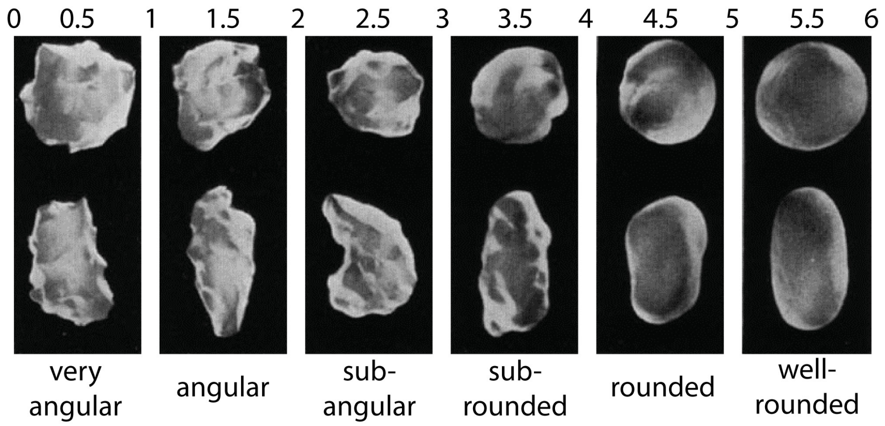


Figure 46. Roundness scale developed by Powers (1953) and modified by Folk (1955).

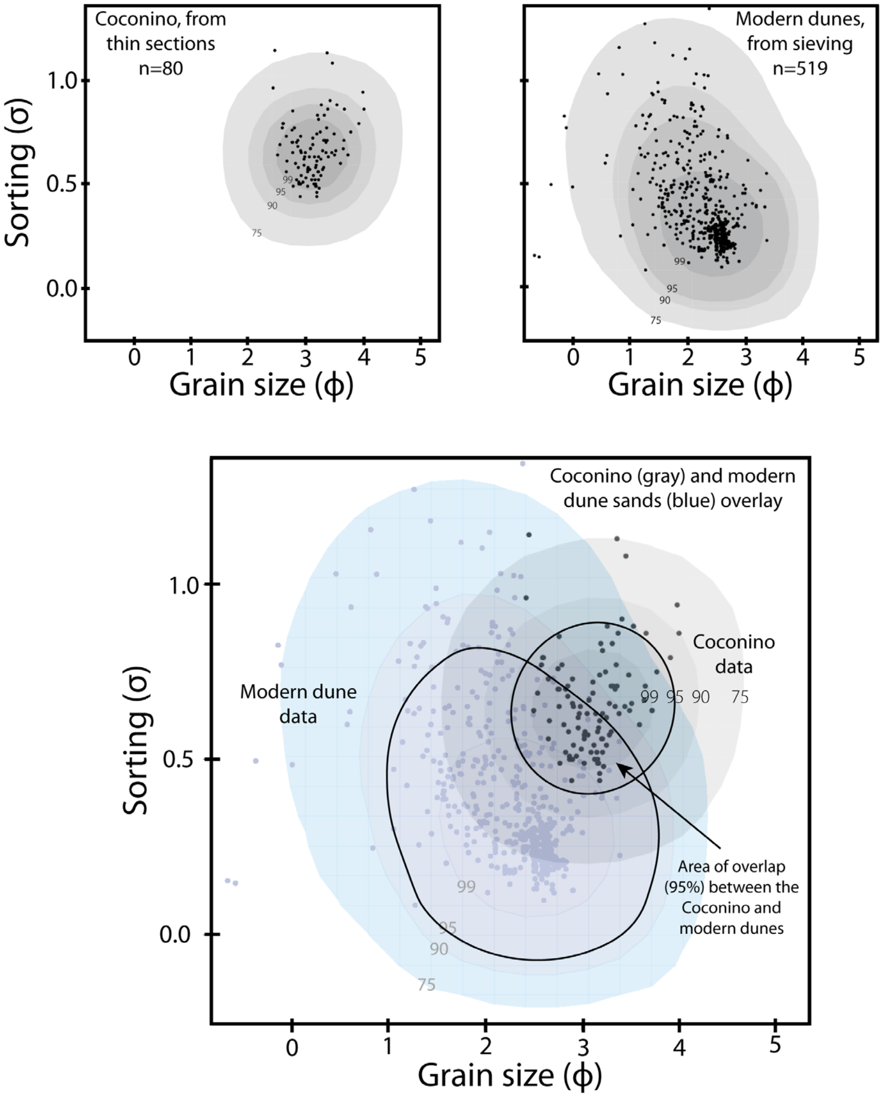


Figure 47. A comparison of overall grain size and sorting of modern eolian sand dunes with the grain size and sorting of the Coconino Sandstone. Sorting data from modern dunes consists of two sets of data: 465 samples from Ahlbrandt (1979) and 54 samples sieved by Whitmore and his students for a total of 519 samples. Ahlbrandt's samples were sieved with ¼ phi sieves and Whitmore's data was prepared with ½ phi sieves. All points are from sand dunes (not interdunes, beaches, etc.). The plot was made with the "R" statistical package and shows the 75, 90, 95, and 99% confidence intervals (R Development Core Team, 2011). The Coconino data was obtained by counting and measuring grains on 80 thin sections; thus the two sets of data were obtained by different methods, but we believe they are comparable. The combined plot shows there is some overlap of the 95% confidence interval between the two plots, but that the Coconino is finer and more poorly sorted than most modern eolian deposits. It is important to note that is is almost no grain-size data from sand waves for which to compare these two data sets.

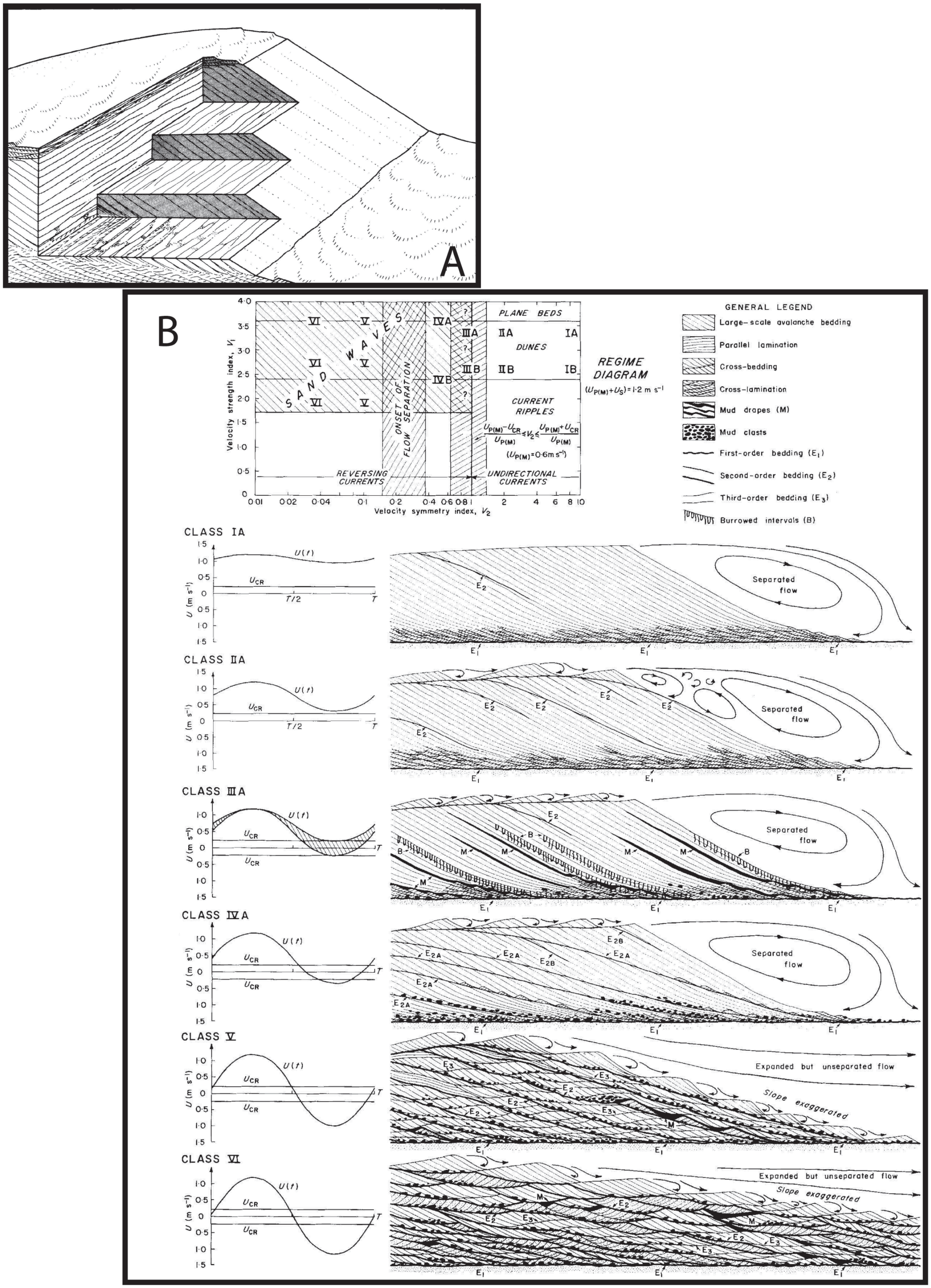


Figure 48. Models of the internal structure and formation of subaqueous dunes. (A) Is after Hunter (1985) and shows the structure that subaqueous avalanches make. Notice the individual sets are broad and tabular compared to the tongue-like avalanche structures of eolian dunes (as seen in Fig. 22). (B) Is after Allen (1980) and shows that large foresets can be expected under conditions of large velocity strength and higher velocity symmetry indexes. The most similar dunes to those found in the Coconino are Class IA. Notice that these dunes are quite close to the plane-bed regime with just a bit more velocity strength.

Table 3. Areal extent and thickness of the Coconino compared to other large cross-bedded sandstone formations and some modern ergs.

Formation or Erg, Location	Age	~Area (1,000 km^2)	~Mean Sand Thickness (m)	References
Coconino and equivalents, western US	Penn. - Permian	2,400	25-300	Whitmore (2016)
Navajo and equivalents, western US	Triassic-Jurassic	>400	150-760	MacLachlan (1972)
Rotliegendes, NW Europe	Permian	~83	225-1500	Glennie (1972)
Nebraska Sandhills, central US	Holocene	~57	9-24	Ahlbrandt and Fryberger (1980)
Erg Oriental, Algeria	Modern	192	26	Wilson (1973)
Issaouane-N-Irarraren, Algeria	Modern	39	43	Wilson (1973)
Erg Occidental, Algeria	Modern	103	21	Wilson (1973)
Simpson Desert, Australia	Modern	300	1	Wilson (1973)

vertebrate tracks as evidence of animals leaving tracks on wet or damp subaerial substrates.

However, subsequent field studies and laboratory experiments, using a wider variety of conditions than those employed by McKee, indicate that the conditions under which the Coconino trackways were formed should be reconsidered. Brand (1979) reported detailed measurements of fossil trackways (n = 82) along the Hermit Trail in Grand Canyon. Fossil footprints were distributed throughout the lower half of the Coconino and were almost all oriented upslope (as also reported by Gilmore 1927b and McKee 1944). Individual prints in the fossil trackways were distinct and separate. Some showed toe marks only, some sole impressions only and some both toe and sole impressions. Crescent-shaped ridges of sand commonly occurred behind the sole impressions, but were never observed to extend backwards into previous footprints.

These fossil trackways were compared with experimental trackways (n = 236) made by living amphibians and reptiles under a variety of substrate conditions (dry, moist, wet and submerged). Five salamander species (*Taricha torosa*, *Taricha granulosa, Notophthalmus viridescens*, *Ambystoma tigrinum* and *Cryptobranchus alleganiensis*) and three lizard species (*Sauromalus obesus*, *Sceloporus occidentalis* and *Dipsosaurus dorsalis*) were employed in the experiments. The animals were placed in experimental chambers and allowed to walk up and down a slope of sand. Most of the laboratory tracks were made on 25°slopes, with some on 15° and 20° slopes.

The laboratory tracks made on dry and damp sand differed in several respects from the fossil tracks. Less than 12% of the dry sand and damp sand tracks displayed toe marks or other fine details, compared with more than 80% of the fossil tracks, underwater tracks and wet sand tracks. Furthermore, sand was often observed flowing backwards into previous prints. Damp sand prints were often surrounded by jumbled pieces of "broken crust", but this was never observed in the fossil tracks. Furthermore, the proportions of the fossil tracks were quite different from those made in dry sand, but similar to those made underwater or in wet sand. Dry sand tracks were longer than they were wide, whereas the fossil tracks, underwater tracks and wet sand tracks were shorter than their width. Other features consistently observed in wet sand tracks (such as an upslope transition from well-defined tracks to toe marks only) were notably absent from the fossil tracks. The experimental tracks most closely resembling the fossil tracks were those made underwater. Similarities included the proportion of tracks bearing toe marks, the uniform appearance of prints along a trackway and the track proportions.

Brand (1996) conducted further experiments with the western newt (Taricha torosa) to study trackways made by one species under a variety of substrate conditions. Trackways were made in mud or fine sand, on level or 25° slopes and with dry, damp, wet or submerged substrates (n = 230). Measured trackway characteristics included the number of toes (manus and pes), stride (pes), pace angulation (pes), glenoacetabular length, width of trackway and mean divergence of middle three toes (manus and pes). Trackways made in wet mud most accurately recorded the number of toes per foot and the arrangement of the toes. All other combinations yielded a reduced average number of toes per foot. Trackways made on sloped, submerged mud or sand, sloped, dry sand and sloped, damp sand rarely yielded the full number of toes per foot. The position and orientation of the toe marks were distorted in trackways made by animals walking underwater or on sloped, damp sand. It is evident that substrate conditions must be considered when drawing systematic conclusions from trackways, and that trackways made on sloped cross-beds are particularly unsuitable in this respect. In this study, the experimental trackways that most closely resembled the Coconino trackways were those made on sloped, underwater sand or mud or subaerial, damp sand. Other criteria must be used to discriminate between these alternatives (such as evidence indicating the buoyancy of the track-makers; see Brand and Tang 1991).

Some other features of the Coconino trackways favour an underwater origin. McKee (1944, 1947) explained the near-absence of downslope trackways in the Coconino by the tendency of track-makers to slide down slip faces and obliterate their own tracks. However, in Brand's (1979) study downslope tracks were produced under all four experimental conditions and were often more clearly defined than the fossil tracks. Brand suggested that the rarity of downslope tracks in the Coconino might be better explained by the underwater behavior of animals than by a preservational bias. Perhaps the track-makers tended to swim when going with the water current and adopted bottom-walking only when moving against the current. Brand (1979) reported that all five species of living salamanders walked on the bottom more than they swam, contrary to earlier observations by Peabody (1959), who stated that salamanders rarely adopted bottom-walking.

McAllister (1989) has suggested that the best criteria for the recognition of underwater trackways are those that indicate the buoyancy of the track-maker. Brand and Tang (1991) described numerous Coconino trackways that they interpreted in this manner. For example, there were trackways in which the individual prints pointed in a different direction to the trackway itself. These sideways-drifting trackways often showed clear pes impressions only, with manus impressions indistinct or absent. Similar oblique and zigzag trackways have also been reported from the De Chelly Sandstone (Lockley et al. 1995) and the Corncockle Sandstone of Scotland (McKeever 1994). Furthermore, Brand and Tang (1991) described trackways that started or ended abruptly without any evidence that slumping of sand had partially obscured the trackway. In one case a trackway was seen to angle upslope before abruptly disappearing. A similar trackway then abruptly began 0.6 m further upslope and progressed across the cross-bed surface at the same angle as the lower trackway.

Brand and Tang (1991) argued that these trackways were made by animals that were partially buoyant in water and drifting with currents. In laboratory experiments, salamanders were sometimes observed to drift sideways with a current while continuing to walk. In such instances the animals left trackways that resembled the oblique trackways found in the Coconino. Partially buoyant live salamanders made long scratch marks that resembled the scratches seen in some fossil prints. Given an eolian setting, no obvious explanation for these features of the Coconino trackways presents itself. Any wind strong enough to move an animal sideways on a dune would almost certainly obliterate its tracks. Suggestions have been made that these distinctive trackways were made on eolian dunes by animals employing unusual methods of locomotion – galloping, loping, trotting or jumping or sideways walking (Lockley 1992; Loope 1992). However, in studies of modern animals that employ sideways loping the toes are only slightly displaced from the angle of the trackway, unlike the sharply oblique angles of displacement observed in many of the fossil tracks. Furthermore, morphological constraints on locomotion must be considered. It is not clear that any known Permian tetrapod possessed the skeletal structure that would have been required for such unusual sideways locomotion (Brand 1992). The best explanation seems to be that these trackways were made on underwater substrates.

B. Invertebrate trackways

With reference to the invertebrate trackways, Brady (1939, 1947, 1949, 1961), Alf (1968) and Sadler (1993) conducted experiments with modern scorpions and spiders and concluded that under certain conditions they made tracks on dry or damp sand that were similar to the fossil trackways assigned to *Paleohelcura* and *Octopodichnus*. Brady (1947) also noted the resemblance of some other Coconino traces to those made by modern millipedes, blattoid beetles and isopods. The *Permichnium coconinensis* trackway described by Kramer et al. (1995) was attributed to a running blattoid beetle.

However, experimental studies clearly reveal that one animal can produce a variety of morphologies even within a single trackway and that, conversely, different animals can produce very similar track morphologies (Brady 1939; Briggs et al. 1984; Crimes 1970; Sadler 1993). Factors affecting track morphology include temperature, moisture content and slope of the track-bearing substrate and the size, speed and foot placement of the track-making organism. Another complicating factor is that fossil tracks may have been made by extinct organisms, perhaps unknown from body fossils. It seems probable that the model organisms employed in these studies has been influenced by the presumed eolian paleoenvironment of the Coconino. Thus, studies of the invertebrate traces have employed terrestrial animals, such as spiders and scorpions. Experiments with a broader range of invertebrates, including marine and freshwater forms, would be instructive. Some authors have noted the resemblance of the Coconino invertebrate ichnofossils to those of marine invertebrates (Lundy 1973, pp. 76-78), including traces made by annelids (Lundy 1973, p. 76), hexapods (Sadler 1993; cf. Manton 1973; Macdonald 1989), sand crabs (Gilmore 1928, p. 5) and eurypterids (Sadler 1993; cf. Briggs and Rolfe 1983; Hantzschel 1975).

A POSSIBLE MODEL FOR COCONINO DEPOSITION

The Coconino does not quite resemble any modern depositional environments that are commonly found today when considering the thickness, areal extent and details of the sedimentology (James and Dalrymple 2010). It is likely the Coconino was deposited during the Flood by depositional processes operating at rates that we have not yet been able to model in the laboratory or with the computer. However, the Coconino does have many broad similarities to sand waves. Sand waves are very common bedforms in high-energy nearshore and shallow marine tidal environments (Garner and Whitmore 2011). They usually take the form of long parallel ridges transverse to the prevailing currents (Hulscher 1996), with crestlines ranging from straight to gently curved to sinuous. Most consist of quartz sand but they may also contain abundant biogenic material and/or gravel. Sand waves are typically 1 to 15 m high, with wavelengths between 100 and 500 m, although some are larger (e.g., the 24-m-high sand waves in the Irish Sea reported by Harvey 1966). In profile, they are most often asymmetrical (Allen 1980; Hulscher and Dohmen-Janssen 2005), with steeper faces pointing in the direction of the dominant currents, although symmetrical forms also occur. The dominant internal architecture, predicted by theoretical models (e.g., McCave 1971; Allen 1980) and confirmed by the available field data (e.g., Berné et al. 1988, 1991), consists of various forms of cross-stratification (Fig. 48). The most important factors promoting the formation of sand waves appear to be an abundant supply of sand and strong unidirectional or tidal currents (e.g., Terwindt 1971 on the sand waves of the North Sea). Sand waves typically develop where the most prevalent sediment size range is from 0.25 to 0.5 mm (2.0-1.0 ϕ) in diameter, and are absent where mud or silt comprises more than about 10-15% of the bottom sediment. Most sand waves occur in water less than 100 m deep, although much greater depths are occasionally recorded (e.g., the sand waves in 475-800 m depths in the Barents Sea described by King et al. 2014; Bøe et al. 2015). Morphodynamic models have shown that modern sand waves develop when the main oscillatory tidal current interacts with irregularities of the sea bottom, promoting crestward sediment transport, and they migrate in response to other harmonic components of the tidal flow (Hulscher and Dohmen-Janssen 2005; Besio et al. 2008a, 2008b).

We think sand waves explain many features of the Coconino Sandstone that an eolian model does not explain. Sediment size, sorting and cross-bed style in sand waves, among other features, are similar to what is found in the Coconino. Seismic studies have shown that sand waves can have foreset lengths up to 50 m, more than twice the length of observed foresets in the Coconino. The average dip of the cross-bed foresets in the Coconino (based on hundreds of measurements by us and others) is about 20°. Modern eolian dunes have foreset dips at the angle of repose (~33°) and modern sand waves have dips ranging from 1 to 35° with an average of 15°. Ancient cross-beds may become compacted during burial, but our work (theoretical and petrographic) shows this can only account for several degrees of dip decrease in the Coconino. The Coconino reaches a maximum thickness of around 300 m in central Arizona. Modern ergs have average thicknesses about an order of magnitude less than this (Table 3). Sand sheet deposits like the Coconino are not unusual, and many of them have an average thickness many times that of modern ergs. The thickness of the Coconino and many other ancient sand sheets is suggestive of marine depositional processes, where thicker sheets of sand can potentially accumulate.

It is a common misconception that the sand grains of the Coconino are well-sorted. Our data shows in many cases that it is poorly sorted or moderately sorted. Subaqueous deposits tend to have a greater mix of grain sizes, like we find in the Coconino. In our studies, we sampled the Coconino widely, both laterally and vertically. Mica grains (mostly muscovite) were found in almost every thin section examined from the Coconino. Our experiments (and others) have shown that mica cannot survive the abrasive eolian environment. Micas are known to be a common accessory mineral in subaqueous sands, but they are not found in modern eolian environments unless they are very close to a felsic igneous or fluvial source. The presence of mica in the Coconino strongly argues for a subaqueous origin. K-feldspar is a common mineral in the Coconino and sometimes shows less rounding than quartz grains of the same size, even though it is a softer mineral. From our studies, we know that K-feldspar can often be rounded in an eolian setting rather quickly (Whitmore and Strom 2017). There are no K-feldspar sources close enough to the Coconino sand sea for it to be supplied via eolian processes and still remain angular. Angular K-feldspars can be better explained via subaqueous depositional processes.

Along the northern margin and in the Oak Creek Canyon area (in the southern area of the outcrop) the Coconino interfingers laterally with the marine Toroweap Formation. Often the same happens vertically with Coconino-style cross-beds and lithologies in the Toroweap Formation. In the northern part of the Coconino outcrop, pure dolomite beds are contained within the lower portion of the Coconino. Subaqueous sand waves best explain these interfingering deposits and the presence of dolomite. We have found large dolomite clasts near the center of the Coconino sand sea, too far for them to be carried by wind-borne processes. The presence of dolomite beds, ooids and cement in many areas is suggestive of widespread marine processes, not eolian ones. In our studies of ancient Permian sandstones from around the world, we have found that many of them have similarities to the Coconino. For example, many others also interfinger with marine formations, have marine facies and contain dolomite beds. Sand waves might be a better interpretation for these sandstones too. In most places, the base of the Coconino is in sharp contact with the underlying Hermit Formation. The contact can be traced the length of the Grand Canyon. It is hard to explain the lack of topographic relief on top of the Hermit if this was a terrestrial setting. Flat contacts are more easily explained in a marine environment. Occasionally the Coconino and Hermit display a transitional contact. This is best illustrated along the Tanner Trail in the Grand Canyon. Two, meter-thick beds of Coconino occur in the Hermit before the Coconino proper begins. In the eastern Grand Canyon, Tanner Trail is the only place known where the transitional contact can be studied in detail, but we think we have seen a similar transitional contact high on the cliff faces, viewed from the Colorado River, from several places in the Marble Canyon area. Some authors have also reported a transitional contact in the Parashant Canyon area in the north-central part of the Grand Canyon. A contact of this nature indicates evidence is lacking for a large erosional hiatus between the Hermit and Coconino and this can best be explained in an underwater setting.

The Coconino (and other Permian sandstones) are well known for their vertebrate footprints. Studies of the trackways, primarily by Leonard Brand, have shown that their unusual characteristics can best be explained by subaqueous track makers. Conventional ideas demand that the tracks were either made or preserved on wetted dunes (light rain or heavy dew). However, there is no hint of adhesion ripples (produced by wind blowing on damp desert sand). Sand waves and various back eddy currents associated with them can nicely explain the unusual features of these tracks, not found in eolian settings. Certain areas of the Coconino contain extensive invertebrate trails and tracks. The substrates probably had to be wet in order to make and preserve these well-defined traces. However, again there is no hint of adhesion ripples or interdunal deposits in these areas. How could these organisms survive in the middle of an erg without water? A better hypothesis would be that the traces were made underwater.

Parabolic recumbent folds are a specific type of penecontemporaneous soft sediment deformation whereby cross-beds become deformed by strong currents into a series of parabolas that lie on their sides (opening downcurrent). The tops of the cross-beds become folded over by strong currents in the water column immediately above the cross-beds. We have found these types of folds in the Sedona area (and a few other places). It is impossible for these features to form in dry sand, damp sand, or even water-saturated sand (by slumping or groundwater movement). The field relationships of the folds show they were formed during the process of the deposition of the cross-beds. There is a wealth of literature documenting how these folds form in laboratory settings, as well as in fluvial and other subaqueous environments. These features can only form by strong, underwater currents and some liquefaction mechanism, demonstrating subaqueous conditions whenever they are found. Some of the folds have been traced for over 400 m along ridge tops. The thickest deformation is about 5-7 m thick which can be traced over 50 m. Slumped eolian dunes do not have these characteristics. The folds strongly imply that the Coconino was deposited by strong, subaqueous currents, such as those found depositing sand waves.

Flat beds can occur in modern eolian environments, but they are usually local in extent, have coarse grain sizes and are notoriously poorly sorted. We have found extensive (and relatively thick) flat beds in the Coconino Sandstone which display sorting patterns not much different than the cross-bedded portions of the Coconino. The flat beds do not have the characteristics of interdunal deposits. Sometimes the flat beds occur in association with parabolic recumbent folds (either directly above or below the folds) which may indicate subaqueous flow regime changes which could cause both the folding and the flat beds.

The cross-bed foresets in the Coconino Sandstone appear to be dominated by wide avalanche deposits. In eolian settings, these deposits are separated by grainfall and sometimes translatent ripple strata. In subaqueous sand waves, the foresets are completely dominated by avalanche deposits, as in the Coconino. The avalanche deposits in the Coconino are tabular in shape (wide, long and relatively thick). Avalanche deposits in eolian settings are tongue-shaped (long, thick, and not very wide, with an arc-like cross-section). Sand waves produce tabular avalanche deposits when currents are flowing quickly and are carrying high loads. The avalanche deposits of the Coconino better match subaqueous conditions. Graded and thinly laminated beds can form in both eolian and subaqueous settings. They occur as layers of exceptionally fine grains below coarser grains. In eolian settings they are often formed by the migration of climbing translatent ripples. In subaqueous settings they can form as the result of bursts and sweeps during upper flow regime conditions. Graded laminae can also form as the result of spontaneous grain segregation during exceptionally high rates of sedimentation. In outcrop and in thin section, one can only tell with certainty that the beds are graded, not if they are normally or reversely graded.

Bounding surfaces can be traced along the canyon walls in the Grand Canyon for kilometers. In modern eolian dunes it is difficult to imagine how bounding surfaces like this could develop. Large, extensive bounding surfaces have been found via seismic work on subaqueous sand waves, although it remains to be seen if they are as extensive as those found in the Coconino. Cross-beds approaching the bounding surfaces in the Coconino often do so abruptly, or with only a slight curve and thinning near the bottom of the cross-bed set. This style has not been found very often in modern eolian deposits (White Sands, New Mexico was the only place we have observed it, but these gypsum sands seem to behave somewhat differently than the more typical quartz sands). Cross-beds in sand waves are known to have these kinds of characteristics.

Modern eolian dunes have topset, foreset and bottomset beds. These types of beds are often found in bulldozer transects of modern dunes (McKee 1966; McKee and Bigarella 1979b; McKee and Tibbitts 1964). However, in the Coconino, these types of deposits are virtually unknown. It is typical for sand wave deposits to have no topset beds, mostly foreset beds and short (or no) bottomset beds. The internal structure of modern dunes (viewed by bulldozer transects) is characterized by varying dips (angle and direction), many sweeping bounding surfaces and shorter cross-bed sets. On the other hand, the Coconino is characterized by fairly uniform cross-bed dips and directions without the variation often seen in modern eolian settings. The Coconino has a very similar bedding style to some known sand wave deposits like the Folkestone Formation (Lower Greensand, Aptian-Albian) of southeast England (Allen and Narayan 1964; Narayan 1971).

Current lineation has been observed to form only in subaqueous settings. It has been seen to develop in both experimental and actualistic settings, resulting from fast-flowing currents. It is unknown from eolian settings. Sand waves would provide the necessary conditions for current lineation to develop. Features similar to “raindrop” prints have been found in the Coconino. Often when “raindrop” prints are found they occur in zones parallel to dip and some penetrate the beds up to 1 cm. They are often found with current lineation, which may indicate the two features are related. At present we have a hypothesis that the “raindrop pits” are gas or water escape features related to current lineation vortices. In a number of circumstances we have found so-called “wind ripples” associated with current lineation in the Coconino. The ripples are often fairly symmetrical, unlike asymmetrical ripples that are caused from directional wind in eolian settings (although the ripples are rather flat and symmetry/asymmetry is difficult to determine). Current lineation is caused by parallel vortices that travel in the same direction as the overall water current. The ripples may therefore be due to parallel vortices and not wind at all. Thus current lineation, “raindrop” prints and “wind” ripples may all be related and explained by fast-moving water (parallel vortices) along the lee face of a sand wave.

CONCLUSION

The present authors and their colleagues have completed a widespread study of the Coconino Sandstone and other related formations from the United States and the United Kingdom. The study included literature research, outcrop visits, sample collection, petrographic work, stratigraphic correlations, and studies of modern sand waves and eolian dunes over the past twenty years. Much of our work has been published in both conventional and creationist outlets which include scientific meeting presentations, abstracts and full-length journal articles. The study is important because sandstones with large cross-beds, like the Coconino, are often assumed to be eolian without any further consideration.

Our findings were unexpected and contrary to conclusions that have been published in the literature about the Coconino beginning with McKee's seminal paper in 1934. The Coconino is purported to have well-sorted and well-rounded sand grains, steep cross-bed dips at the angle of repose, mechanically frosted sand grains, no mica grains, wind-ripple laminae, mud cracks at its base, raindrop prints, and vertebrate and invertebrate trackways that were made in rather dry conditions. After a widespread study of dozens of outcrops and hundreds of thin sections we found the Coconino sand is only moderately sorted and subangular to subrounded, has cross-bed dips averaging about 20°, has chemically frosted sand grains, muscovite in almost every thin section, no clear wind-ripple laminae, sand injectites at its base, features that only resemble raindrop craters in mud (not in sand) and trackways that are better explained with an underwater origin. Additionally we found that the formation contains extensive dolomite (in the form of beds, ooids, cement, clasts and rhombs), widespread parting lineation, parabolic recumbent folds, angular K-feldspar grains, interfingers with other marine formations, lacks narrow avalanche tongues (found in eolian dunes) and many other features unexpected if this were an eolian deposit.

Although there is more study that can certainly be completed, we believe the evidence that the Coconino is a subaqueous deposit is substantial and will be difficult for our critics to explain in any other way. There are no modern analogs that match the precise sedimentology of the Coconino, but we believe that subaqueous sand waves may be a start in the right direction to understand how the Coconino was deposited. Instead of the Coconino being a problem for creationists, it can be one of our most powerful arguments in support of the biblical account of the Flood. There are many other similar cross-bedded sandstones in the western United States and around the world; the Coconino may be the key to unlocking their origin as well.

ACKNOWLEDGEMENTS:

We would like to thank Cedarville University and Biblical Creation Trust for allowing us to invest so much of our time in studying the Coconino and related sandstones, and the Institute for Creation Research for their generous financial support of this multi-year project. We are also hugely indebted to our friends Ray Strom of Calgary Rock and Materials Services Inc. and Guy Forsythe of Crying Rocks Ministry, with whom we have spent many happy hours in the field. Thanks are also due to Stephen Cheung for processing many of the samples we collected and to several of John Whitmore's students for contributing to the project in significant ways, notably Sarah Maithel who has continued to study the Coconino since graduating from Cedarville.

REFERENCES

Abbott, L., and T. Cook. 2004. *Hiking the Grand Canyon's Geology*. Seattle, Washington: Mountaineers Books.

Ahlbrandt, T.S. 1979. Textural parameters of eolian deposits. In *A Study of Global Sand Seas*, ed. E.D. McKee, pp. 21-51. U.S. Geological Survey Professional Paper 1052.

Ahlbrandt, T.S., and S.G. Fryberger. 1980. Eolian deposits in the Nebraska Sand Hills. *U.S. Geological Survey Professional Paper* 1120A:1-24.

Alf, R.M. 1968. A spider trackway from the Coconino Formation, Seligman, Arizona. *Bulletin of the Southern California Academy of Sciences* 67:125-128.

Aliotta, S., and G.M.E. Perillo. 1987. A sand wave field in the entrance to Bahia Blanca Estuary, Argentina. *Marine Geology* 76:1-14.

Allen, J.R.L. 1970a. The avalanching of granular solids on dune and similar slopes. *The Journal of Geology* 78:326-351.

Allen, J.R.L. 1970b. *Physical Processes of Sedimentation*. New York: American Elsevier Publishing Company, Inc.

Allen, J.R.L. 1980. Sand waves: A model of origin and internal structure. *Sedimentary Geology* 26:281-328.

Allen, J.R.L. 1984. Parallel lamination developed from upper-stage plane beds: a model based on the larger coherent structures of the turbulent boundary layer. *Sedimentary Geology* 39:227-242.

Allen, J.R.L. 1985. *Principles of Physical Sedimentology*. London: George Allen & Unwin Publishers Ltd.

Allen, J.R.L. and J. Narayan. 1964. Cross-stratified units, some with silt bands, in the Folkestone Beds (Lower Greensand) of southeast England. *Geologie en Mijnbouw* 43:451-461.

Anderson, C.J., A. Struble, and J.H. Whitmore. 2017. Abrasion resistance of muscovite in aeolian and subaqueous transport experiments. *Aeolian Research* 24:33-37.

Arvidson, R.S., and F.T. Mackenzie. 1999. The dolomite problem; control of precipitation kinetics by temperature and saturation state. *American Journal of Science* 299:257-288.

Baars, D.L. 1961. Permian blanket sandstones of Colorado Plateau. In *Geometry of Sandstone Bodies*, eds. J.A. Peterson, and J.C. Osmond, pp. 179-207. Tulsa, Oklahoma: American Association of Petroleum Geologists.

Baird, D. 1952. Revision of the Pennsylvanian and Permian footprints Limnopus, Allopus, and Baropus. *Journal of Paleontology* 26:832-840.

Baltz, R.M. 1982. *Geology of the Arica Mountains* [MS Thesis]. San Diego: San Diego State University.

Basma, A.A., A.S. Al-Homoud, A.I.H. Malkawi, and M.A. Al-Bashabsheh. 1996. Swelling-shrinkage behavior of natural expansive clays. *Applied Clay Science* 11:211–227.

Beard, L.S., R.E. Anderson, D.L. Block, R.G. Bohannon, R.J. Brady, S.B. Castor, E.M. Duebendorfer, J.E. Faulds, T.J. Felger, K.A. Howard, M.A. Kuntz, and V.S. Williams. 2007. Preliminary geologic map of the Lake Mead 30' x 60' Quadrangle, Clark County, Nevada and Mohave County, Arizona. *U.S. Geological Survey Open File Report* 2007-1010 [map and pamphlet].

Berné, S., J. Durand, and O. Weber. 1991. Architecture of modern subtidal dunes (sand waves), Bay of Bourgneuf, France. In *The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery*, eds. A.D. Miall, and N. Tyler, pp. 245-260. Tulsa, Oklahoma: SEPM (Society for Sedimentary Geology). Concepts in Sedimentology and Paleontology, volume 3.

Berné, S., J.-P. Auffret, and P. Walker. 1988. Internal structure of subtidal sandwaves revealed by high-resolution seismic reflection. *Sedimentology* 35:5-20.

Besio, G., P. Blondeaux, M. Brocchini, S.J.M.H. Hulscher, D. Idier, M.A.F. Knaapen, A.A. Németh, P. Roos, and G. Vittori. 2008a. The morphodynamics of sand waves: A model overview. *Coastal Engineering* 55:657-670.

Besio, G., P. Blondeaux, V. Van Lancker, E. Verfaillie, and G. Vittori. 2008b. Sand waves characteristics: Theoretical predictions versus field data. In *River, Coastal and Estuarine Morphodynamics: RCEM*

2007, vol. 2, eds. C.M. Dohmen-Janssen, and S.J.M.H. Hulscher, pp. 985-992. London: Taylor & Francis. Proceedings of the 5th IAHR symposium on river, coastal and estuarine morphodynamice, Enschede, the Netherlands, 17-21 September 2007.

Billingsley, G.H,. and H.C. Dyer. 2003. G*eologic map of the Upper Hurricane Wash and vicinity, Mohave County, Northwestern Arizona*, Miscellaneous Field Studies Map [and pamphlet] MF-2410. U.S. Geological Survey.

Billingsley, G.H., and J.B. Workman. 2000. *Geologic Map* [and pamphlet] o*f the Littlefield 30' x 60' Quadrangle, Mohave County, Northwestern Arizona*. Map I-2628. U.S. Geological Survey.

Billingsley, G.H., and S.E. Graham. 2003. *Geologic map of the Lower Hurricane Wash and vicinity, Mohave County, northwestern Arizona*. Miscellaneous Field Studies Map MF-2396, U.S. Geological Survey [map and pamphlet].

Blakey, R.C. 1984. Marine sand-wave complex in the Permian of central Arizona. *Journal of Sedimentary Petrology* 54:29-51.

Blakey, R.C. 1988. Basin tectonics and erg response. *Sedimentary Geology* 56:127-151.

Blakey, R.C. 1990. Stratigraphy and geologic history of Pennsylavanian and Permian rocks, Mogollon Rim region, central Arizona and vicinity. *Geological Society of America Bulletin* 102:1189-1217.

Blakey, R.C. 1996. Permian eolian deposits, sequences, and sequence boundaries, Colorado Plateau. In *Paleozoic Systems of the Rocky Mountain Region*, eds. M.W. Longman, and M.D. Sonnenfeld, pp. 405-426. Denver, Colorado: Rocky Mountain Section, SEPM (Society for Sedimentary Geology).

Blakey, R.C. 2003. Supai Group and Hermit Formation. In *Grand Canyon Geology*, 2nd edition, eds. S.S. Beus, and M. Morales, pp. 136-162. New York: Oxford University Press.

Blakey, R.C., and R. Knepp. 1989. Pennsylvanian and Permian geology of Arizona. *Arizona Geological Society Digest* 17:313-347.

Blakey, R.C., F. Peterson, and G. Kocurek. 1988. Late Paleozoic and Mesozoic eolian deposits of the Western Interior of the United States. *Sedimentary Geology* 56:3-125.

Bøe, R., J. Skarðhamar, L. Rise, M.F.J. Dolan, V.K. Bellec, M. Winsborrow, Ø. Skagseth, J. Knies, E.L. King, O. Walderhaug, S. Chand, S. Buenz, and J. Mienert. 2015. Sand waves and sand transport on the Barents Sea continental slope offshore northern Norway. *Marine and Petroleum Geology* 60:4-53.

Börmann, C., R. Gast, and F. Görisch. 2006. Structural and sedimentological analysis of an early Late Rotliegendes graben based on 3D seismic and well log data, German North Sea. *Petroleum Geoscience* 12:195-204.

Borsch, K., J.H. Whitmore, R. Strom, and G. Hartree. 2018. The significance of micas in ancient cross-bedded sandstones. In *Proceedings of the Eighth International Conference on Creationism*, ed. J.H. Whitmore, pp. 306-326. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Braddy, S.J. 1995. The ichnotaxonomy of the invertebrate trackways of the Coconino Sandstone (Lower Permian), northern Arizona. *In Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 219-224. Albuquerque: New Mexico Museum of Natural History and Science, Bulletin 6.

Brady, L.F. 1939. Tracks in the Coconino Sandstone compared with those of small living arthropods. *Plateau* 12:32-34.

Brady, L.F. 1947. Invertebrate tracks from the Coconino Sandstone of northern Arizona. *Journal of Paleontology* 21:466-472.

Brady, L.F. 1949. Onischoidichnus, a new name for Isopodichnus Brady 1947 not Bornemann 1889. *Journal of Paleontology* 23:573.

Brady, L.F. 1961. A new species of *Paleohelcura* Gilmore from the Permian of northern Arizona. *Journal of Paleontology* 35:201-202.

Brand, L.R. 1978. Footprints in the Grand Canyon. *Origins* 5, no. 2:64-82.

Brand, L.R. 1979. Field and laboratory studies on the Coconino Sandstone (Permian) vertebrate footprints and their paleoecological implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 28:25-38.

Brand, L.R. 1992. Reply on "Fossil vertebrate footprints in the Coconino Sandstone (Permian) of northern Arizona: Evidence for underwater origin." *Geology* 20:668-670.

Brand, L.R. 1996. Variations in salamander trackways resulting from substrate differences. *Journal of Paleontology* 70:1004-1010.

Brand, L.R., and J. Kramer. 1996. Underprints of vertebrate and invertebrate trackways in the Permian Coconino Sandstone in Arizona. *Ichnos* 4:225-230.

Brand, L.R., and T. Tang. 1991. Fossil vertebrate footprints in the Coconino Sandstone (Permian) of northern Arizona: Evidence for underwater origin. *Geology* 19:1201-1204.

Briggs, D.E.G., A.G. Plint, and R.K. Pickerill. 1984. Arthropleura trails from the Westphalian of eastern Canada. *Palaeontology* 27:843-855.

Briggs, D.E.G., and W.D.I. Rolfe. 1983. A giant arthropod trackway from the Lower Mississippian of Pennsylvania. *Journal of Paleontology* 57:377-390.

Brookfield, M.E. 1978. Revision of the stratigraphy of Permian and supposed Permian rocks of southern Scotland. *Geologische Rundschau* 67:110-149.

Brookfield, M.E. 1980. Permian intermontane basin sedimentation in southern Scotland. *Sedimentary Geology* 27:167-194.

Brookfield, M.E. 2000. Temporary desert lake deposits, Lower Permian (Rotliegendes) southern Scotland, U.K. In *Lake Basins Through Space and Time*, eds. E.H. Gierlowski-Kordesch, and K.R. Kelts, pp. 67-74. Tulsa, Oklahoma: American Association of Petroleum Geologists, AAPG Studies in Geology 46.

Bryant, G., and A. Miall. 2010. Diverse products of near-surface sediment mobilization in an ancient eolianite: Outcrop features of the early Jurassic Navajo Sandstone. *Basin Research* 22:578-590.

Carrigy, M.A. 1970. Experiments on the angles of repose of granular material. *Sedimentology* 14:147-158.

Castor, S.B., J.E. Faulds, S.M. Rowland, and C.M. dePolo. 2000. *Geologic map of the Frenchman Mountain Quadrangle, Clark County, Nevada*. Nevada Bureau of Mines and Geology, Map [and pamphlet] 127.

Cheel, R. 2003. Parting lineations and current crescents. In *Encyclopedia of Sediments and Sedimentary Rocks*, ed. G.V. Middleton, pp. 512-514. Dordrecht: Kluwer Academic Publishers.

Cheel, R.J., and G.V. Middleton. 1986. Horizontal laminae formed under upper flow regime planebed conditions. *Journal of Geology* 94:489-504.

Cheevers, C.W., and R.R. Rawson. 1979. Facies analysis of the Kaibab Formation in northern Arizona, southern Utah and southern Nevada. In *Permianland*, ed. D.L. Baars, pp. 105-113. Four Corners Geological Society Guidebook, 9th Field Conference.

Cheung, S.P., R. Strom, J.H. Whitmore, and P.A. Garner. 2009. Occurrence of dolomite beds, clasts, ooids and unidentified microfossils in the Coconino Sandstone, northern Arizona. *Geological Society of America*

Abstracts with Programs 41, no. 7:119.

Corbett, K.D. 1972. Features of thick-bedded sandstones in a proximal flysch sequence, Upper Cambrian, southwest Tasmania. *Sedimentology* 19:99-114.

Cornish, V. 1901. On sand-waves in tidal currents. *Geographical Journal* 18:170-202.

Crimes, T.P. 1970. Trilobite tracks and other traces from the Upper Cambrian of north Wales. *Geology* 7:47-68.

Crouvi, O., R. Amit, Y. Enzel, N.Porat, and A. Sandler. 2008. Sand dunes as a major proximal dust source for late Pleistocene loess in the Negev Desert, Israel. *Quaternary Research* 70:275-282.

Dalrymple, R.W. 1984. Morphology and internal structure of sandwaves in the Bay of Fundy. *Sedimentology* 31:365-382.

Darton, N.H. 1910. A reconnaissance of parts of northwestern New Mexico and northern Arizona. *U.S. Geological Survey Bulletin* 435:27.

Doelling, H.H., R.E. Blackett, A.H. Hamblin, J.D. Powell, and G.L. Pollock. 2003. Geology of Grand Staircase-Escalante National Monument, Utah. In *Geology of Utah's Parks and Monuments*, 2nd edition, eds. D.A. Sprinkel, T.C. Chidsey, Jr., and P.B. Anderson, pp. 189-231. Salt Lake City, Utah: Utah Geological Association and Bryce Canyon Natural History Association. Utah Geological Association Publication 28.

Dott, R.H. 2003. The importance of eolian abrasion in supermature quartz sandstones and the paradox of weathering on vegetation-free landscapes. *Journal of Geology* 111:387-405.

Elcock, E. 1993. *A Study of the Early Permian Coconino Sandstone Arizona* [BSc Thesis]. Wolverhampton, West Midlands, United Kingdom: University of Wolverhampton.

Elliott, T., and A.R. Gardiner. 1981. Ripple, megaripple and sandwave bedforms in the macrotidal Loughor Estuary, South Wales, U.K. In *Holocene Marine Sedimentation in the North Sea Basin*, eds. S.-D. Nio, R.T.E. Shüttenhelm, and T.C.E. Van Weering, pp. 51-64. Oxford: Blackwell Scientific Publications. Special Publication Number 5 of the International Association of Sedimentologists.

Emery, M.K., S.A. Maithel, and J.H. Whitmore. 2011. Can compaction account for lower-than expected cross-bed dips in the Coconino Sandstone (Permian), Arizona? *Geological Society of America Abstracts with Programs* 43, no. 5:430.

Ettensohn, F.R., N. Rast, and C.E. Brett, eds. 2002. *Ancient Seismites*. Boulder, Colorado: Geological Society of America Special Paper 359.

Fielding, C.R. 2006. Upper flow regime sheets, lenses and scour fills: Extending the range of architectural elements for fluvial sediment bodies. *Sedimentary Geology* 190:227-240.

Fisher, W.L. 1961. *Upper Paleozoic and Lower Mesozoic Stratigraphy of Parashant and Andrus Canyons, Mohave County, Northwestern Arizona* [PhD Thesis]. Lawrence, Kansas: University of Kansas.

Folk, R.L. 1955. Student operator error in determination of roundness, sphericity, and grain size. *Journal of Sedimentary Petrology* 25:297-301.

Garner, P.A., and J.H. Whitmore. 2011. What do we know about marine sand waves? A review of their occurrence, morphology and structure. *Geological Society of America Abstracts with Programs* 43, no. 5:596.

Garzanti, E., S. Andò, G. Vezzoli, A. Pereira, M. Lustrino, M. Boni, and P. Vermeesch. 2012. Petrology of the Namib Sand Sea: long-distance transport and compositional variability in the wind-displaced Orange Delta. *Earth-Science Reviews* 112:173-189.

Garzanti, E., A. Resentini, S. Andò, G. Vezzoli, A. Pereira, and P. Vermeesch. 2015. Physical controls on sand composition and relative durability of detrital minerals during ultra-long distance littoral and aeolian transport (Namibia and southern Angola). *Sedimentology* 62:971-996.

Gehrels, G.E., R. Blakey, K.E. Karlstrom, J.M. Timmons, B. Dickinson, and M. Pecha. 2011. Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona. *Lithosphere* 3:183-200.

Gilmore, C.W. 1926. Fossil footprints from the Grand Canyon. *Smithsonian Miscellaneous Collections* 77, no. 9:1-41.

Gilmore, C.W. 1927a. Collecting fossil footprints in the Grand Canyon, Arizona. *Smithsonian Miscellaneous Collections* 78, no. 7:45-48.

Gilmore, C.W. 1927b. Fossil footprints from the Grand Canyon: second contribution. *Smithsonian Miscellaneous Collections* 80, no. 3:1-78.

Gilmore, C.W. 1928. Fossil footprints from the Grand Canyon: third contribution. *Smithsonian Miscellaneous Collections* 80, no 8:1-16.

Glennie, K.W. 1972. Permian Rotliegendes of northwest Europe interpreted in light of modern desert sedimentation studies. *Bulletin of the American Association of Petroleum Geologists* 56:1048-1071.

Glennie, K.W. 1983. Lower Permian Rotliegend desert sedimentation in the North Sea area. In *Eolian Sediments and Processes*, eds. M.E. Brookfield, and T.S. Ahlbrandt, pp. 521-541. Oxford: Elsevier. Developments in Sedimentology 38.

Glennie, K.W., G.C. Mudd, and P.J.C. Nagtegaal. 1978. Depositional environment and diagenesis of Permian Rotliegendes Sandstones in Leman Bank and Sole Pit areas of the UK southern North Sea. *Journal of the Geological Society of London* 135:25-34.

Gouidie, A.S., and A. Watson. 1981. The shape of desert sand grains. *Journal of Arid Environments* 4:185-190.

Hantzschel, W. 1975. *Treatise on Invertebrate Paleontology, Part W, Miscellanea, Supplement I. Trace Fossils and Problematica*. Lawrence, Kansas: Geological Society of America and the University of Kansas.

Harianto, T., S. Hayashi, and Y.-J. Du. 2008. Effects of fiber additives on the desiccation crack behavior of the compacted Akaboku Soil as a material for landfill cover barrier. *Water, Air, and Soil Pollution* 194:141–149.

Harvey, J.G. 1966. Large sand waves in the Irish Sea. *Marine Geology* 4:49-55.

Haubold, H. 1971. *Ichnia Amphibiorum et Reptiliorum fossilium*. Stuttgart: Gustav Fischer Verlag.

Haubold, H. 1984. *Saurierfährten*. Wittenberg Lutherstadt: A. Ziemsen Verlag.

Haubold, H. 1996. Ichnotaxonomie und Klassifikation von Tetrapodenfaehrten aus dem Perm. *Hallesches Jahrbuch für Geowissenschaften* B18:23-88.

Haubold, H., A.P. Hunt, S.P. Lucas, and M.G. Lockley. 1995a. Wolfcampian (Early Permian) vertebrate tracks from Arizona and New Mexico. In *Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 135-165. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 6.

Haubold, H., M.G. Lockley, A.P. Hunt, and S.P. Lucas. 1995b. Lacertoid footprints from Permian dune sandstones, Cornberg and DeChelly Sandstones. In *Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 235-244. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 6.

Helble, T. 2011. Sediment transport and the Coconino Sandstone: A reality check on flood geology. *Perspectives on Science and Christian Faith* 63:25-41.

Hill, C., G. Davidson, T. Helble, and W. Ranney, eds. 2016. *The Grand Canyon Monument to an Ancient Earth*. Grand Rapids, Michigan: Kregel Publications.

Houbolt, J.J.H.C. 1968. Recent sediments in the southern bight of the North Sea. *Geologie en Mijnbouw* 47:245-273.

Hulscher, S.J.M.H., and C.M. Dohmen-Janssen. 2005. Introduction to special section on marine sand wave and river dune dynamics. *Journal of Geophysical Research* 110:F04S01 [6 pages, doi:10.1029/2005JF000404].

Hulscher, S.J.M.H. 1996. Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. *Journal of Geophysical Research* 101:20727-20744.

Hunt, A.P., and S.G. Lucas. 1998. Implications of the cosmopolitanism of Permian tetrapod ichnofaunas. In *Permian Stratigraphy and Paleontology of the Robledo Mountains, New Mexico*, eds. S.G. Lucas, J.W. Estep, and J.M. Hoffer, pp. 55-58. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 12.

Hunt, A.P., and S.G. Lucas. 2005. Tetrapod ichnofacies and their utility in the Paleozoic. In *Pennsylvanian Footprints in the Black Warrior Basin of Alabama*, eds. R.J. Buta, A.K. Rindsberg, and D.C. Kopaska-Merkel, pp. 113-119. Alabama Paleontological Society, Monograph 1.

Hunt, A.P., and V.L. Santucci. 1998. Taxonomy and ichnofacies of Permian tetrapod tracks from Grand Canyon National Park, Arizona. In *National Park Service Paleontological Research*, eds. V.L. Santucci, and L. McClelland, pp. 94-96. National Park Service Geological Resources Division, Technical Report NPS/NRGRD/GRDTR-98/01.

Hunt, A.P., and V.L. Santucci. 2001. An unusual tetrapod track morphology from the Permian Coconino Sandstone, Grand Canyon National Park, Arizona. In *Proceedings of the 6th Fossil Resource Conference: 2001 A Fossil Odyssey*, eds. V.L. Santucci, and L. McClelland, pp. 44-47. United States National Park Service, Geological Resource Division, Technical Report NRS/NRGRD/GRDTR-01/01.

Hunt, A.P., S.G. Lucas, M.G. Lockley, H. Haubold, and S. Braddy. 1995. Tetrapod ichnofacies in Early Permian red beds of the American Southwest. In *Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 295-301. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 6.

Hunter, R.E. 1977. Basic types of stratification in small eolian dunes. *Sedimentology* 24:361-387.

Hunter, R.E. 1981. Stratification styles in eolian sandstones: Some Pennsylvanian to Jurassic examples from the western interior U.S.A. In *Recent and Ancient Nonmarine Depositional Environments: Models for Exploration*, eds. F.G. Ethridge, and R.M. Flores, pp. 315-329. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists, Special Publication 31.

Hunter, R.E. 1985. Subaqueous sand-flow cross-strata. *Journal of Sedimentary Petrology* 55: 886-894.

Hurst, A., and J. Cartwright, eds. 2007. *Sand Injectites: Implications for Hydrocarbon Exploration and Production*. Tulsa, Oklahoma: American Association of Petroleum Geologists, Memoir 87.

James, N.P., and R.W. Dalrymple, eds. 2010. *Facies Models 4*. Geological Association of Canada, GEOtext 6.

Jardine, W. 1850. Note to Mr Harkness's paper "On the position of the impressions of footsteps in the Bunter Sandstones of Dumfriesshire." *Annals and Magazine of Natural History* 6:208-209.

Jardine, W. 1853. *The Ichnology of Annandale, or Illustrations of Footmarks Impressed on the New Red Sandstone of Corncockle Muir*. Edinburgh.

Jerolmack, D.J., and T.A. Brzinski, III. 2010. Equivalence of abrupt grain-size transitions in alluvial rivers and eolian sand seas: a hypothesis. *Geology* 38:719-722.

Jones, A.T., J.M. Kennard, G.A. Logan, E. Grosjean, and J. Marshall. 2009. Fluid expulsion features associated with sand waves on Australia's central North West Shelf. *Geo-Marine Letters* 29:233-248.

Julien, P.Y., Y. Lan, and G. Berthault. 1994. Experiments on stratification of heterogeneous sand mixtures. *Creation Ex Nihilo Technical Journal* 8, no. 1:37-50.

King, E.L., R. Bøe, V.K. Bellec, L. Rise, J. Skarðhamar, B. Ferré, and M.F.J. Dolan. 2014. Contour current driven continental slope-situated sandwaves with effects from secondary current processes on the Barents Sea margin offshore Norway. *Marine Geology* 353:108-127.

Kleinhans, M.G. 2004. Sorting in grain flows at the lee side of dunes. *Earth-Science Reviews* 65:75-102.

Kozur, H., M., Löffler, and E. Sittig. 1994. First evidence of *Paleohelcura* (arthropod trackway) in the Rotliegend of Europe. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen* 10:613-632.

Kramer, J.M., B.R. Erickson, M.G. Lockley, A.P. Hunt, and S.J. Braddy. 1995. Pelycosaur predation in the Permian: Evidence from *Laoporus* trackways from the Coconino Sandstone with description of a new species of *Permichnium*. In *Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 245-249. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 6.

Kuenen, Ph. H., and W.G. Perdok. 1962. Experimental abrasion 5. Frosting and defrosting of quartz grains. *Journal of Geology* 70:648-658.

Kuenen, Ph.H. 1960. Experimental abrasion 4: Eolian action. *Journal of Geology* 68:427-449.

Lancaster, N. 1995. *Geomorphology of Desert Dunes*. New York: Routledge.

Langhorne, D.N. 1982. A study of the dynamics of a marine sandwave. *Sedimentology* 29:571-594.

Lippman, F. 1973. *Sedimentary Carbonate Minerals*. New York: Springer-Verlag.

Lockley, M.G. 1992. Comment on "Fossil vertebrate footprints in the Coconino Sandstone (Permian) of northern Arizona: Evidence for underwater origin." *Geology* 20:666-667.

Lockley, M.G., A.P. Hunt, H. Haubold, and S.G. Lucas. 1995. Fossil footprints in the De Chelly Sandstone of Arizona: With paleoecological observations on the ichnology of dune facies. *Bulletin of New Mexico Museum of Natural History and Science* 6:225-233.

Loope, D.B. 1992. Comment on "Fossil vertebrate footprints in the Coconino Sandstone (Permian) of northern Arizona: Evidence for underwater origin." *Geology* 20:667-668.

Lowe, D.R. 1975. Water escape structures in coarse-grained sediments. *Sedimentology* 22:157-204.

Ludwick, J.C. 1970. *Sand waves and tidal channels in the entrance to Chesapeake Bay. Norfolk, Virginia*: Institute of Oceanography, Old Dominion University. Technical Report No. 1.

Lull, R.S. 1918. Fossil footprints from the Grand Canyon of the Colorado. *American Journal of Science* 45:337-346.

Lundy, W.L. 1973. *The Stratigraphy and Evolution of the Coconino*

Sandstone of Northern Arizona [MS Thesis]. Tulsa, Oklahoma: University of Tulsa.

Macdonald, J.P. 1989. *Finding Footprints: Tracking New Mexico's Pre-Dinosaurs*. Las Cruces, New Mexico: The Paleozoic Trackways Project.

MacLachlan, M.E. 1972. Triassic System. In *Geologic Atlas of the Rocky Mountain Region*, ed. W.W. Mallory, pp. 166-176. Denver, Colorado: Rocky Mountain Association of Geologists.

Maithel, S.A., L.R. Brand, and J.H. Whitmore. 2013. Morphology of avalanche beds in the Coconino Sandstone at Chino Wash, Seligman, Arizona. *Geological Society of America Abstracts with Programs* 45, no. 7:126.

Maithel, S.A., L.R. Brand, and J.H. Whitmore. 2014. "Ripple marks," "slump features," and "rainprints" in the Coconino Sandstone near Ash Fork, Arizona. *Geological Society of America Abstracts with Programs* 46, no. 6:78.

Maithel, S.A., L.R. Brand, and J.H. Whitmore. 2015. Morphological analysis of "grainflow" cross-strata in the Coconino Sandstone (Permian), Arizona. *Geological Society of America Abstracts with Programs* 47, no. 7:589.

Maithel, S.A., L.R. Brand, and J.H. Whitmore. 2016. Using textural trends to interpret cross-bed depositional processes in the Coconino Sandstone (Permian), Arizona. *Geological Society of America Abstracts with Programs* 48, no. 7: doi: 10.1130/abs/2016AM-286508.

Maithel, S.A., L.R. Brand, and J.H. Whitmore. 2017. Along-dip textural trends in the Permian Coconino Sandstone from thin section and laser diffraction particle analysis. *Geological Society of America Abstracts with Programs* 49, no. 6: doi: 10.1130/abs/2017AM-307885.

Maithel, S.A., P.A. Garner, and J.H. Whitmore. 2015. Preliminary assessment of the petrology of the Hopeman Sandstone (Permo-Triassic), Moray Firth Basin, Scotland. *Scotish Journal of Geology* 51:177-184.

Makse, H.A., R.C. Ball, H.E. Stanley, and S. Warr. 1998. Dynamics of granular stratification. *Physical Review E* 58(3):3357-3368.

Makse, H.A., S. Havlin, P.R. King, and H.E. Stanley. 1997. Spontaneous stratification in granular mixtures. *Nature* 386:379-381.

Manton, S.M. 1973. The evolution of arthropodan locomotory mechanisms. Part 11. Habits, morphology and evolution of the Uniramia (Onychophora, Myriapoda, Hexapoda) and comparisons with the Arachnida, together with a functional review of uniramian musculature. *Zoological Journal of the Linnaean Society* 53:257-375.

Mantz, P.A. 1978. Bedforms produced by fine, cohesionless, granular and flakey sediments under subcritical water flows. *Sedimentology* 25:83-103.

Marzolf, J.E. 1976. Sand-grain frosting and quartz overgrowth examined by scanning electron microscopy: The Navajo Sandstone (Jurassic (?)), Utah. *Journal of Sedimentary Petrology* 46:906-912.

McAllister, J.A. 1989. Dakota Formation tracks from Kansas: Implications for the recognition of tetrapod subaqueous traces. In *Dinosaur Tracks and Traces*, eds. D.D. Gillette, and M.G. Lockley, pp. 343-348. Cambridge: Cambridge University Press.

McCave, I.N. 1971. Sand waves in the North Sea off the coast of Holland. *Marine Geology* 10:199-225.

McKee, E.D. 1934. The Coconino Sandstone – its history and origin. In *Papers Concerning the Palaeontology of California, Arizona and Idaho*, pp. 77-115. Carnegie Institute of Washington, Publication 440.

McKee, E.D. 1944. Tracks that go uphill in Coconino Sandstone, Grand Canyon, Arizona. *Plateau* 16:61-72.

McKee, E.D. 1945. Small-scale structures in Coconino sandstone of northern Arizona. *Journal of Geology* 53:313-325.

McKee, E.D. 1947. Experiments on the development of tracks in fine cross-bedded sand. *Journal of Sedimentary Petrology* 17:23-28.

McKee, E.D. 1966. Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). *Sedimentology* 7:1-69.

McKee, E.D. and G.W. Weir. 1953. Terminology for stratification and cross-stratification in sedimentary rocks. *Bulletin of the Geological Society of America* 64:381-390.

McKee, E.D., and C. Tibbitts, Jr. 1964. Primary structures of a seif dune and associated deposits in Libya. *Journal of Sedimentary Petrology* 34:5-17.

McKee, E.D., and J.J. Bigarella. 1979a. Ancient sandstones considered to be eolian. In *A Study of Global Sand Seas*, ed. E.D. McKee, pp. 187-238. U.S. Geological Survey Professional Paper 1052.

McKee, E.D., and J.J. Bigarella. 1979b. Sedimentary structures in dunes. In *A Study of Global Sand Seas*, ed. E.D. McKee, pp.83-134. U.S. Geological Survey Professional Paper 1052.

McKee, E.D, ed. 1979. *A Study of Global Sand Seas*. U.S. Geological Survey Professional Paper 1052.

McKee, E.D., J.R. Douglass, and S. Rittenhouse. 1971. Deformation of lee-side laminae in eolian dunes. *Geological Society of America Bulletin* 82:359-378.

McKeever, P.J. 1994. The behavioural and biostratigraphical significance and origin of vertebrate trackways from the Permian of Scotland. *Palaios* 9:477-487.

McKeever, P.J., and H. Haubold. 1996. Reclassification of vertebrate trackways from the Permian of Scotland and related forms from Arizona and Germany. *Journal of Paleontology* 70:1011-1022.

Melchor, R.N. 1997. Permian tetrapod ichnofaunas from Argentina: Further evidence of redbed shallow lacustrine and aeolian vertebrate ichnofacies. In *Abstracts and Papers of Workshop on the Ichnofacies and Ichnotaxonomy of the Terrestrial Permian*, pp. 59-60. Halle: Martin Luther University, Halle-Wittenberg Institute of Geoscience and Geiselthal Museum.

Melchor, R.N. 2001. Permian tetrapod footprints from Argentina. *Hallesches Jahrbuch für Geowissenschaften* B23:35-43.

Middleton, L.T., D.K. Elliott, and M. Morales. 2003. Coconino Sandstone. In *Grand Canyon Geology*, 2nd edition, eds. S.S. Beus and M. Morales, pp. 163-179. New York: Oxford University Press.

Miller, F.K., and E.H. McKee. 1971. Thrust and strike-slip faulting in the Plomosa Mountains, southwestern Arizona. *Geological Society of America Bulletin* 82:717-722.

Millhouse, A.M. 2009. *Analysis of Trackways in the Permian Coconino Sandstone of Ash Fork and Grand Canyon, Arizona* [MS Thesis]. Flagstaff, Arizona: Northern Arizona University.

Morales, M., and H. Haubold. 1995. Tetrapod tracks from the Lower Permian De Chelly Sandstone of Arizona: Systematic description. In *Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 251-261. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 6.

Morrow, D.W. 1988. Dolomite — Part 1: The chemistry of dolomitization and dolomite precipitation. *Geoscience Canada* 9:113-123.

Narayan, J. 1971. Sedimentary structures in the Lower Greensand of the Weald, England, and Bas-Boulonnais, France. *Sedimentary Geology* 6:73-109.

Olson, E.C. 1952. The evolution of a Permian vertebrate chronofauna. *Evolution* 6:181-196.

Olson, E.C. 1983. Coevolution or coadaptation? Permo-Carboniferous vertebrate chronofauna. In *Coevolution*, ed. M.H. Nitecki, pp. 307-338. Chicago: University of Chicago Press.

Owen, R. 1842. Report on British fossil reptiles: Part 2. *Report of the British Association for the Advancement of Science* (for 1841), pp. 94-103, 156.

Paola, C., S.M. Wiele, and M.A. Reinhart. 1989. Upper-regime parallel lamination as the result of turbulent sediment transport and low-amplitude bed forms. *Sedimentology* 36:47-59.

Peabody, F.E. 1959. Trackways of living and fossil salamanders. *University of California Publications in Zoology* 63:1-48.

Peirce, H.W., N. Jones, and R. Rogers. 1977. *A Survey of Uranium Favorability of Paleozoic Rocks in the Mogollon Rim and Slope Region – East Central Arizona*. Tucson, Arizona: State of Arizona Bureau of Geology and Mineral Technology, Circular 19.

Peters, R.A., and L.R. Brand. 1999. Origin of polygonal compaction cracks in Permian Coconino Sandstone, Arizona. *Geological Society of America Abstracts with Programs* 31, no. 7:160.

Picard, M.D., and J.B. Hulen. 1969. Parting lineation in siltstone. *Geological Society of America Bulletin* 80:2631-2636.

Poole, F.G. 1962. Wind directions in Late Paleozoic to Middle Mesozoic time on the Colorado Plateau. U*.S. Geological Survey Professional Paper* 450-D:D147-D151. Short Papers in Geology, Hydrology, and Topography, Articles 120-179.

Poppe, L.J., M.L. DiGiacomo-Cohen, S.M. Smith, H.F. Stewart, H.F., and N.A. Forfinski. 2006. Seafloor character and sedimentary processes in eastern Long Island Sound and western Block Island Sound. *Geo-Marine Letters* 26:59-68.

Powers, M.C. 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology* 23:117-119.

Pye, K., and Tsoar, H. 2009. *Aeolian Sand and Sand Dunes*. Berlin: Springer-Verlag.

R Development Core Team. 2011. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing [http://www.R-project.org/].

Ranney, W.D.R. 2001. *Sedona Through Time*, 2nd ed. Flagstaff, Arizona: Zia Interpretive Services.

Rawson, R.R., and C.E. Turner-Peterson. 1980. Paleogeography of northern Arizona during the deposition of the Permian Toroweap Formation. In *Paleozoic Paleogeography of West-central United States*, eds. T.D. Fouch, and E.R. Magathan, pp. 341-352. Denver, Colorado: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 1.

Reiche, P. 1938. An analysis of cross-lamination the Coconino Sandstone. *Journal of Geology* 46:905-932.

Roth, A.A. 2009. "Flat gaps" in sedimentary rock layers challenge long geologic ages. *Journal of Creation* 23, no. 2:76-81.

Rouse, S.C. 2017. Characterization of massive vs. laminated texture of the Coconino Sandstone (Permian), Arizona from the study of thin sections. *Cedarville University Research and Scholarship Symposium* [poster]. http://digitalcommons.cedarville.edu/research_scholarship_symposium/2017/poster_presentations/4/.

Russell, R.D., and R.E. Taylor. 1937. Roundness and shape of Mississippi River sands. *The Journal of Geology* 45:225-267.

Sadler, C. 1993. Arthropod trace fossils from the Permian De Chelly Sandstone, northeastern Arizona. *Journal of Paleontology* 67:240-249.

Salsman, G.G., W.H. Tolbert, and R.G. Villars. 1966. Sand-ridge migration in St. Andrew Bay, Florida. *Marine Geology* 4:11-19.

Schult, M.F. 1995. Comparisons between the Las Cruces ichnofauna and other Permian ichnofaunas, including inferred trackmakers. In *Early Permian Footprints and Facies*, eds. S.G. Lucas, and A.B. Heckert, pp. 127-133. Albuquerque, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 6.

Selley, R.C. 1985. *Ancient Sedimentary Environments*, 3rd edition. London: Chapman and Hall.

Sharp, R.P. 1966. Kelso dunes, Mojave Desert, California. *Geological Society of America Bulletin* 77:1045-1074.

Smalley, I.J., and C. Vita-Finzi. 1968. The formation of fine particles in sandy deserts and the nature of 'desert' loess. *Journal of Sedimentary Petrology* 38:766-774.

Spamer, E.E. 1984. Paleontology in the Grand Canyon of Arizona: 125 years of lessons and enigmas from the late Precambrian to the present. *The Mosasaur* 2:45-128.

Steel, R.J. 1977. Triassic rift basins of north-western Scotland – their configuration, infilling and development. In P*roceedings: Mesozoic Northern North Sea Symposium 1977 (MNNSS-77)*, eds. K.G. Finstad, and R.C. Selley, pp. MNNSS/7-1 to MNNSS/7-18. NORSK Petroleumsforening (NPF) and Norwegian Petroleum Society.

Stemmerik, L., J.R. Ineson, and J.G. Mitchell. 2000. Stratigraphy of the Rotliegend Group in the Danish part of the Northern Permian Basin, North Sea. *Journal of the Geological Society of London* 157:1127-1136.

Stokes, W.L. 1947. Primary lineation in fluvial sandstones: A criterion of current direction. *Journal of Geology* 55:52-53.

Stokes, W.L. 1968. Primary current lineation or parting lineation. *Geological Society of America Bulletin* 79:1419-1420.

Stone, P., K.A. Howard, and W. Hamilton. 1983. Correlation of metamorphosed Paleozoic strata of the southeastern Mojave Desert region, California and Arizona. *Geological Society of America Bulletin* 94: 1135-1147.

Strahler, A.N. 1999. *Science and Earth History — The Evolution/Creation Controversy*. Amherst, New York: Prometheus Books.

Strömback, A.C., and J.A. Howell. 2002. Predicting distribution of remobilized aeolian facies using sub-surface data: The Weissliegend of the UK Southern North Sea. *Petroleum Geoscience* 8:237-249.

Sumner, C.D. 1999. *Stratigraphy of the Northern Depositional Margin of the Coconino Sandstone, Northern Arizona and Southern Utah* [MS Thesis]. Nacogdoches, Texas: Stephen F. Austin State University.

Tanner, L.H. 2001. On the origin of parting-step lineation in eolian sandstones. *Geological Society of America Abstracts with Programs* 33, no. 6:74.

Terwindt, J.H.J. 1971. Sand waves in the southern bight of the North Sea. *Marine Geology* 10:51-67.

Twenhofel, W.H. 1945. The rounding of sand grains. *Journal of Sedimentary Petrology* 15:59-71.

Walker, T.R. and J.C. Harms. 1972. Eolian origin of flagstone beds, Lyons Sandstone (Permian), type area, Boulder County, Colorado. *Mountain*

Geologist 9:279-288.

Weber, C.G. 1980. The fatal flaws of Flood geology. *Creation/Evolution* 1, no. 1:24-37.

Weedman, S.D., and R. Slingerland. 1985. Experimental study of sand streaks formed in turbulent boundary layers. *Sedimentology* 32:133-145.

Werner, F. 2000. New aspects of sand waves (Fehmarn Belt, western Baltic) by using high-resolving sonography. *Baltica* 13:85-87.

White, D. 1929. *Flora of the Hermit Shale, Grand Canyon, Arizona*. Washington D.C.: Carnegie Institution of Washington, Publication 405.

Whitmore, J.H. 2005. Origin and significance of sand-filled cracks and other features near the base of the Coconino Sandstone, Grand Canyon, Arizona. *Creation Research Society Quarterly* 42:163-180.

Whitmore, J.H. 2016. Preliminary correlation and isopach map of the Pennsylvanian and Permian sandstones of the western United States. *Cedarville University Research and Scholarship Symposium* [poster]. http://digitalcommons.cedarville.edu/research_scholarship_symposium/2016/poster_presentations/42/.

Whitmore, J.H., and R. Strom. 2010. Sand injectites at the base of the Coconino Sandstone, Grand Canyon, Arizona. *Sedimentary Geology* 230:46-59.

Whitmore, J.H., and R. Strom. 2017. Rounding of quartz and K-feldspar sand from beach to dune settings along the California and Oregon coastlines: implications for ancient sandstones. *Answers Research Journal* 10:259-270.

Whitmore, J.H., and R. Strom. 2018. The significance of angular K-feldspar grains in ancient sandstones. In *Proceedings of the Eighth International Conference on Creationism*, ed. J.H. Whitmore, pp. 628-651. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Whitmore, J.H., and R.A. Peters. 1999. Reconnaissance study of the contact between the Hermit Formation and the Coconino Sandstone, Grand Canyon, Arizona. *Geological Society of America Abstracts with Programs* 31, no. 7:A-235.

Whitmore, J.H., G. Forsythe, and P.A. Garner. 2015. Intraformational parabolic recumbent folds in the Coconino Sandstone (Permian) and two other formations in Sedona, Arizona (USA). *Answers Research Journal* 8:21-40.

Whitmore, J.H., R. Strom, P.A. Garner, S. Cheung, and G. Forsythe. 2012. *Catastrophic subaqueous deposition of the Coconino Sandstone and its equivalents during Noah's Flood, western United States*. [Unpublished] report submitted to the Institute for Creation Research, Dallas, Texas.

Whitmore, J.H., R. Strom, S. Cheung, and P.A. Garner. 2014. Petrology of the Coconino Sandstone. *Answers Research Journal* 7:499-532.

Wilson, I.G. 1973. Ergs. Sedimentary Geology 10:77-106.

Wright, J. 2001. Making loess-sized quartz silt: data from laboratory simulations and implications for sediment transport pathways and the formation of 'desert' loess deposits associated with the Sahara. *Quaternary International* 76/77:7-19.

Yassoglou, N., C.S. Kosmas, N. Moustakas, E. Tzianis, and N.G. Danalatos. 1994. Cracking in recent alluvial soils as related to easily determined soil properties. *Geoderma* 63:289–298.

Yesiller, N., C.J. Miller, G. Inci, and K. Yaldo. 2000. Desiccation and cracking behavior of three compacted landfill liner soils. *Engineering Geology* 57:105–121.

Young, D.A., and R.F. Stearley. 2008. *The Bible, Rocks and Time*. Downers Grove, Illinois: InterVarsity Press.

THE AUTHORS

John H. Whitmore is senior professor of geology at Cedarville University where he has been teaching since 1991. He has a B.S. in Geology (Kent State University), M.S. in Geology (Institute for Creation Research) and a Ph.D. in Biology with a Paleontology emphasis (Loma Linda University). He is widely published in both the conventional and creation literature. His primary interests are fossil fish taphonomy, the Green River Formation, the Flood/post-Flood boundary and Grand Canyon geology. He has been studying the Coconino Sandstone since 1998. He is a coauthor of *The Heavens and the Earth*, a college-level earth science text.

Paul A. Garner is a full-time Researcher and Lecturer for Biblical Creation Trust in the UK. He has an MSc in Geoscience from University College London, where he specialised in palaeobiology. He is a Fellow of the Geological Society of London and a member of several other scientific societies. His first book, *The New Creationism: Building Scientific Theories on a Biblical Foundation*, was published by Evangelical Press in 2009.