UNEXPECTED DISCOVERIES IN THE COCONINO SANDSTONE (PERMIAN, ARIZONA)

WHITMORE, John H., Department of Science and Mathematics, Cedarville University, 251 N. Main St, Cedarville, OH 45314 johnwhitmore@cedarville.edu, **GARNER, Paul A.**, P.O. Box 325, Ely, CB7 5YH, United Kingdom and **STROM, Raymond**, Calgary Rock and Materials Services Inc, #3, 3610-29th St. NE, Calgary, Alberta, T1Y 5Z7, Canada

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ABSTRACT

Edwin McKee published the first comprehensive study of the Coconino Sandstone in 1934, and since then, little original research has appeared on this prominent Grand Canyon formation. Over the past 20 years, we visited numerous outcrops covering the thickness and areal extent of the formation and studied 400 thin sections with the goal of better understanding the nature of this well-known but little-studied formation. The following is a summary of our published findings.

Regarding petrology, the sand has an average grain size of about 3.0 ϕ, is moderately sorted, subrounded to subangular and increases slightly in grain size and sorting from north to south (in the same direction as cross-bed dip). Dolomite occurs widely as occasional beds, ooids, clasts, cement and rhombs. Detrital muscovite occurs in nearly every thin section; sometimes the flakes are bigger than the quartz grains that surround them. Detrital K-feldspar comprises about 10% of most samples and is often angular or subangular. Thin sections show little indication of significant compaction, most having 10-15% porosity.

Regarding sedimentology, our large data set of cross-bed dips average about 20° and are similar to Reiche's data (1938). Narrow grainflow tongues, which commonly occur on eolian dunes, were not observed; instead, parallel laminae can be traced for many meters along strike on bounding surfaces. Patterns resembling primary current lineation occur on most foreset surfaces and trend down-dip. Especially in western outcrops of Coconino, linear bands of circular pits can be found, also trending down dip. Along Tanner Trail, the Coconino interfingers with the underlying Hermit Formation. Our published data suggest that tabular sand bodies extending downward into the Hermit in Grand Canyon are sand injectites and not desiccation cracks due to their orientation, internal structure, association with the Bright Angel Fault, and the sparsity of clay (< 3%) in the Hermit. In Sedona, multiple examples of large-scale soft sediment deformation features, confined between sets of planar- and cross-beds, extend continuously for 50-400 m in dip direction. The deformation matches the characteristics of subaqueous parabolic recumbent folds. Considering all these data, it is time for more work in order to refine depositional models for the Coconino Sandstone.

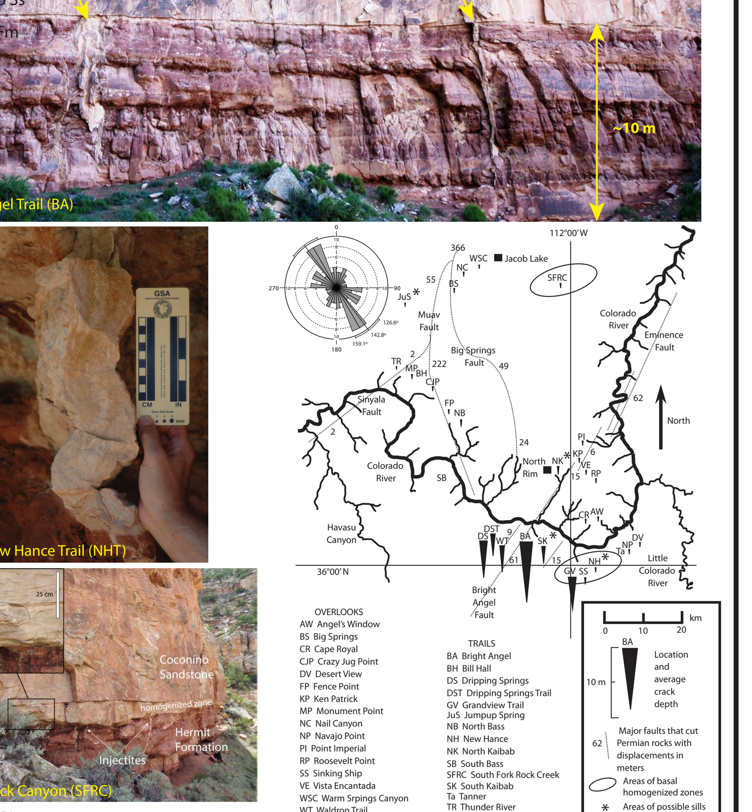
STUDY AND SAMPLE AREAS

AC-Andrus Canyon
AP-Andrus Point
ASF-Ash Fork
ASR-American Sandstone Ridge
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
Navajo Bridge
NC-North Canyon
NHT-New Hance Trail
OC- Oak Creek Canyon
PB-Picacho Butte
PCT- Pine Creek Trail
RC- Rhodes Canyon
RM- Ramsey Mine
SED- Sedona (includes SBR)
SFRC- South Fork Rock Creek
SK-South Kaibab
SKR-Soap Creek Rapid
SRM-Sunrise Mountain
SR-Scherrer Ridge
TC-Trail Canyon
TT-Tanner Trail
VRG-Virgin River Gorge
WC- Whitmore Canyon
WSC-Warm Springs Canyon

Lateral extent of Coconino Sandstone in Arizona, California and Nevada

INJECTITES

In the Grand Canyon region, large sand-filled cracks can often be found penetrating from the Coconino Sandstone into the Hermit Formation below. Cracks penetrate deepest when they are close to the Bright Angel Fault, and become shorter as the displacement of the fault decreases and the distance from the fault increases. The cracks show preferred orientation. XRD results show the Hermit lacks the necessary clay minerals and clay-sized particles for it to crack via desiccation.

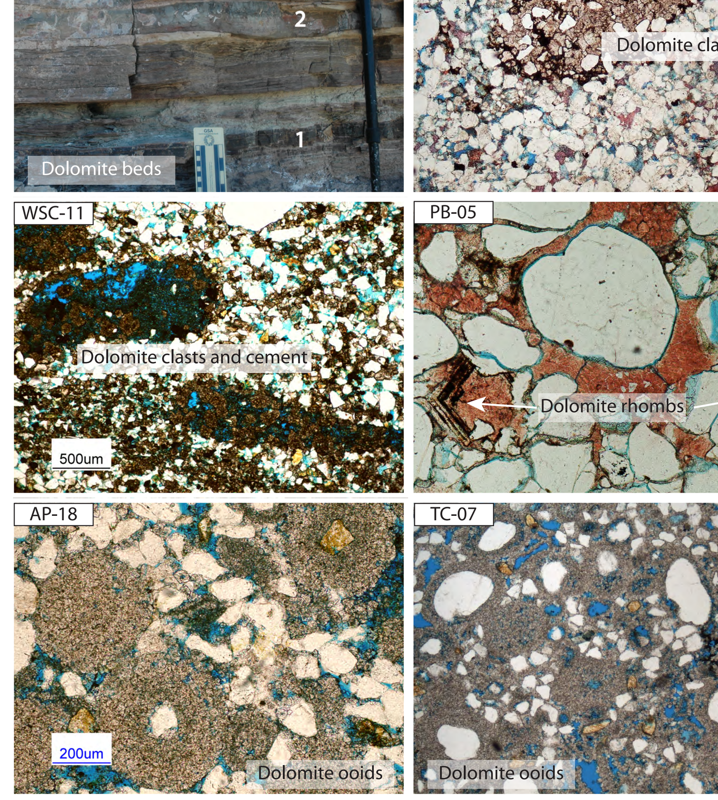


Significance:
Some have argued the Hermit represents a large floodplain that cracked via desiccation, and then the open cracks filled passively when the Coconino desert sands blew into the area. This argument should no longer be used. Instead, flow patterns in the sand-filled cracks indicate that the unlithified Coconino sand was forcefully injected, probably during Laramide time, due to seismic activity along the Bright Angel Fault.

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

DOLOMITE

Dolomite occurs in the Coconino Sandstone in five different forms: beds, ooids, rhombs, cement and clasts. It was not concentrated in a small area, but occurred over much of the northwestern region of Coconino outcrops.

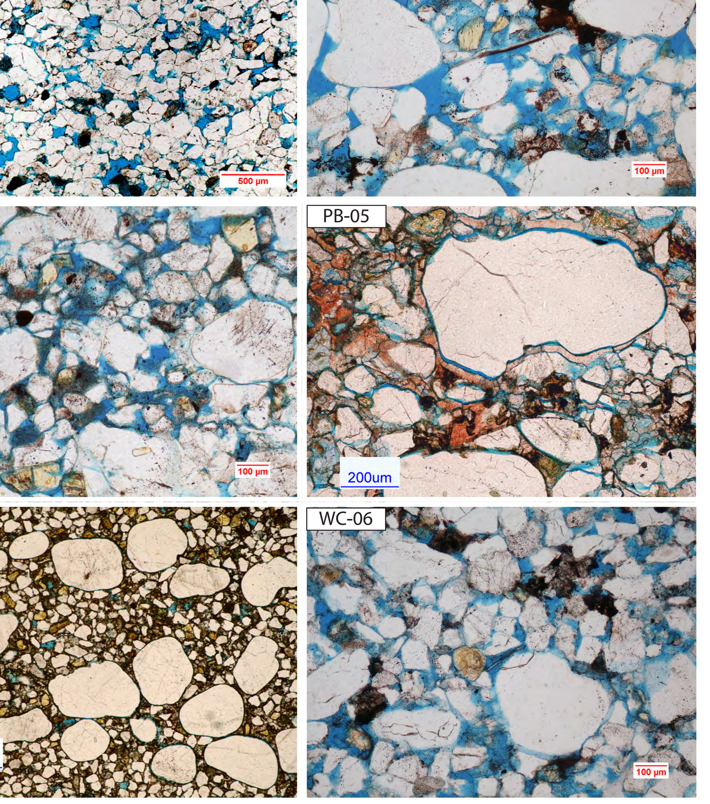


Significance:
Although dolomite is now known to form in small quantities in specialized desert settings, the dolomite in the Coconino is so widespread, a desert model for its formation is not sufficient to explain it. Note the size disparity (bimodality) of the dolomite clasts and ooids compared to the surrounding sand grains.

• 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(7):119.
• Whitmore, J.H., R. Strom, S. Cheung, and P.A. Garner. 2014. The petrology of the Coconino Sandstone (Permian), Arizona, USA. *Answers Research Journal* 7:499-532.

MODERATE SORTING

Sorting in the Coconino Sandstone was determined by thin section techniques from samples covering the full thickness and breadth of the formation. It was found that it ranges from poorly- to well-sorted, with most samples occurring in the moderately-sorted range. The southern part of the Coconino is better sorted than the northern part.

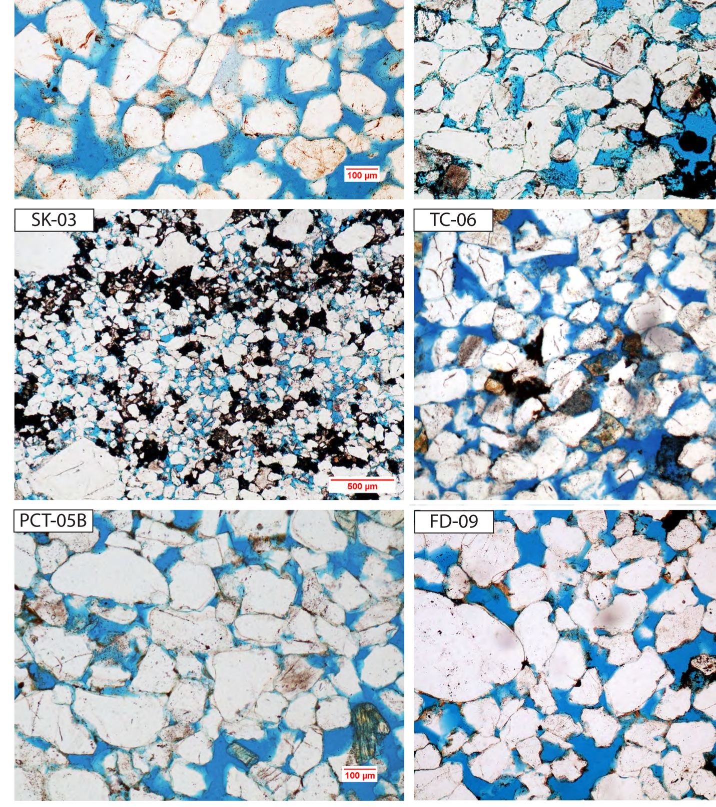


Significance:
Without referring to any data, many authors have claimed the Coconino is "well-sorted," probably based on the assumption that it is an eolian deposit. "Moderately-sorted" is the best description for the Coconino. Although moderate sorting can be a characteristic of eolian sands, the sorting in the Coconino is also consistent with what might be expected from aqueously deposited sand.

• Whitmore, J.H., and R. Strom. 2009. Petrographic analysis of the Coconino Sandstone, northern and central California. *Geological Society of America Abstracts with Programs* 41(7):122.
• Whitmore, J.H., R. Strom, S. Cheung, and P.A. Garner. 2014. The petrology of the Coconino Sandstone (Permian), Arizona, USA. *Answers Research Journal* 7:499-532.

SUB-ANGULAR QUARTZ

Grain roundness in the Coconino Salndstone was determined by thin section techniques from samples covering the full thickness and breadth of the formation. It was found that it ranges from angular to sub-rounded, with most samples falling in the sub-rounded to sub-angular range. The southern part of the Coconino was better rounded than the northern part, probably as a function of grain size.

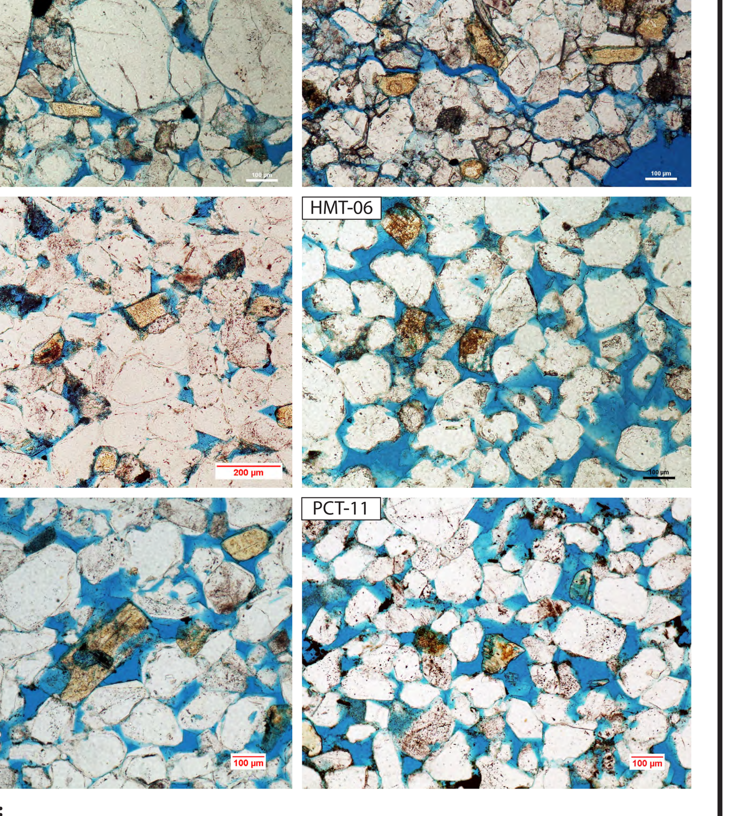


Significance:
Without referring to any data, many authors have claimed the Coconino is "well-rounded," probably based on the assumption that it is an eolian deposit. "Sub-rounded" to "sub-angular" is a better description for the Coconino. The angularity of the quartz is likely a function of the small grain size (about 3.0 ϕ) and not depositional environment.

• Whitmore, J.H., and R. Strom. 2009. Petrographic analysis of the Coconino Sandstone, northern and central California. *Geological Society of America Abstracts with Programs* 41(7):122.
• Whitmore, J.H., R. Strom, S. Cheung, and P.A. Garner. 2014. The petrology of the Coconino Sandstone (Permian), Arizona, USA. *Answers Research Journal* 7:499-532.

ANGULAR K-FELDSPAR

Angular K-feldspar was found in numerous thin sections throughout the Coconino Sandstone. Observations show that K-feldspar becomes rounded quickly when transported from beaches to eolian settings.

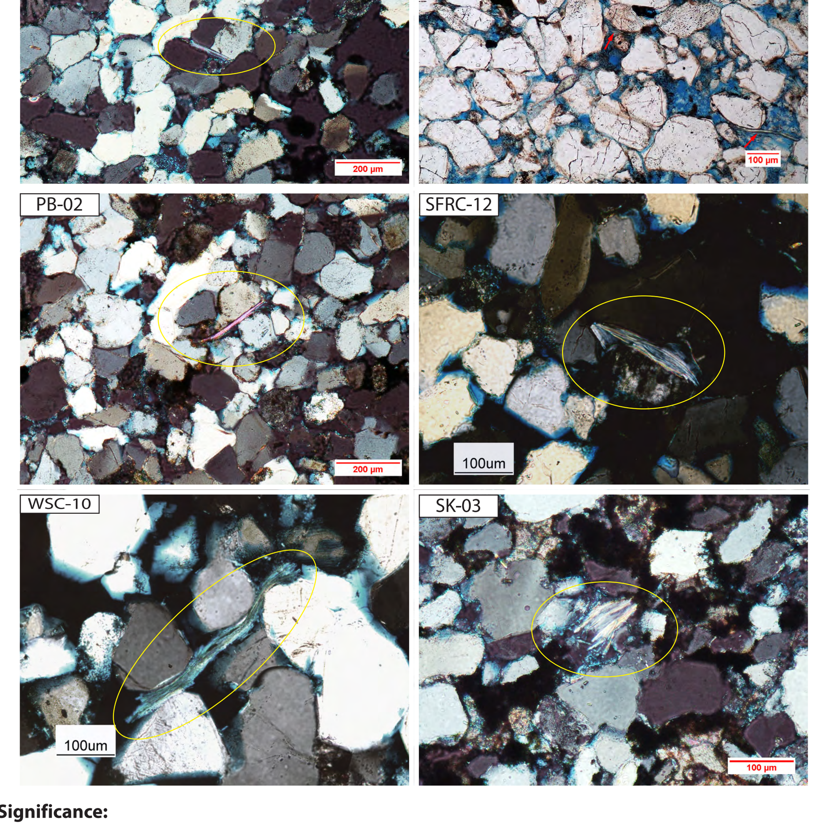


Significance:
K-feldspar remains angular in marine settings, but is quickly rounded when carried from beaches to nearby eolian dunes. Angular K-feldspar throughout the Coconino strongly suggests it was not deposited in eolian conditions.

• Whitmore, J.H., and R. Strom. 2017. Rounding of K-feldspar and quartz sand grains from beach to dune environments: Implications for ancient sandstones. *Geological Society of America Abstracts with Programs* 49(6) [electronic; no page numbers issued].
• 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.

MICA

Muscovite, and to a lesser extent biotite, was found in almost all of the 400 thin sections of Coconino Sandstone that were cut. Samples cover the thickness and areal extent of the Coconino.

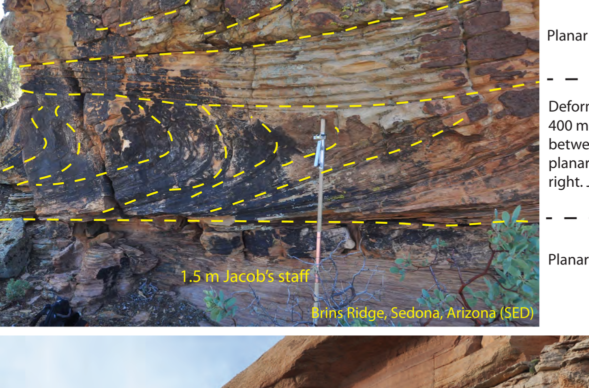


Significance:
Mica deteriorates quickly in actual and experimental eolian settings. However, it persists in marine environments, even under conditions of continual longshore transport in coastal settings. Mica has been found in some eolian settings, but only in the immediate vicinity of a mica source. The presence of mica throughout the Coconino strongly suggests an aqueous depositional origin.

• 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.
• Whitmore, J.H., and R. Strom. 2009. Petrographic analysis of the Coconino Sandstone, northern and central California. *Geological Society of America Abstracts with Programs* 41(7):122.
• Whitmore, J.H., R. Strom, S. Cheung, and P.A. Garner. 2014. The petrology of the Coconino Sandstone (Permian), Arizona, USA. *Answers Research Journal* 7:499-532.

PARABOLIC RECUMBENT FOLDS

Soft sediment deformation features resembling parabolic recumbent folds have been found in several locations in the Sedona area. The regular pattern can be traced along the outcrops for 10's to 100's of meters. The folds are confined to cross-bed sets and often occur between planar beds, which are only rarely found in the Coconino Sandstone.



Deformed cross-beds

Planar beds

Deformed cross-beds. 400 m of parabolic folds between the same two planar beds occur to the right. Jacob's staff is 1.5 m.

Planar beds

The parabolic cross-beds continue for at least 50 m along this outcrop. The fold is about 7 m thick and is bounded by planar beds above.

Significance:
Parabolic recumbent folds (PRFs) are penecontemporaneous soft-sediment deformation features that are only known to form in subaqueous settings during cross-bed formation. The Coconino folds are different than folds that occur in other cross-bedded sandstones, like the Navajo Sandstone. The Navajo folds are often *not* confined to cross-bed sets, meaning the deformation took place sometime *after* multiple cross-bed sets were deposited. Attempts to make PRFs in the laboratory have been largely unsuccessful. Four models have been suggested in the literature for PRF formation, all involving strong subaqueous currents. Flipping of the cross-bed sets might occur by 1) a strong shear current alone, 2) a strong current combined with liquefaction during an earthquake, 3) a strong current combined with liquefaction from pressure changes due to large wave crests and troughs, and 4) a strong current combined with liquefaction from flow regime change.

• Whitmore, J.H., G. Forsythe, R. Strom, and P.A. Garner. 2011. Unusual bedding styles for the Coconino Sandstone (Permian), Arizona. *Geological Society of America Abstracts with Programs* 43(5):433.
• 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.

PRIMARY CURRENT LINEATION

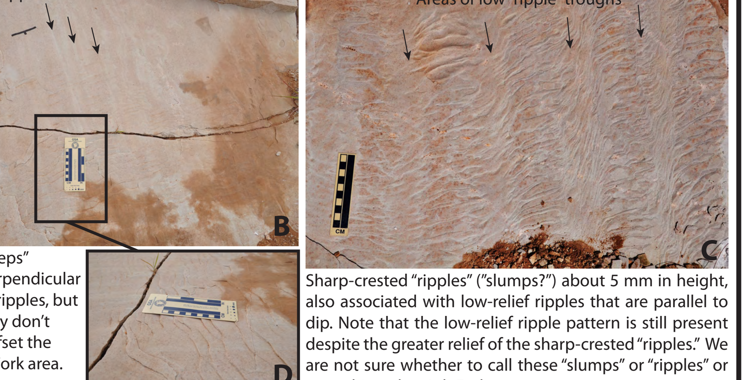
A feature resembling primary current lineation (sometimes called parting lineation, parting-step lineation or sand streaks) is commonly found on most cross-bed foresets of the Coconino Ss. The features are usually parallel to dip and occur from lower to upper bounding surfaces. Often it is closely related to low-relief ripples and circular pits which also trend down dip ("A" in next panel to the right).

Significance:
Parting lineation is well known from subaqueous current deposits of various types (Allen 1970; Cheel 2003; Corbett 1972; Picard and Hulen 1969; Stokes 1947) and has been produced experimentally in the laboratory (Mantz 1978; Weedman and Slingerland 1985). Allen (1970, p. 68) reports it "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. As far as we know, these features have not been reported from modern eolian depositional environments.

RAINPRINTS, RIPPLES AND SLUMPS

The northwestern outcrops of the Coconino Sandstone, especially in the Ash Fork area, have multiple surfaces that are covered with linear sets of dimple-like features and low-relief ripples parallel with dip. Sharp ripple-like features and slump-like features occur perpendicular to dip. The dimple-like features are often associated with the low-relief ripples and occur in linear patterns. These features occur on surfaces that are much less than the angle of repose (low to mid 20's).

Ash Fork (ASF), underside of a rippled and "rainprinted" slab. All the features are low-relief. The slab is positioned with the sun directly overhead to highlight the features.



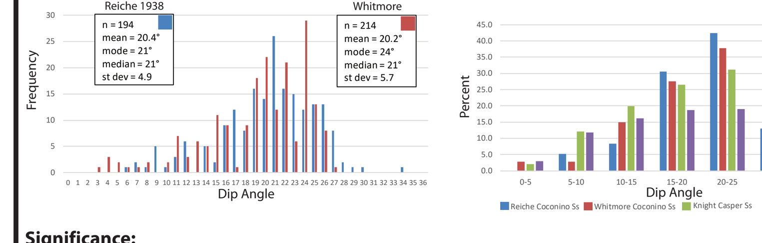
Low-relief "steps" (slumps?) perpendicular to low-relief ripples, but note that they don't destroy or offset the ripples. Ash Fork area.

Sharp-crested "ripples" ("slumps?") about 5 mm in height, also associated with low-relief ripples that are parallel to dip. Note that the low-relief ripple pattern is still present despite the greater relief of the sharp-crested "ripples." We are not sure whether to call these "slumps" or "ripples" or something else. Ash Fork area.

Significance:
We are not yet sure how to interpret these features. They don't seem to bear the characteristics we might expect from rainprints, ripples and slumps. The "rainprints" are in parallel lines; rainprints in sand often produce a mottled pattern, not a crater-like pattern. Slumps likely would be produced at or greater than the angle of repose and these slopes are not steep enough. Can two sets of perpendicular features (photo "C") be produced by wind? Why wasn't one set destroyed?

CROSS-BED DIPS AND POROSITY

Cross-bed dips were measured by Reiche (1938) and by us during our research. Dips in both sets of data average about 20˚. Examination of Coconino Sandstone thin sections shows there has been little reduction of dip due to compaction as evidenced by lack of fractured grains and the amount of porosity in many of our thin sections (porosity is indicated by "blue" in the thin section photos on this poster; blue is colored epoxy that is injected into the samples before the thin sections are cut). Most of the cross-bed dips fall well short of the angle of repose.



Significance:
Cross-bed dips are often reported in the literature as "steep" for the Coconino and other cross-bedded sandstones, implying that the cross-beds were formed at or near the angle of repose, without any reference to actual data. However, data that has been in the literature for more than 80 years contradicts this assertion. Some may argue that cross-bed dip angle has been reduced due to compaction of the sand; but our preliminary research shows dip can only be reduced by a few degrees before significant grain fracturing and reduction in porosity would occur. It is interesting that cross-bed dips in the Nebraska Sand Hills also average about 20˚, the difference being that a significant number of dips (~4-24%, depending on dune type) are greater than 30˚.

• Ahlbrandt, T.S., and S.G. Fryberger. 1980. Eolian deposits in the Nebraska Sand Hills. *U.S. Geological Survey Professional Paper* 1120A:1-24.
• 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(5):430.
• Knight, S.H. 1929. The Fountain and the Casper Formations of the Laramie Basin. *University of Wyoming Publications in Science (Geology)* 1:1-82.
• Reiche, P. 1938. An analysis of cross-lamination the Coconino Sandstone. *Journal of Geology* 46:905-932.
• Whitmore, J.H., R. Strom, S. Cheung, and P.A. Garner. 2014. The petrology of the Coconino Sandstone (Permian), Arizona, USA. *Answers Research Journal* 7:499-532.

PLANAR CONTACTS BETWEEN LAMINAE

Grainflow processes on modern dunes produce avalanche features that are tongue-shaped in profile (Great Sand Dunes) and in cross-section (Imperial Dunes). Bounding surfaces within the Coconino Sandstone show laminae that are parallel to one another and lack the toungue-shaped cross-section that can be observed in modern eolian settings. As can be seen at Great Dunes, avalanche tongues can proceed part-way or all the way down the slipfaces.

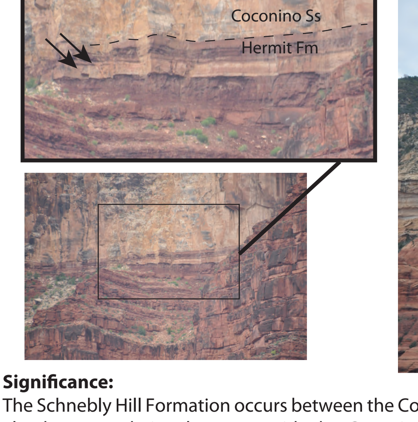
Significance:
Even if a significant part of the dune is missing from above the bounding surfaces in the Coconino, it seems as though the bounding surfaces should at least occasionally show tongue-like avalanche scars as observed in modern eolian dunes. Instead, individual lamina can be traced for many meters along strike on bounding surfaces, much wider than observed grainflows in modern eolian settings. Although grainfall and translatent ripples can theoretically form a significant part of eolian dune deposits, it is odd the Coconino does not display any tongue-like avalanche scars. Could the laminae in the Coconino represent subaqueous grainflows, which are much wider? In cross-secion, the Coconino is more similar to subaqueous flows illustrated by Hunter (1985, fig. 7) than eolian flows illustrated by Hunter (1977, fig. 7).

TRANSITIONAL CONTACT

At most locations, the contact between the Hermit Formation and Coconino Sandstone is sharp with no obvious erosion. However, in eastern Grand Canyon, the contact can be characterized as transitional. Two beds of Coconino-like lithology can be found within the Hermit. At various places in the Marble Canyon area, two Coconino-like beds can also be seen within the Hermit.

The Co conino-Hermit (Pc-Ph) contact along Tanner Trail. The lowest Pc bed is about 2 m thick, and the upper about 0.5 m thick. At many locations, including this one, the red Hermit color is bleached just below the base of the Coconino.

Enlarged view of the Coconino-Hermit contact viewed from the Colorado River near North Canyon



The transitional contact between the Coconino Ss and Schnebly Hill Fm in Boynton Canyon, Sedona.

Significance:
The Schnebly Hill Formation occurs between the Coconino and Hermit south of the Grand Canyon and also has a gradational contact with the Coconino. Thus, in places, the Coconino has gradational contacts with both of the formations that lie below it. The lack of obvious erosion below the Coconino (in Grand Canyon) and the Coconino's transitional contact with both the Schnebly Hill and the Hermit suggest there is only a minimal unconformity, if any at all, between the Hermit and Coconino.

• 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(7):A-235.