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THE SIGNIFICANCE OF MICAS IN ANCIENT CROSS-BEDDED SANDSTONES

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ABSTRACT
The cross-bedded Coconino Sandstone is almost certainly within the stratigraphic range of the Flood, however it is commonly cited by conventional geologists as the classic example of an eolian deposit, and thus an argument against the scientific viability of the Flood. In our petrographic study of the Coconino Sandstone, we discovered muscovite mica (and sometimes biotite mica) in almost every thin section. This is surprising given that micas have not previously been reported in this, or any, "eolian" cross-bedded deposit. The mica found is detrital in character (i.e., it is not an alteration product) and thus is part of the primary depositional fabric. This led to the investigation of other cross-bedded sandstones from around the world, especially those of similar stratigraphic age, all of which have been conventionally interpreted as wholly or partly eolian– the same frequent occurrence of micas was observed. Previous laboratory experiments have provided some framework for understanding this discovery. Based on those experiments, it was found that mica cannot survive continuous transport much more than four days (or about 500 km) by simulated eolian processes, but can last for more than a year (or about 7,500 km) when transported continuously by simulated subaqueous processes. Field observations confirm that modern ergs contain virtually no micas, of any size, except in cases where mica sources (such as granite outcrops, beach sand or fluvial sand) are located in the immediate vicinity (~<10 km) of the erg. By contrast, the Coconino sand body and its correlative stratigraphic units stretch for many hundreds of kilometers across (with a total area of 2.4 million km^2), and therefore the interior of the deposit should be virtually mica-free if formed by eolian processes. We catalog and illustrate a large number of cross-bedded sandstones that contain mica grains (mostly muscovite) as an accessory mineral. The dominant conventional view is that these sandstones are eolian in origin, but experimental data and field observations suggest otherwise. The presence of micas in cross-bedded sandstones is a previously neglected criterion that can be used to argue for a subaqueous depositional environment for the formation of cross-bedded sandstones.

KEY WORDS
experimental mica abrasion, cross-bedded sandstones, muscovite, biotite, Casper Sandstone, Coconino Sandstone, Corrie Sandstone, Dawlish Sandstone, Glorieta Sandstone, Hopeman Sandstone, Locharbriggs Sandstone, Lyons Sandstone, Navajo Sandstone, Penrith Sandstone, Schnebly Hill Formation, Tensleep Sandstone, Weber Sandstone

INTRODUCTION AND BACKGROUND

Geologists have long suspected that eolian sands and sandstones should not contain mica, although little experimental or observational data is present in the literature to support this notion. Eolian dune environments are overwhelmingly dominated by the mineral quartz (having a hardness of 7.0 Mohs scale) and should rapidly abrade micas which are much softer (Mohs = 2.5) and have fragile sheets that easily cleave. Standard petrographic texts suggest mica should be found in subaqueous sediments, but not in eolian ones (Hallam 1981, p. 20; Mader 1983, p. 589, 590; Moorhouse 1959, p. 343; Tucker 1981, p. 45). This notion is so entrenched in the minds of some geologists that they proclaim the absence of mica in certain sandstones based only on their assumption that a particular sandstone is eolian (without doing any petrographic work!). For example, Young and Stearley, in referring to the Coconino Sandstone in particular state (2008, p. 305):

> "Mainstream sedimentologists feel that the eolian, that is, wind-blown, nature of such sand accumulations [the Coconino Sandstone] is well founded. The very fine sand of these formations has a uniform grain size that is characteristic of wind-blown sand in general. The grains consist of resistant quartz. *Less resistant mica grains and ultra-fine clay particles have been abraded to oblivion and /or wafted off site by wind* (emphasis added)."

Studying cross-bedded "eolian" sandstones is an important endeavor for creationists because many of these sandstones occur in Permo-Triassic rocks which are often sandwiched in between rocks that are generally agreed to be Flood deposits. Thus, sandstones like the Coconino and the Navajo have been used as *prima facie* evidence against the Flood. 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." A wide variety of other skeptics, some theistic, have come to similar conclusions about these cross-bedded sandstones.

Examples include Helble (2011), Hill et al. (2016), Ranney (2001), Weber (1980) and Young and Stearley (2008).

Two of the present authors (Strom and Whitmore) have been studying the Permian cross-bedded Coconino Sandstone for some time, along with other similar sandstones (see Whitmore and Garner 2018, in these proceedings). They discovered muscovite as a trace mineral in nearly every one of the hundreds of thin sections that they analyzed (Whitmore et al. 2014). As part of the same study they also investigated other cross-bedded sandstones in western North America and Great Britain and found many micas in these deposits as well.

During a larger study of the Coconino, we also collected sand samples from along the California and Oregon coastline and compared those samples with coastal dune samples from the same location (Whitmore and Strom 2017). We also collected and studied a number of sand samples from inland dune locations in the western United States. We found that mica was conspicuously absent from dune samples, unless those dunes were in close proximity (less than tens of kilometers) from mica-bearing bedrock, stream (fluvial) sediments or beach sands. In studies of sand transport along the southwestern coast of Africa, Garzanti et al. (2012, 2015) found that the composition of sediment transported for hundreds of kilometers along the coastline (which contained micas) did not appreciably change. However, when the beach sand was picked up by wind and transported to the Namib dunes, all minerals became quickly rounded and the mica either disappeared or possibly was never transported to the dunes.

To investigate the durability of mica in experimental eolian and subaqueous environments, Anderson et al. (2017) devised a series of experiments (also Anderson et al. 2013). To simulate an eolian transport environment, a small amount of muscovite-rich sand was placed in a one-gallon glass jar with an RC airplane propeller attached on the inside of the lid. The velocity of the propeller was adjusted so that a small "dune" slowly migrated around the bottom of the jar. After just four days of continuous transport in this apparatus, virtually all micas had been pulverized such that they could not be found in thin section, except where small (<100 μm) grains had become wedged inside the crevices of quartz grains, which effectively preserved them from abrasion; this transport time corresponded to roughly 500 km of linear transport. To simulate a subaqueous transport environment, the same mica-rich sand was placed in glass jar and laid on a rock tumbler assembly, which sustained a lateral dune. Surprisingly, after one year of continuous operation (roughly 7500 km), not only did the sand still contain an appreciable number of muscovite grains, but they were large enough to be seen with the naked eye. This can potentially be explained by a cushioning effect of the water, which has a much higher viscosity than air and reduces the kinetic energy of grain-grain collisions, thereby preventing the rapid degradation of mica and other softer minerals. Despite the simplicity of these experiments, they confirm our field and experimental observations that mica is rare in modern eolian deposits and commonly present in subaqueously deposited sands.

The experiments of Marsland and Woodruff (1937) further confirm our observations. In their experiments with the abrasion of gypsum, calcite, apatite, magnetite, orthoclase, quartz and garnet sand, they noted that although there are many factors that probably effect rounding rates, softer minerals round much more rapidly than harder minerals during experimental eolian transport.

There are significant implications for the discovery of appreciable quantities of mica in supposedly eolian sandstones. Only two environments are commonly known to produce cross-bedded sandstones: eolian and subaqueous. Both experiments and observations suggest that wind transportation rapidly degrades mica, while water transportation can preserve mica, perhaps almost indefinitely. Thus, when micas occur in a cross-bedded sandstone (such as Coconino Sandstone) it is likely a good indicator of its depositional environment. For this purpose, we here catalog and illustrate a large number of cross-bedded sandstones that contain mica (mostly muscovite) as an accessory mineral.

METHODS

This project is part of the Coconino Sandstone FAST project (Whitmore et al. 2012; Whitmore and Garner 2018) and included sandstone samples (primarily Permian) collected from the Coconino Sandstone (Arizona), Casper Sandstone (Wyoming), Cedar Mesa Sandstone (Utah), De Chelly Sandstone (Arizona), Glorieta Sandstone (New Mexico), Lyons Sandstone (Colorado), Navajo Sandstone (Utah), Schnebly Hill Formation (Arizona), Tensleep Sandstone (Wyoming), Weber Sandstone (Utah) and White Rim Sandstone (Utah). European samples included the Bridgnorth Sandstone (England), Corrie Sandstone (Scotland), Yellow Sand (England), Dawlish Sandstone (England), Hopeman Sandstone (Scotland), Locharbriggs Sandstone (Scotland) and the Penrith Sandstone (England). While we collected rock samples from all of these formations, we have vastly more sample material from the Coconino. Appendix I gives the conventional geological age, who identified the formation as eolian, and a few notes and references about each formation. Appendix II is a catalog for all of the individual samples chosen for use in this manuscript along with their approximate collection coordinates.

The Coconino Sandstone primarily outcrops in northern Arizona and extends into other states as the same sand body, but with different names. Whitmore (2016; Figure 1) has done some preliminary correlation which shows the Coconino sand body can be correlated over many of the western United States with a surface area of approximately 2.4 million km^2. Thus, the Coconino and many of the other Pennsylvanian and Permian sand bodies in the western United States are closely related to each other.

After the samples were collected, they were made into thin sections (30 micron thickness) and stained using two methods. Double carbonate stain (potassium ferricyanide and alizarin red S – red stain for calcite, purple stain for ferroan calcite and blue stain for ferroan dolomite) was used to distinguish carbonate types. K-feldspar stain (yellow stain using HF etch and sodium cobaltinitrite indicator) was used to identify potassic feldspars in order to isolate them from other clear grains such as quartz. This work was done at Calgary Rock and Materials Services Inc. in Calgary, Alberta. Most microscope work was completed at Cedarville University with a Nikon Eclipse 50i Pol microscope equipped with the Br software package.

RESULTS

The results of this study are presented as a series of figures (Figs. 2-10) showing many examples of micas (primarily muscovite) in many different sandstones from the western United States and Great Britain. The photographs are grouped roughly by location. In these photos, blue is pore space (the empty space between grains and which has been impregnated with epoxy), white is quartz or chert, red is calcite and yellow is K-feldspar. Micas are evidenced by their recognizable edge-wise cleavage into thin sheets and high birefringence (rainbow-like appearance) under cross polarized

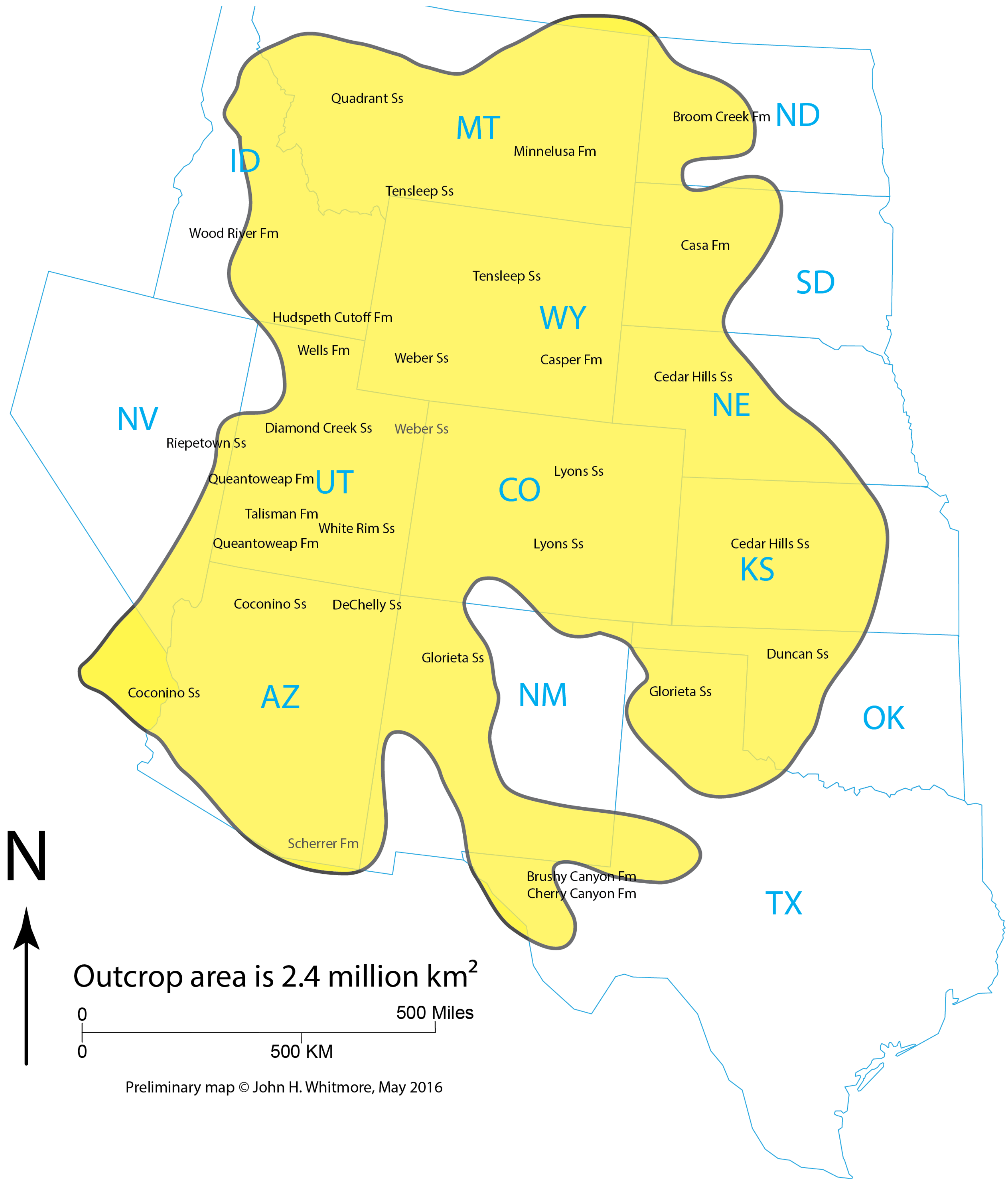

Figure 1. Areal extent of the Coconino Sandstone and its near equivalents covering about 2.4 million km^2 in the western United States. Preliminary work by Whitmore (2016).

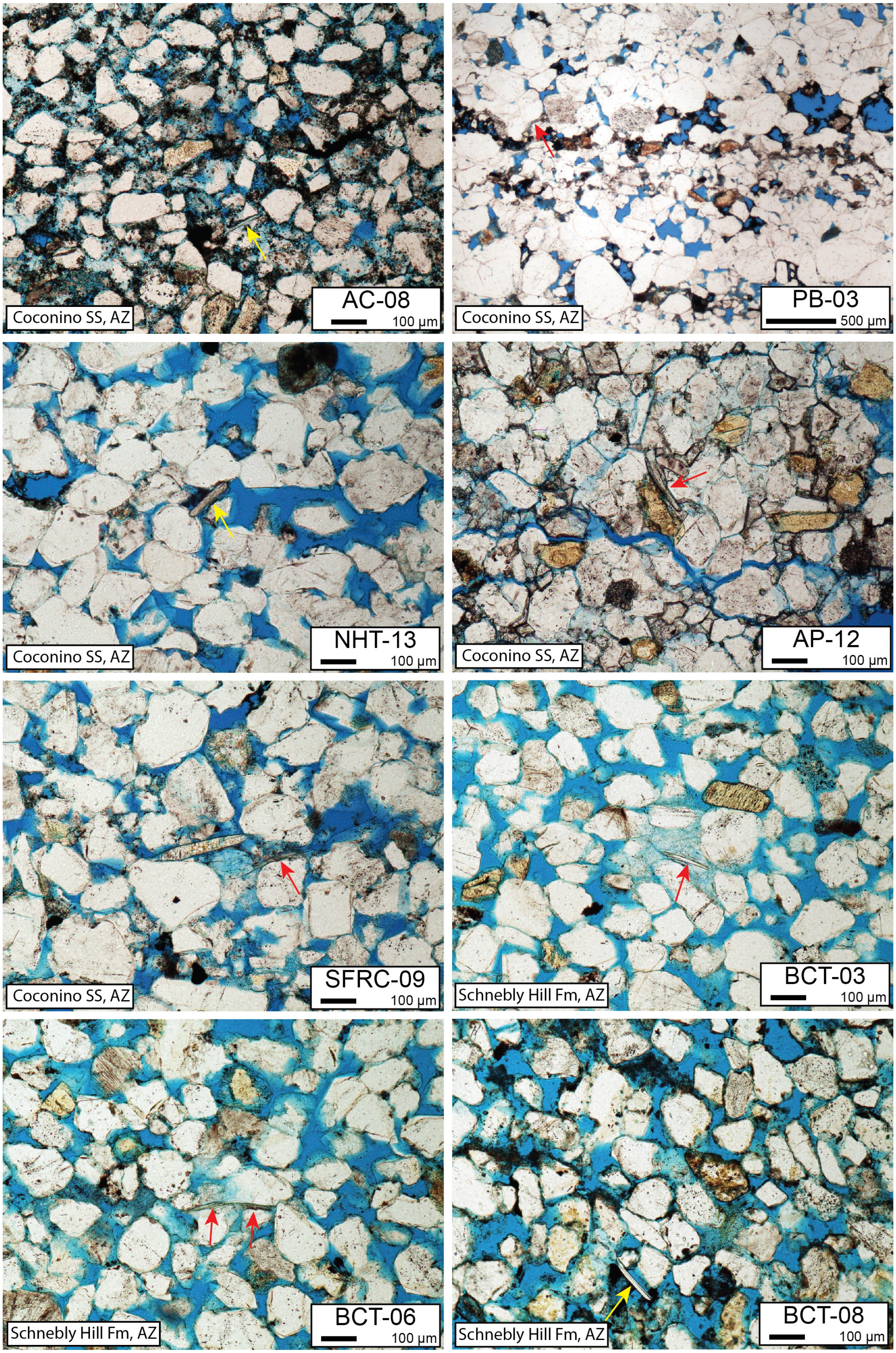

Figure 2. Micas in the Coconino Sandstone and the Schnebly Hill Formation, Arizona. The photographs are oriented so that "up" is also the top of the photograph.

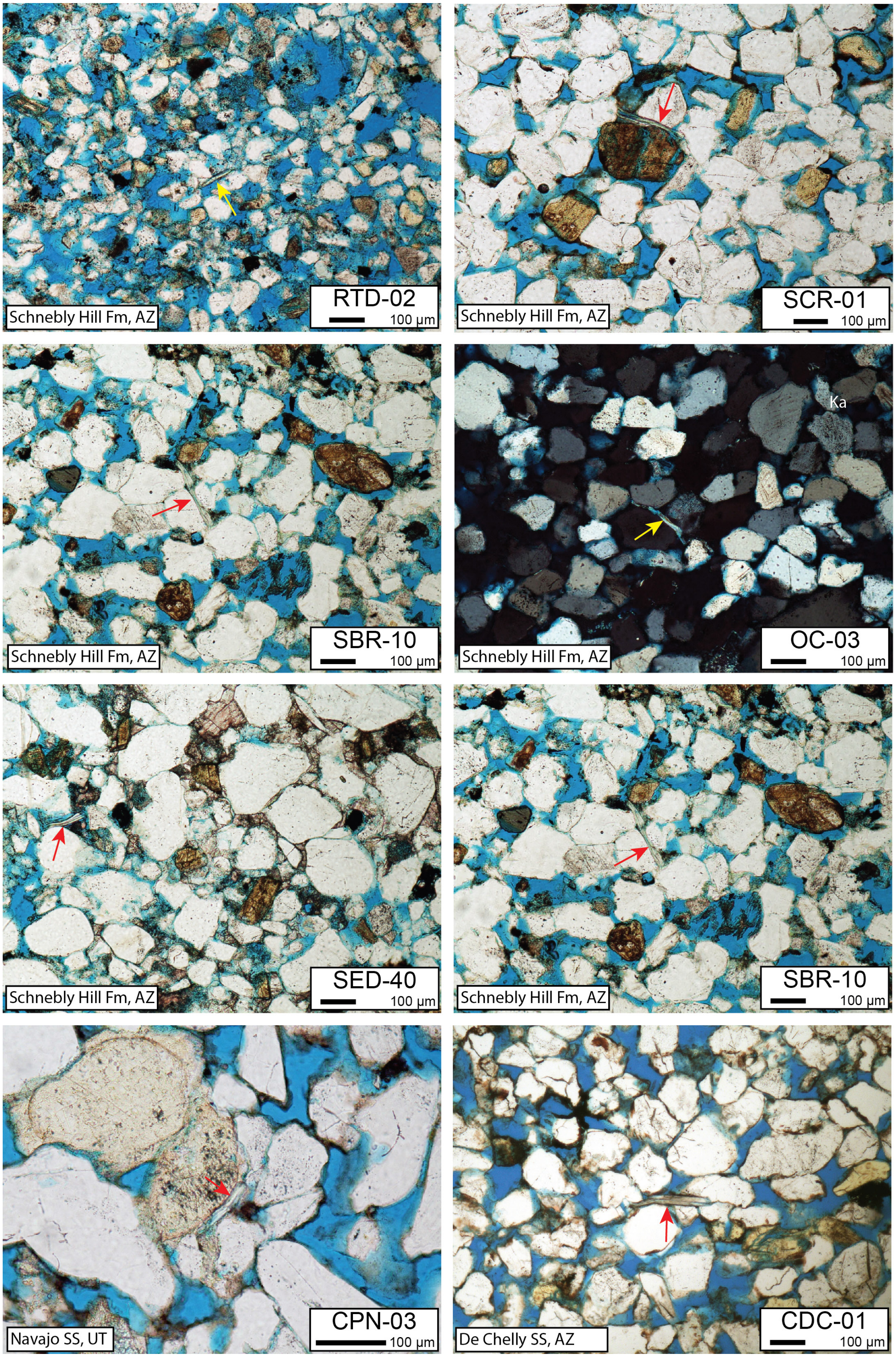

Figure 3. Micas in the Schnebly Hill Formation, Navajo Sandstone and the De Chelly Sandstone, Arizona and Utah. OC-03 is viewed with cross polarized light. The photographs are oriented so that "up" is also the top of the photograph.

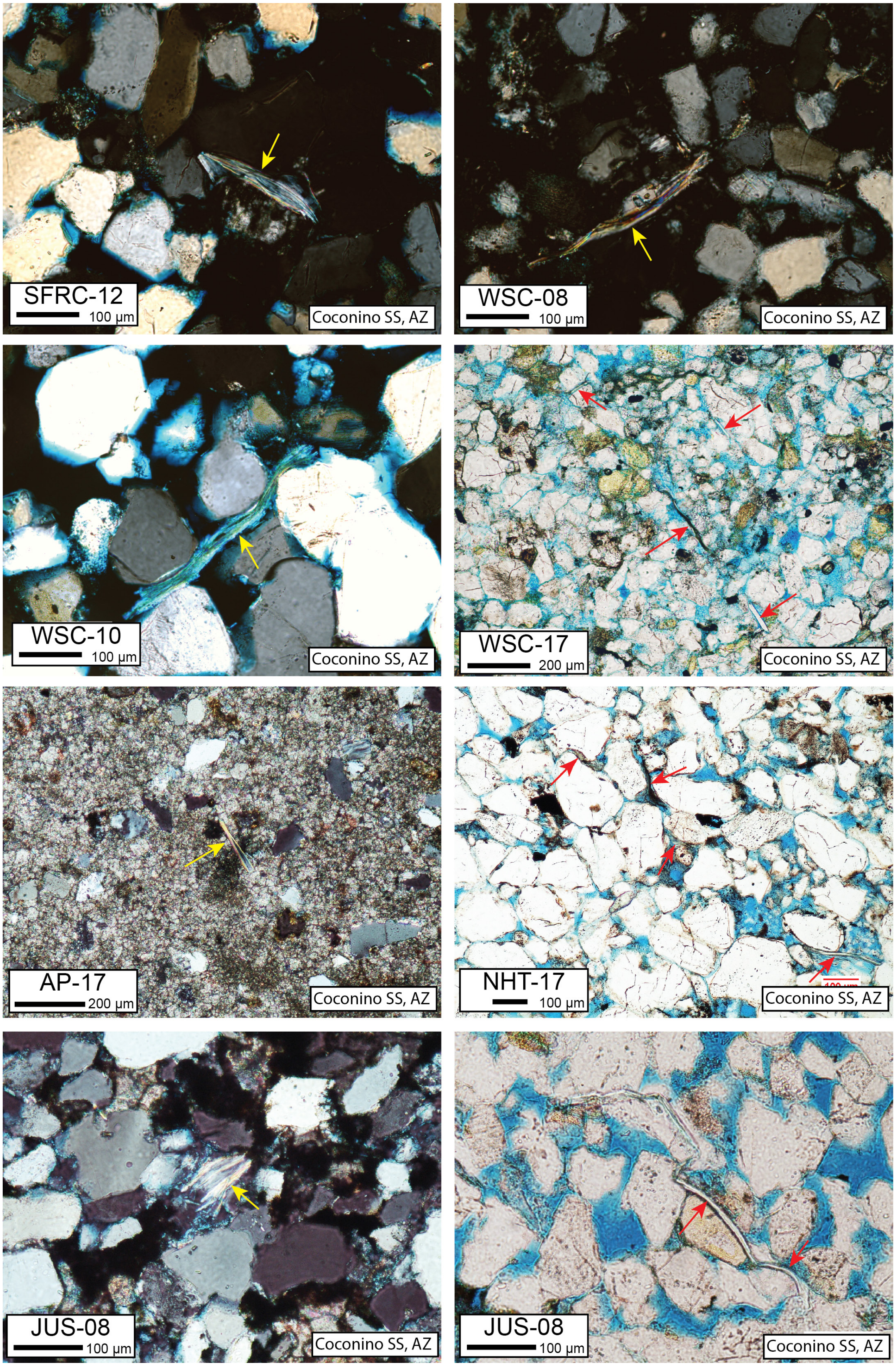

Figure 4. Micas in the Coconino Sandstone, Arizona. SFRC-12, WSC-08, WSC-10 and JUS-08 are viewed with cross polarized light. WSC-10 has biotite; WSC-17 and NHT-17 contain biotite and muscovite. The photographs are oriented so that "up" is also the top of the photograph.

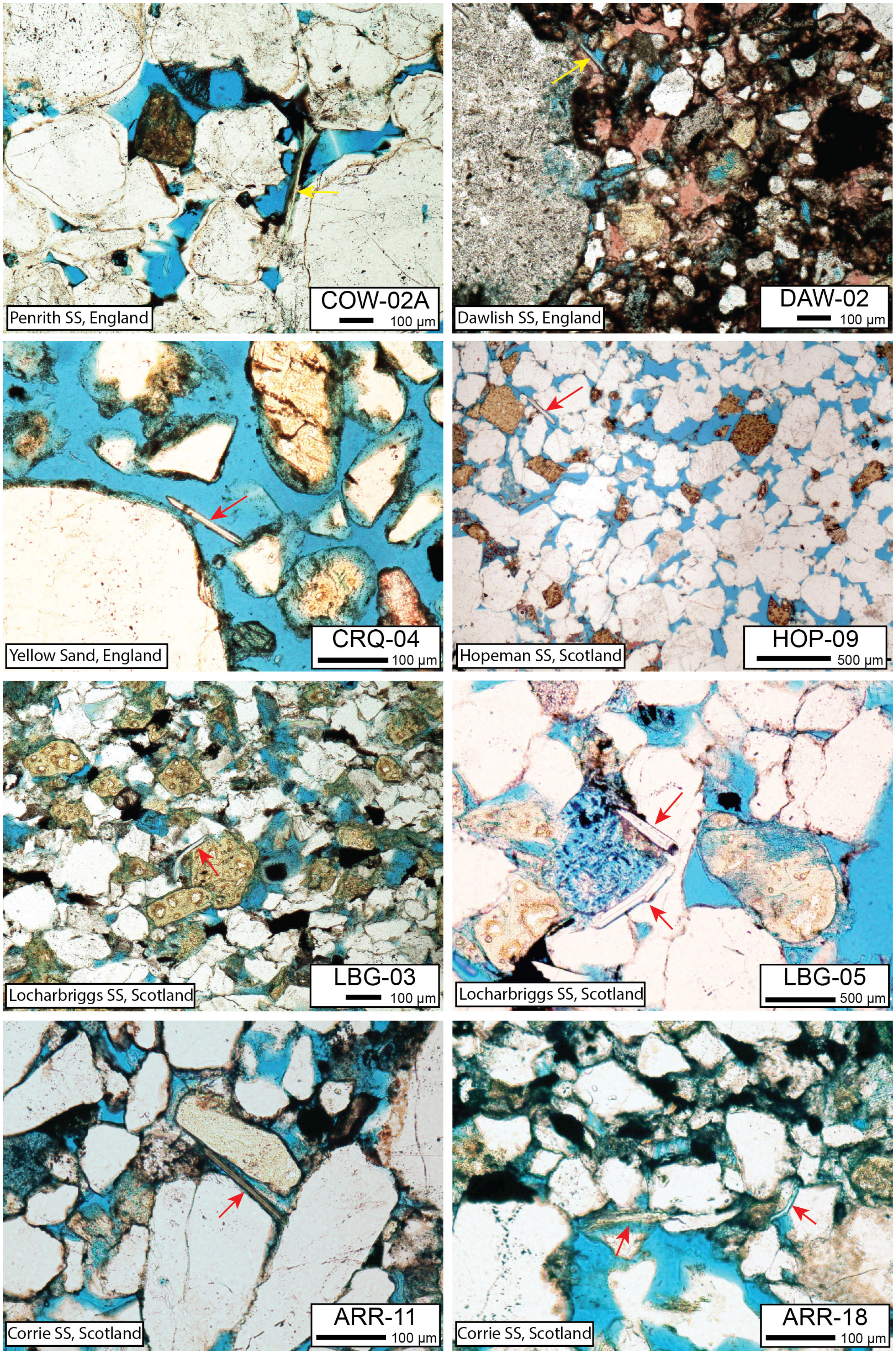

Figure 5. Micas from the Penrith, Dawlish, Yellow Sand, Hopeman, Locharbriggs, and Corrie Sandstone of Great Britain. Note that the mica in LBG-05 is broken and fractured in several places. The photographs are oriented so that "up" is also the top of the photograph.

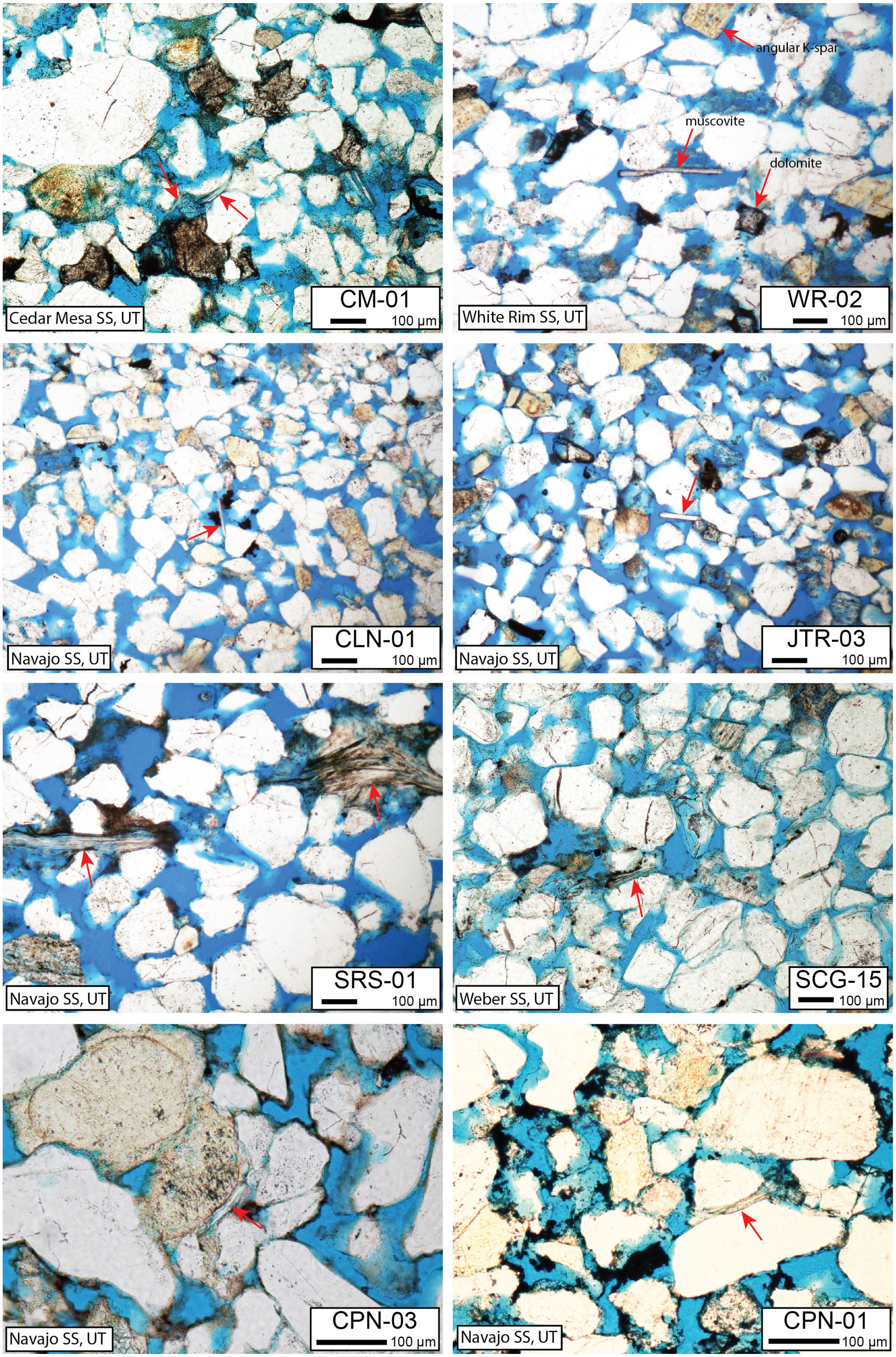

Figure 6. Micas from the Cedar Mesa, White Rim, Navajo, and Weber Sandstones of Utah. The photographs are oriented so that "up" is also the top of the photograph.

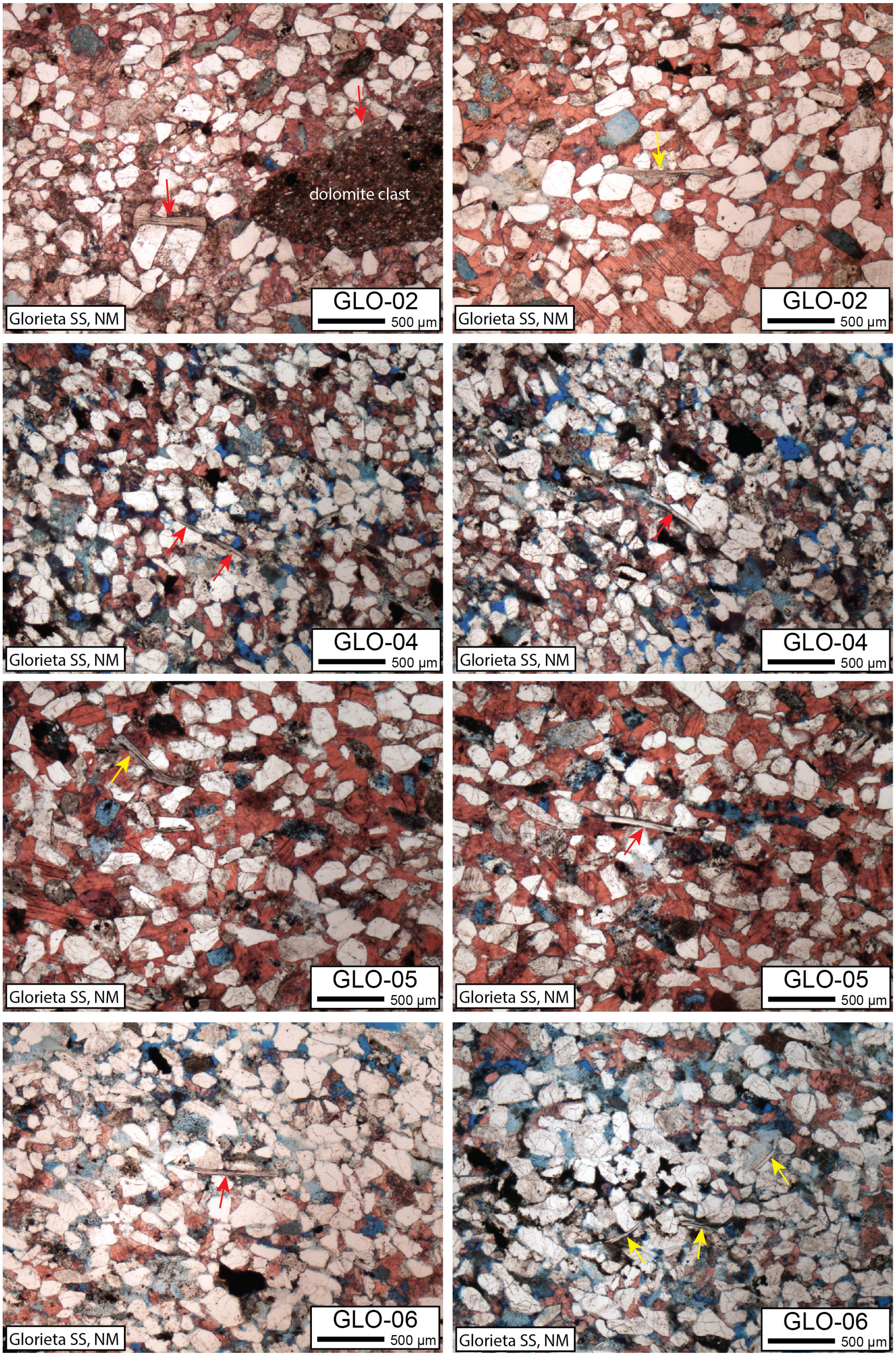

Figure 7. Micas from the Glorieta Sandstone of New Mexico. The red color is calcite cement. The photographs are oriented so that "up" is also the top of the photograph. GLO-02, in the upper left, also includes a large dolomite clast.

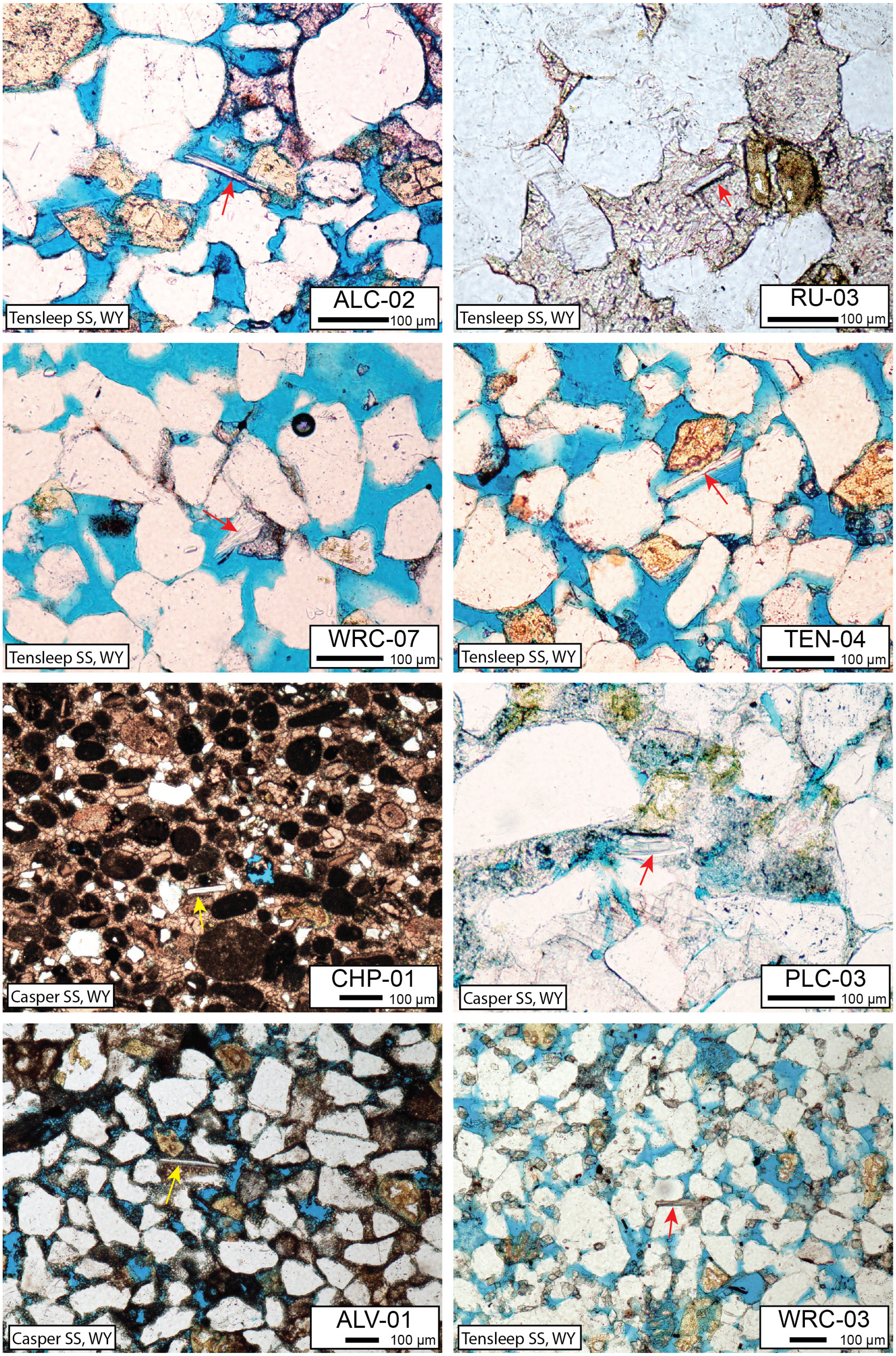

Figure 8. Micas from the Tensleep and Casper Sandstones of Wyoming. The photographs are oriented so that "up" is also the top of the photograph.

light. Displayed in the figures are micas from seventeen different sandstones and from thirty-seven different locations. It is important to note that we have many more thin sections with mica than are shown in the figures. Detrital (not diagenetic) micas appear to be ubiquitous in the Coconino and in the other cross-bedded sandstones studied here.

DISCUSSION

In order to determine whether a sandstone was deposited in an eolian or subaqueous environment, a wide variety of criteria can be used. Mader (1983, p. 589) lists criteria that can be used to determine if a deposit is eolian or fluvial: 1) stratification, 2) composition, 3) intercalations, 4) transport directions, 5) petrography and texture, 6) deformation and 7) "miscellaneous." In the "petrography and texture" section for eolian deposits, the "absence of mica" is the very first thing listed, along with rarity of authigenic tourmaline and rutile, weak lithification by slender quartz overgrowths, abundance of nest burrows of recent solitary bees, high textural and mineralogical maturity, and frosted grain surfaces. In the list of criteria for fluvial deposits (p. 590), the first characteristic listed is the "presence of mica."

However, our review of the literature suggest that sandstones are not identified as eolian or subaqueous based on a comprehensive list of criteria, but only a few factors, which often do not include petrographic study. The most commonly used criteria for identification of eolian deposits are large-scale foreset beds (stratification), steep cross-bed slopes (stratification), frosted grains (petrography), exceptional sorting (petrography), fine to medium sand (petrography) and several other characteristics (see McKee and Bigarella 1979). Even these criteria, however, are not always carefully examined before reaching an "eolian" conclusion. For example, Whitmore et al. (2014) and Whitmore and Garner (2018) found that the commonly cited criteria for eolian deposition of the Coconino Sandstone were not substantiated by petrographic study or extensive field work. Some authors claim "eolian" status can be "easily verified" with only precursory examination. For example, Young and Stearley state (2008, p. 215)" A hiker along one of the [Grand C]anyon's many trails can easily verify that the Coconino Formation (sic) is composed almost entirely of very pale sand grains of a uniform size," but careful petrographic study has determined that the Coconino Sandstone is on the whole poorly to moderately sorted (not uniform grain size; see Appendix I). Even in the latest, most comprehensive report of the Coconino by Middleton et al. (2003), petrology and detailed sedimentology are not demonstrated–they are only assumed.

This paper highlights one of the criteria listed by Mader (1983),

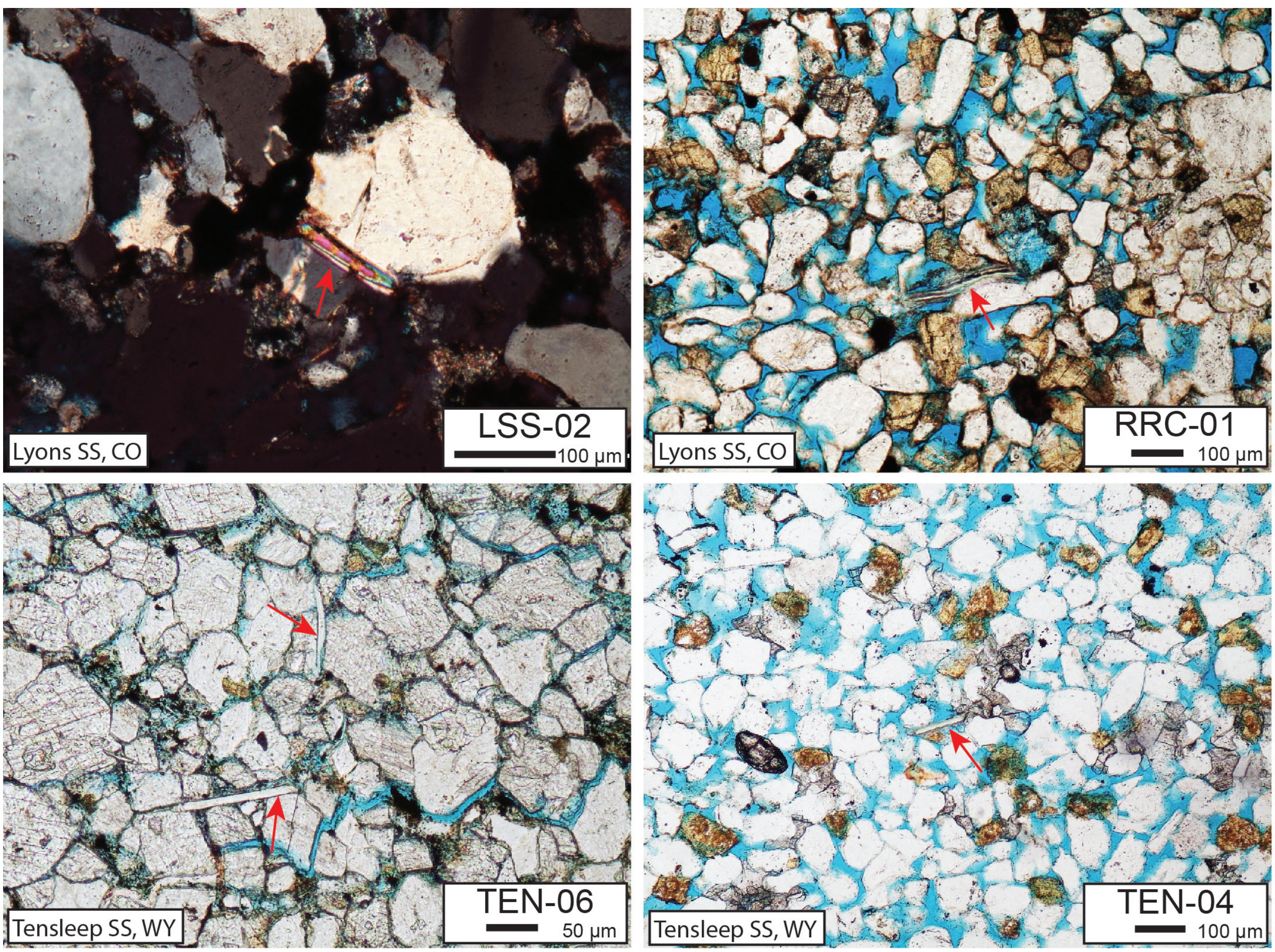

Figure 9. Micas from the Lyons Sandstone of Colorado and the Tensleep Sandstone of Wyoming. LSS-02 is view with cross polarized light. The photographs are oriented so that "up" is also the top of the photograph.

namely the presence or absence of mica. Mica is expected to be absent in eolian sandstones due to the difference in hardness between mica (Mohs = 2.5) and quartz (Mohs = 7). Observations and experiments show that ballistic impact of grains rapidly abrade and disintegrate mica during wind transport (Anderson et al. 2017, 2013; Marsland and Woodruff 1937). Water, however, provides a cushion between the grains, lessening grain collisions and allowing mica to survive, as suggested by Anderson et al. in their papers. Another example is found in coastal Namibia, where Garzanti et al. (2012) report mica in the Orange River, Kuiseb River, Gaub River, and the shoreline sediments but no mica in either the coastal or eastern dune fields; they credited this compositional discrepancy to the winnowing of micas by longshore currents and followed by deposition in offshore sediments. In Garzanti et al. (2015) the only dune sample in which they found mica was the Suzie dune, which they attributed to "sampling too close to outcrops of metamorphic rocks with the Namib Erg (p. 990)" that contained muscovite.

It is important to note that the micas we have found in cross-bedded sandstones are detrital (transported) rather than diagenetic (altered from other minerals post-deposition) in character. For example, muscovite can be formed via the following chemical alteration of K-feldspar (orthoclase): $3KAlSi_3O_{8\ (orthoclase)} + 2H^+ \rightarrow KAl_3Si_3O_{10}(OH)_{2\ (muscovite)} + 6SiO_2 + 2K^+$ in the presence of an acid (H^+). The mica produced in this conversion is known as sericite, which most often occurs entirely within the host grain, and is visible in thin section as fibrous bundles. Consequently, sericite is generally much smaller than the host grain and randomly oriented. By contrast, many of the micas observed in this study were longer than the matrix grains (size inversion), and the characteristic fibrous textures were not observed. Furthermore, in our samples we observed 1) books of mica bent around other grains (often quartz), 2) contorted mica books with splayed ends, 3) mica grains don't often occupy the fairly common empty spaces of dissolved K-feldspar grains and 4) significant amounts of orthoclase (often ~8- 15%) are often found in the thin sections along with the mica (i.e., orthoclase has not been diagenetically altered). Together, these clearly indicate that the micas we observed (and show in this paper) are detrital, and thus are part of the original depositional fabric. See Figures 2-9, but especially Figure 10 for numerous examples of these four points.

There are some desert sands that contain detrital mica, but in all these cases the mica can be traced to a nearby source, such as an igneous pluton, beach, or wadi. For example, Venzo et al. (1985) report the presence of micas in the southern Algerian Sahara, where the source of this mica is likely the Hoggar Mountains in southern Algeria. We have found micas in various California dunes including in the Palm Canyon area, Johnson Valley, near the Salton Sea, and the Glamis Dunes. In all of these cases the micas (mainly biotite, but also sometimes phlogopite) were well-rounded and either adjacent to or within a few kilometers of igneous bedrock (mostly granite) or wadis.

However, the contiguous area of the Coconino and its correlative deposits is many hundreds of kilometers across. If the Coconino was eolian, how could mica reach the center of this giant erg? Mica was not only found along the edges of the Coconino sand body, but *everywhere* we sampled, and our samples were collected from the entire exposed breadth and width of the Coconino.

Field observations and laboratory experiments demonstrate that mica is unlikely to survive more than 10 km of transport by known eolian processes (and certainly not hundreds of km) without disappearing by abrasion. Moreover, there is no sedimentological evidence within the midst of the Coconino sand body of any nearby beach, nearshore or fluvial deposits, which would be the most reasonable sources for the mica.

Based on the U-Pb signatures of zircons (Gehrels et al. 2011, p. 197), it is believed that the source of the Coconino sand is the mid-Proterozoic rocks of eastern North America (Appalachian orogen), or possibly, but less likely, from the Ouachita orogen. These authors suggested that large rivers and northeasterly trade winds carried the Coconino sand >3000km from these areas to where it was reworked into 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, the ubiquity of muscovite, as well as angular K-feldspar (Whitmore and Strom 2018), that we have documented in the formation, strongly suggests that the primary mode of transport was some type of aqueous process; eolian transport would have quickly rounded the K-feldspars and caused the micas to disappear. In a conventional model, mica does not have a reasonable way to be transported to the middle of an erg, except perhaps by fluvial processes, and no fluvial deposits are known in the immediate vicinity of the Coconino sand body.

On a larger scale, many of the Coconino's correlatives and stratigraphic units (that laterally or vertically bound the Coconino) are thought by most to be partly or completely marine. *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). *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 interpret part of the Toroweap as 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. 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). Whitmore and Garner (2018, in these proceedings) provide some more of these details. Some of the Coconino's correlatives are discussed in Appendix I, and the references there provide evidence for the marine origin of many of these units. Thus it was not surprising that we found mica in many of those units.

In light of the fact that micas are not expected in eolian sandstones, it is odd that we have found micas in so many supposedly eolian sandstones from all over the world. Either every one of these

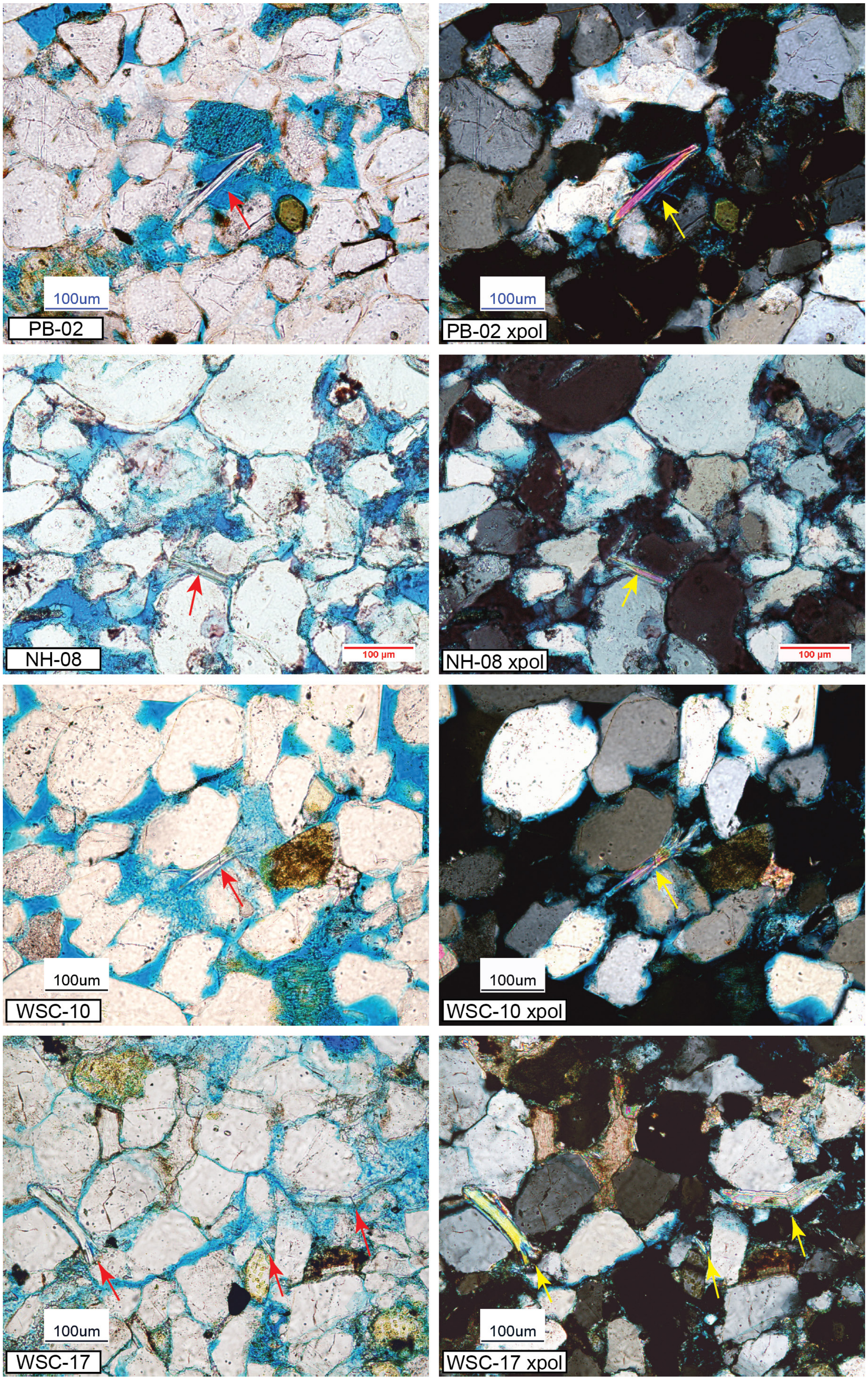

Figure 10. Micas from the Coconino Sandstone, Arizona that exhibit splayed ends indicating they are detrital grains and did not grow within the rock after deposition. Many of the previous images illustrate the same thing along with mica flakes that are fractured or broken into two or more pieces. The images on the left are in plane polarized light and the images on the right are the same images viewed under cross polarized light. The photographs are oriented so that "up" is also the top of the photograph.

sandstones must have had a very nearby mica source during its deposition, or perhaps they are not eolian and rather subaqueous in origin. We have not extensively sampled all of the formations in this paper, with the exception of the Coconino, but, with that formation in particular, there are no nearby beaches, mica-bearing outcrops or known fluvial deposits stratigraphically within the formation. We expect that some of the other formations we have mentioned in this report may exhibit the same textural characteristics and stratigraphic relationships.

There are many other criteria besides mica to consider when determining an environment of deposition for cross-bedded sandstones. One of these, angular K-feldspar, is addressed by Whitmore and Strom (2018). We do not think it is a coincidence that many of our samples had both angular feldspars and mica grains. Although these are only two criteria, they raise serious questions that need to be answered by the conventional model, or else re-explained in light of a different model for the deposition of these sandstones, namely with subaqueous processes as the primary mode of transport. As further research emerges on these sandstones, we expect that it will continue to call into question the eolian model of their deposition, and to further align with Flood geology. Whitmore and Garner (2018) and Whitmore et al. (2014, 2015) provide many more indicators that the Coconino is a subaqueous deposit including dolomite (ooids, cement, clasts, rhombs, beds), parabolic recumbent folds, texture, petrology and sedimentology. These and other features are likely present in many other cross-bedded sandstones, which if identified, could lead to a reinterpretation of their depositional environments as well.

FURTHER WORK

We encourage further petrographic work on many of the sandstones we have examined in this study, especially those other than the Coconino Sandstone. We were shocked to find out how very little petrographic work has been completed and/or published on many of these formations. Further documentation of micas in cross-bedded sandstones, along with investigations of other criteria (K-feldspar rounding, soft-sediment deformation, petrology, sedimentology, etc.), will likely bolster our conclusion that these sandstones were deposited in a subaqueous environment, such as provided by the Genesis Flood. We also encourage further experimentation on the conditions under which mica disintegrates, such as those performed by Anderson et al. (2017), in order to determine what exactly is the mechanism that preserves mica for long transport distances underwater.

CONCLUSION

Mica is commonly found as an accessory mineral in cross-bedded sandstones that are currently understood to be either entirely or partially eolian in origin, and the mica found is detrital, rather than diagenetic. Laboratory and field observations have shown mica can only survive very short periods (or distances) of transport by eolian processes, but can persist for very long durations and distances by subaqueous transport. For these reasons, we suggest that the presence of mica in cross-bedded sandstones is an important criterion when determining the depositional environment. While this has already been suggested by many authors (Hallam 1981, p. 20; Mader 1983, p. 589, 590; Moorhouse 1959, p. 343; Tucker 1981, p. 45), it has been previously neglected, often in favor of cursory observation and hasty interpretation without detailed petrographic analysis. We believe this is the case because, as far as we know, this is the first time widespread mica has been reported from any of these formations. Although more research is necessary to extend our conclusions to similar deposits around the world, ubiquitous mica in cross-bedded sandstones is something that Flood critics will need to reckon with if they want to continue to use these sandstones as evidence against the Flood.

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APPENDIX I. Sandstones, location, references and general notes about sandstone formations referred to in this paper. Paul Garner was a significant contributor to the descriptions in this table.

Formation	Location and (conventional age)	Selected references and author(s) who made eolian identification (*)	General description and notes about the formation
Casper Sandstone	Wyoming (Pennsylvanian and Permian)	Knight 1929; McKee and Bigarella 1979*; Steidtmann 1974*	McKee and Bigarella (1979) use this as one of their examples of "ancient sandstones considered to be eolian," although they concede that its identification has been difficult to determine. They state (p. 221): "The cross-stratified sandstone of the Casper is fine grained and well sorted" and that the formation has a maximum thickness of about 700 ft. (200 m) thick. Knight (1929) believed the sandstone could only be explained by aqueous processes.
Cedar Mesa Sandstone	Utah (Permian)	Baars 1979; Mack 1977; Mountney and Jagger 2004*	This southeastern Utah sandstone is about 1280 m thick and consists of a variety of facies including cross-bedded sandstones, redbeds and mudstones. Baars (1979) and also Mack (1977) believed much of the sandstone was marine based on type and orientation of cross-strata, marine fossils and ripples. Mountney and Jagger (2004) believed that it was primarily eolian based on cross-bed spatial variation and architecture. They believed it was deposited in a wet eolian system with a fluctuating water table and occasional fluvial flooding. They give considerable data on cross-bed dips, many averaging about 20°.
Coconino Sandstone	Arizona, Nevada, California (Permian)	Baars 1961*; Baltz 1982; Blakey and Knepp 1989; McKee and Bigarella 1979*; Middleton et al. 2003*, Whitmore et al. 2014.	Whitmore et al. (2014) report that It is a nearly pure, subrounded to subangular, fine grained quartz sandstone that is poorly to moderately sorted. It contains occasional dolomite beds, clasts, ooids, cement and rhombs. Its greatest thickness is in the Pine area where it approaches 300 m. Baltz (1982) reports 27-177 m thick beds in the Arica mountains of California. The Glorieta Sandstone of New Mexico is a direct stratigraphic equivalent of the Coconino (Baars 1961). The Schnebley Hill Formation and the DeChelly Sandstone mostly lie stratigraphically below the Coconino; the upper parts interfinger with the Coconino (Blakey and Knepp 1989). The White Rim Sandstone of Utah probably is stratigraphically equivalent with the upper part of the Coconino (Blakey and Knepp 1989).
Corrie Sandstone	Scotland (Permian)	Clemmensen and Abrahamsen 1983*; Gregory 1915*; Piper 1970*	The Lower Permian Corrie Sandstone of the Isle of Arran in southwestern Scotland is at least 700 m thick (Clemmensen and Abrahamsen 1983). Piper (1970) described the sandstones in the type section at Corrie, Scotland as medium-grained, very well-sorted, rounded and with frosted grains. The Corrie Sandstone has long been regarded as eolian in origin (Gregory 1915) and more recent workers have agreed with this assessment. Clemmensen and Abrahamsen (1983) proposed that the sandstone was deposited as part of a small erg system bounded to the northwest by alluvial fans.
Dawlish Sandstone	England (Permian)	Clemmensen et al. 1994*; Laming 1966*; Newell 2001*	The Dawlish Sandstone Formation (Upper Permian) comprises a series of sandstones and conglomerates exposed along the Devon coast of southwest England identified by Clemmensen et al. (1994) as units produced by alternating arid-humid climatic fluctuations. Much of the formation, especially the lower part, is characterized by cross-bedded units with foresets dipping at angles up to 33^{o} (Laming 1966). Newell (2001) interpreted cross-bedded facies as eolian dune deposits and tabular facies as eolian sand sheets.
De Chelly Sandstone	Arizona, Utah, New Mexico (Permian)	Baars 1979*; Blakey 1990*; Stanesco 1991*	The type section is located in Canyon De Chelly National Monument in the Four Corners area of northeastern Arizona. To the northwest, north and northeast, it becomes part of the Cutler Group of Utah and Colorado where it likely correlates with part of the White Rim Formation. It is similar in cross-bed style and appearance to the Coconino except that it is more orange in color. To the south and east, it likely correlates with the Schnebly Hill Formation which lies conformably below and interfingers with the Coconino Sandstone in the Sedona area. To the southwest, the De Chelly correlates with the Meseta Blanca Sandstone Member of the Yeso Formation in New Mexico according to Baars (1979). The fine to medium-grained sand is bimodal and most of the grains are coated with iron oxide. Some beds have considerable silt content.

Glorieta Sandstone	New Mexico (Permian)	Baars 1974; Blakey 1990; Brill 1952; Dinterman 2001*; Irwin and Morton 1969.	The Glorieta is recognized in New Mexico, Texas and Oklahoma. Baars (1974) describes the Glorieta as a fine to medium-grained quartz sandstone with thin to medium cross-beds with dips of 10 to 20 degrees. It ranges from 30-90 m in thickness. Baars thought that most of the Glorieta was aqueously deposited. Dinterman (2001) describes the Glorieta (in NM) as being primarily a well-sorted, fine-grained quartz arenite. According to Blakey (1990) it is probably correlative with the main body of the Coconino in Arizona and Brill (1952) believes it is correlative to the Lyons in Colorado.
Hopeman Sandstone	Scotland (Permian)	Maithel et al 2015; Ogilvie et al. 2000*; Peacock 1966*; Peacock et al. 1968*	Borehole data suggest a maximum thickness of 60 m for this sandstone (Ogilvie et al., 2000). The formation is characterized by large-scale cross-bedded sandstones with well-rounded quartz and feldspar grains and minor amounts of mica (Peacock et al. 1968) which have been interpreted as the products of eolian deposition. Coarse pebbly sandstone lenses with small-scale cross-bedding also occur (Peacock, 1966) which are interpreted as water-deposited. Contrary to other published reports, Maithel et al (2015) found that the sandstone was not as well-sorted or rounded as previously reported. They noted that orthoclase and muscovite in the formation could suggest a non-eolian depositional environment.
Lochar-briggs Sandstone	Scotland (Permian)	Brookfield 1977*, 1978*; McKeever 1991*	The Locharbriggs Sandstone (Lower Permian) is known from outcrops in the Dumfries Basin of southwestern Scotland (Bookfield 1977) and is thought to have been deposited as transverse dunes (McKeever 1991). The overall thickness of the unit may be around 1000 m and consists of large-scale cross-bedding and well-sorted fine to medium grained sand (Brookfield 1978).
Lyons Sandstone	Colorado (Permian)	Brill 1952*; Hubert 1960; McKee and Bigarella 1979*; Maher 1954*; Ross et al 2010; Thompson 1949; Walker and Harms 1972*	The Lyons Sandstone is best known from the Colorado Front Range where it extends into the subsurface of southeastern Colorado, western Kansas, and parts of Wyoming and Nebraska (Maher, 1954). The Lyons can be traced into New Mexico and is correlative with the Glorieta Sandstone (Brill, 1952) which has been long recognized to correlate with the Coconino Sandstone in Arizona. At most locations the Lyons has been divided into three units: a lower, middle, and upper. At its type locality, in Lyons, Colorado, the formation is about 107 m thick. The Lyons is very similar to the Coconino in many respects (McKee and Bigarella 1979) but authors have disagreed over the years whether the deposit is a shallow marine or coastal dune deposit.
Navajo Sandstone	Utah, Arizona (Triassic?-Jurassic)	Biek et al. 2010*; Bryant et al. 2016*; Doe and Dott 1980*; Freeman and Visher 1975; McKee and Bigarella 1979*	The Navajo Sandstone covers most of eastern Utah and parts of Arizona, New Mexico and Colorado. It extends into Wyoming and a small portion of Idaho where it is known as the Nugget Sandstone and into Nevada and California were it is recognized as the Aztec Sandstone. Some of its more spectacular outcrops occur in Zion National Park where locally it exceeds 600 meters in thickness (Biek et al. 2010). In 1975, Freeman and Visher created a firestorm in the literature when they came to the conclusion that the Navajo was a subaqueous deposit based on stratigraphic and grain size analysis. There are many contorted beds and soft sediment deformation features in the Navajo which have been attributed to ground water movement by some authors (Bryant et al. 2016; Doe and Dott 1980). Its large foresets, rounded and frosted grains, sorting and ripple types are often cited as evidence for its eolian origin.
Penrith Sandstone	England (Permian)	Arthurton et al., 1978; Lovell et al. 2006*; Waugh 1970*	The formation reaches a maximum thickness of over 400 m in the Appleby-Hilton area (Arthurton et al. 1978). Published petrographic and grain size studies have reported that it is a well-sorted, well-rounded orthoquartzite, with subordinate orthoclase feldspar and rock fragments (Waugh 1970). Detrital clay minerals and mica have been reported to be absent (Lovell et al. 2006). The large-scale cross-bedding in the Penrith Sandstone is mostly wedge-planar with some tabular-planar and lenticular-trough units and foreset dips from 20^o to 33^o (Waugh 1970).
Schnebly Hill Formation	Arizona (Permian)	Blakey and Knepp 1989*; Blakey and Middleton 1983*	The Schnebly Hill's type section is in the Sedona area and it is correlative with the De Chelly Sandstone and grades into the Yeso Formation of New Mexico (Blakey and Knepp 1989). It intertongues with the Coconino Sandstone in the Sedona area and it reaches thicknesses of up to 600 m in the Holbrook Basin (Blakey and Knepp 1989). Based on sedimentary structures Blakey and Middleton (1983) identified the Schnebly Hill has having various marine, coastal dune and inland dune facies.

Tensleep Sandstone	Wyoming (Pennsylvanian)	Agatston 1952; Kerr and Dott 1988*; Mankiewicz and Steidtmann 1979*	The Tensleep Sandstone of Wyoming correlates with the Quadrant Sandstone of Montana, the Weber Sandstone of Utah and the Casper and Minnelusa Sandstones of Wyoming and South Dakota. It is about 55 m thick at its type section near Ten Sleep, Wyoming (Mankiewicz and Steidtmann 1979). Based on Pennsylvanian marine fusilinids, carbonate cement and limestone and dolomite beds, it was originally thought to be entirely a shallow marine deposit (Agatston 1952; for a summary see Kerr and Dott 1988). However, others now believe it to be eolian (especially the upper part) based on its very fine to fine-grained quartz-rich sands, sorting, wind-ripple laminae, grainfall strata, avalanche strata and large-scale tabular-planar cross-beds with dips of 19-34º (Kerr and Dott 1988; Mankiewicz and Steidtmann 1979).
Weber Sandstone	Utah, Colorado (Pennsylvanian)	Doe and Dott 1980*; Fryberger 1979*	According to Fryberger (1979) the Weber has multiple evidences for the eolian origin of its beds including large scale cross-beds, raindrop imprints, contorted stratification, well-sorted quartz sandstones (with interbedded fluvial deposits). However, he does recognize that parts of the Weber further to the west are marine. Fryberger measured several sections of Weber in the Dinosaur National Monument Area; the section in Sand Canyon was 280 m thick. He reported that the Weber is correlative with the Tensleep Sandstone of Wyoming and the Wells Formation of northeastern Utah.
White Rim Sandstone	Utah (Permian)	Baars and Seager 1970; Baars 2010; Blakey et al. 1988*; Chan 1989*; Tubbs 1989*;	The best exposures of the White Rim Sandstone occur in the vicinity of Canyonlands National Park, Utah where it forms a "white rim" around much of the Colorado and Green River canyons. The sandstone probably correlates with the upper portion of the Coconino (Blakey et al. 1988). Its greatest thickness is about 80 meters (Chan 1989). Baars and Seager (1970) thought that the sandstone represented a nearshore shallow marine bar, a view which Baars still held in 2010. But, Tubbs (1989) and most others now identify the White Rim as a coastal dune deposit based on wind-ripple strata, sandflow toes, raindrop imprints, planar bounding surfaces, eolian textural trends, high percentage quartzose composition, lack of clay and silt in the deposit and deformational features.
Yellow Sand	England (Permian)	Steele 1983*; Versey 1925*; Pryor 1971	The Lower Permian Yellow Sand is usually described as fine- to coarse-grained and is said to consist of well-sorted, well-rounded to subangular clasts with common "frosting" of grain surfaces. Versey (1925) claimed that the Yellow Sand was the product of eolian processes, which is still the dominant view. However, Pryor (1971) challenged the eolian interpretation and argued that the Yellow Sand was deposited as a series of submarine sand ridges comparable to those from the modern North Sea shelf. He presented petrographic data showing that the Yellow Sand is in fact only poorly to moderately sorted, mostly subrounded, with <15% of the constituent grains being well-rounded and substantial amounts of subangular and angular grains. He documented the presence of muscovite and found cross-bed dips were about 18°. Pryor (1971) argued that these features were indicative of a shallow marine origin, although his reinterpretation has not been generally accepted.

APPENDIX II. Locality information on the samples used in this study.

Sample #	Formation	Location	Conventional Age	Approximate Coordinates	
				latitude	longitude
AC-08	Coconino SS	Arizona	Permian	36.212°	-113.434°
ALC-02	Tensleep SS	Wyoming	Pennsylvanian	44.371°	-107.565°
ALV-01	Casper SS	Wyoming	Penn-Permian	42.550°	-106.723°
AP-12	Coconino SS	Arizona	Permian	36.204°	-113.37920
AP-17	Coconino SS	Arizona	Permian	36.204°	-113.37920
ARR-11	Corrie SS	Scotland	Permian	55.641°	-5.138°
ARR-18	Corrie SS	Scotland	Permian	55.641°	-5.138°
BCT-03	Schnebly Hill Fm	Arizona	Permian	34.674°	-111.664°
BCT-06	Schnebly Hill Fm	Arizona	Permian	34.674°	-111.664°
BCT-08	Schnebly Hill Fm	Arizona	Permian	34.674°	-111.664°
CDC-01	De Chelly SS	Arizona	Permian	36.133°	-109.469°
CHP-01	Casper SS	Wyoming	Penn-Permian	41.045°	-105.548°
CLN-01	Navajo SS	Utah	Triassic-Jurassic	38.645°	-109.736°
CM-01	Cedar Mesa SS	Utah	Permian	37.524°	-109.675°
COW-02A	Penrith SS	England	Permian	54.672°	-2.710°
CPN-01	Navajo SS	Utah	Triassic-Jurassic	37.102°	-112.680°
CPN-03	Navajo SS	Utah	Triassic-Jurassic	37.102°	-112.680°
CRQ-04	Yellow Sand	England	Permian	54.767°	-1.459°
DAW-02	Dawlish SS	England	Permian	50.591°	-3.445°
GLO-02	Glorieta SS	Arizona	Permian	35.515°	-105.834°
GLO-04	Glorieta SS	Arizona	Permian	35.515°	-105.834°
GLO-05	Glorieta SS	Arizona	Permian	35.515°	-105.834°
GLO-06	Glorieta SS	Arizona	Permian	35.515°	-105.834°
HOP-09	Hopeman SS	Scotland	Permian	57.713°	-3.421°
JTR-03	Navajo SS	Utah	Triassic-Jurassic	37.496°	-109.637°
JUS-08	Coconino SS	Arizona	Permian	36.585°	-112.547°
LBG-03	Locharbriggs SS	Scotland	Permian	55.112°	-3.582°
LBG-05	Locharbriggs SS	Scotland	Permian	55.112°	-3.582°
LSS-02	Lyons SS	Colorado	Permian	40.219°	-105.261°
NH-08	Coconino SS	Arizona	Permian	35.997°	-111.938°
NHT-13	Coconino SS	Arizona	Permian	35.997°	-111.938°
NHT-17	Coconino SS	Arizona	Permian	35.997°	-111.938°
OC-03	Schnebly Hill Fm	Arizona	Permian	34.977°	-111.746°
PB-02	Coconino SS	Arizona	Permian	35.236°	-112.762°
PB-03	Coconino SS	Arizona	Permian	35.236°	-112.762°
PLC-03	Casper SS	Wyoming	Penn-Permian	41.388°	-105.484°
RRC-01	Lyons SS	Colorado	Permian	38.853°	-104.880°
RTD-02	Schnebly Hill Fm	Arizona	Permian	34.679°	-111.722°
RU-03	Tensleep SS	Wyoming	Pennsylvanian	41.945°	-107.332°
SBR-10	Schnebly Hill Fm	Arizona	Permian	34.897°	-111.781°
SCG-15	Weber SS	Utah	Pennsylvanian	40.915°	-109.791°
SCR-01	Schnebly Hill Fm	Arizona	Permian	34.803°	-111.774°
SED-40	Schnebly Hill Fm	Arizona	Permian	34.932°	-111.855°
SFRC-09	Coconino SS	Arizona	Permian	36.642°	-112.053°
SFRC-12	Coconino SS	Arizona	Permian	36.642°	-112.053°
SRS-01	Navajo SS	Utah	Triassic-Jurassic	38.847°	-110.898°
TEN-04	Tensleep SS	Wyoming	Pennsylvanian	107.351°	-44.074°
TEN-06	Tensleep SS	Wyoming	Pennsylvanian	107.351°	-44.074°
WR-02	White Rim SS	Utah	Permian	37.889°	-110.410°
WRC-03	Tensleep SS	Wyoming	Pennsylvanian	43.572°	-108.211°
WRC-07	Tensleep SS	Wyoming	Pennsylvanian	43.572°	-108.211°
WSC-08	Tensleep SS	Wyoming	Pennsylvanian	43.572°	-108.211°
WSC-10	Coconino SS	Arizona	Permian	36.692°	-112.301°
WSC-17	Coconino SS	Arizona	Permian	36.692°	-112.301°