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THE SIGNIFICANCE OF ANGULAR K-FELDSPAR GRAINS IN ANCIENT SANDSTONES

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ABSTRACT

In our studies of ancient sandstones, many of which are purported in the conventional literature to be eolian deposits, we frequently encountered angular K-feldspar sand grains. In particular, we encountered them while studying the Coconino Sandstone of Arizona, but we have found them in many other ancient sandstones as well. To gain some insights on the petrology of ancient “eolian” sandstones, we studied the petrology of a number small ergs in the western United States, beach and dune sands along the California and Oregon and reviewed the literature on the petrology of modern eolian and subaqueous deposits.

In our literature review and from our own observations along the California and Oregon coastlines, we found that fluvial and shoreline processes are not sufficient to cause rounding of sand grains of any type, even after energetic and prolonged longshore transport and frequent tidal activity. Conversely, when sand grains are picked up by eolian processes and transported to coastal dunes, all species of mineral grains are quickly rounded, even over short distances. K-feldspar is rounded faster than quartz probably because it is softer and cleaves easier. We frequently encountered rounded K-feldspar grains in the small ergs we examined despite many of them being close in proximity to sources of angular K-feldspar sand grains. In larger ergs, all types of sand grains become quickly rounded and angular grains only occur if there are local fluvial or coastal sources for them.

The frequent occurrence of angular K-feldspar grains that we found in ancient cross-bedded sandstones, purported to be made by eolian processes, causes us to question whether these deposits were made by eolian activities or not. The presence of angular K-feldspar may be one petrographic criterion for identifying ancient fluvial and marine deposits. The goal of this paper is to document the ubiquitous occurrence of angular K-feldspar grains in many supposed ancient cross-bedded sandstones. Coupled with other criteria, angular K-feldspar sand grains are a crucial piece of data that might be used to argue that these ancient sandstones were formed by aqueous rather than eolian processes.

KEY WORDS

K-feldspar, abrasion experiments, rounding of K-feldspar, rounding of quartz, Aztec Sandstone, Bridgnorth Sandstone, Casper Sandstone, Cedar Mesa Sandstone, Coconino Sandstone, Corrie Sandstone, Hopeman Sandstone, Locharbriggs Sandstone, Lyons Sandstone, Navajo Sandstone, Penrith Sandstone, Schnebly Hill Formation, Tensleep Sandstone, Weber Sandstone, Yellow Sand

INTRODUCTION

In our studies of thin sections from the Coconino Sandstone, we encountered angular K-feldspar sand grains that were sometimes more angular than the similar-sized quartz grains that surrounded them (Whitmore et al., 2014). We found this to be unusual because K-feldspar has a hardness of 6.0 on Mohs scale of hardness, while quartz has a hardness of 7.0. To better understand our Coconino data, a series of modern sand samples were collected to investigate the rounding rates of sand. We chose to study the rounding of quartz and K-feldspar grains as they were transported by eolian processes from beach to dune environments along the Oregon and California coastlines. The results of those studies have been reported in several places (Whitmore and Strom 2017a, 2017b; McMaster et al. 2010; McKevitt 2012) with the most extensive report published late last year (Whitmore and Strom 2017c). In that paper, we also reported on samples that we collected and studied from a number of small ergs in the western United States. We noted rounded and well-rounded K-feldspar was prevalent in those eolian dunes.

Those studies concluded that both K-feldspar and, to a lesser extent, quartz sand can be noticeably rounded by eolian transport even over short distances (less than 0.5 km) as angular sand grains are carried from the beach to nearby coastal dunes. The change in rounding was statistically significant. In our observations, sometimes angular K-feldspar grains can occasionally be found in ergs, but it is only common when beaches, rivers or a plutonic source of bedrock provides a nearby source for the angular sand. Under normal conditions, K-feldspar in particular, becomes noticeably rounded even after being transported over distances as small as 125 m. It becomes rounded to well-rounded as it gets transported further into the erg. We used standardized rounding definitions that were developed by Powers (1953) and slightly modified by Folk (1955) and are illustrated in Fig. 1.

Similar observations and conclusions were reached by Garzanti et al. (2012, 2015). They studied sand that was carried 100’s of kilometers from the Orange Delta northward along the Namibian coast by longshore and tidal currents. During aqueous transport the sand, it remained angular and the composition fairly constant. It wasn’t until eolian transport ensued, that sand grains of all types, became quickly rounded as they were transported to the nearby coastal erg.

The conclusion of our previous studies was that rounded

K-feldspar grains could be a reliable criterion for an ancient eolian processes and that angular K-feldspar would almost certainly indicate subaqueous transport and deposition since it becomes rounded so quickly by eolian activity. The goal of this paper is to document the presence of angular K-feldspar grains in many supposed ancient eolian sandstone bodies and use this criterion, as one among many, as a likely indicator of subaqueous deposition. Thus, rounded K-feldspar grains are typical of eolian transport and angular K-feldspar grains may be indicative of 1) a local (probably < 1 km) source of the K-feldspar grains, 2) diagenetic dissolution of parts of the grains to make them more angular, or 3) subaqueous transport of the sand body containing the K-feldspar grains. It should be noted that quartz, and more rarely K-feldspar, grains can develop "overgrowths" as part of the diagenetic process (Odom 1975; Fig. 2). This occurs when a small amount of the mineral begins to re-grow around the weathered surface of the grain producing flat surfaces and sometimes angular corners. The overgrowths often act as cement to hold the grains of the rock together and are separated from weathered sand grains by a thin, dark "dust rim." When we refer to "angular" quartz or K-feldspar we are referring to the original shape of the grain, not the shape imparted by an overgrowth (which is often angular).

It is important for creationists to study ancient cross-bedded sandstones because many of these sand bodies, especially the Coconino and Navajo Sandstones, have been used to show that creationists are wrong when it comes to Noah's Flood. The problem is that many of these sandstones are found sandwiched in between marine deposits that we would like to identify as Flood deposits; and we cannot have desert sand dune deposits in the midst of the Flood. For example, Strahler (1999, p. 217) states:

> Exposed in the walls of Grand Canyon is the Coconino Formation [sic] of Permian age. It is about 90 m thick and qualifies in all respects as a dune formation. In the walls of Zion Canyon the Navajo Formation [sic] of Jurassic age, over 500 m thick, consists of cross-laminated dune sand… The evidence of subaerial origin of the dune-sand formations is undisputed as to its significance by mainstream geology; in itself it is sufficiently weighty to totally discredit the biblical story of the Flood of Noah as a naturalistic phenomenon occurring in one year.

Additionally, these sand bodies are often used in paleogeographic reconstructions and interpretations. Because they are assumed to represent eolian deposits (primarily because of their large and "steep" cross-bed dips and "well-sorted" and "well-rounded" sand), vast areas of paleocontinents are shown as deserts (Blakey and Ranney 2008) when in fact they probably represent shallow sandy seas that covered the paleocontinent of Pangea.

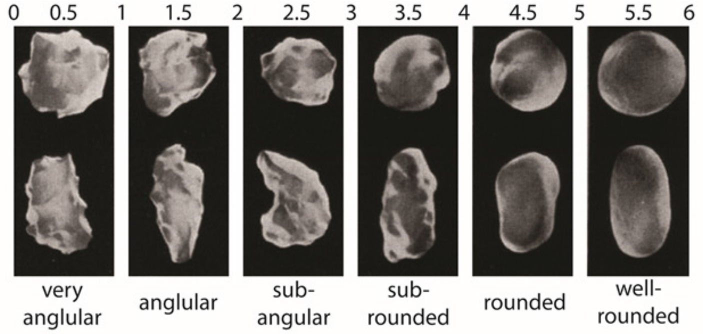

Figure 1. The roundness scale developed by Powers (1953, p. 118) and slightly modified by Folk (1955) who added the rho scale class values.

METHODS

As part of the Coconino Sandstone FAST project, sandstone samples (mostly Permian) were collected from the Coconino Sandstone (Arizona), the Aztec Sandstone (Nevada), 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). We also collected European samples: Bridgnorth Sandstone (England), Corrie Sandstone (Scotland), Yellow Sand (England), Dawlish Sandstone (England), Hopeman Sandstone (Scotland), Locharbriggs Sandstone (Scotland) and Penrith Sandstone (England). Appendix I lists the sandstones referenced in this paper, their conventional geological age, those who have identified the formation as eolian, and a few notes about each formation. Appendix II lists all of the individual samples used in this paper along with their approximate collection coordinates. Sampling was most extensively done in the Coconino Sandstone. We sampled the entire breadth and thickness of the formation at many different localities (Whitmore et al. 2014). The other sandstones were sampled less extensively.

Thin sections were made from the samples by impregnating the rock with blue epoxy and cutting and polishing to 30 µm so the rock could be examined under the petrographic microscope. The samples were stained with double carbonate stain (potassium ferricyanide and alizarin red s) and sodium cobaltinitrite to reveal the presence of calcite (red) and K-feldspar (yellow) and to distinguish it from quartz (white). Preparatory work was completed at Calgary Rock and Materials Services Inc. in Calgary, Alberta. Microscope work was completed at Cedarville University with a Nikon Eclipse 50i Pol microscope equipped with the Br software package.

RESULTS

The goal of this paper is to document the ubiquitous occurrence of angular K-feldspars in many ancient sandstones. We document

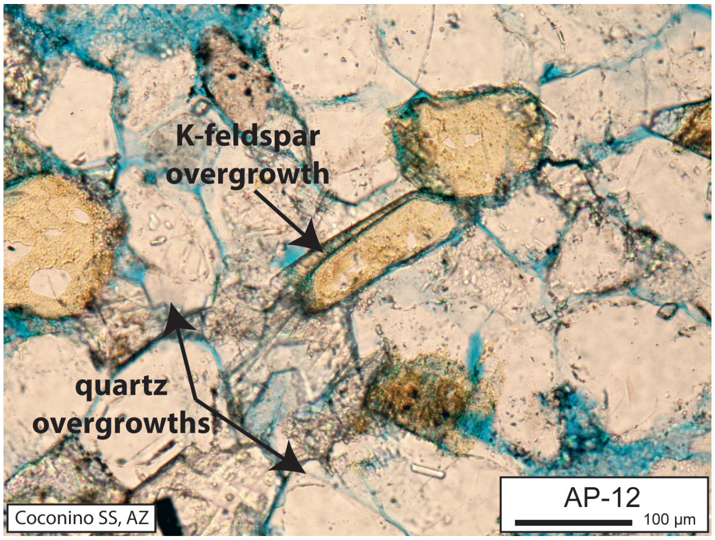

Figure 2. Overgrowths are most common in quartz (the white mineral) and the can more rarely be found in K-feldspar. They most often develop diagenetically as small amounts of the minerals dissolve and recrystallize forming the cement that holds the grains of the rock together. When we describe "roundness" we are looking at the mineral grain inside of the "dust rim," not the part of the grain that has grown from diagenesis.

angular K-feldspars in many ancient sandstones (Figs. 3-10) and rounded K-feldspars in modern eolian deposits (Figs. 11-12). Some angular grains were found in modern ergs, but only if the erg was near a source for the angular grains like a stream bed, beach or crystalline bedrock. Our results show examples of angular K-feldspar sand grains in many different sandstones from the western United States and Great Britain. The photographic plates are grouped by similar location or formation. Generally, the more photos we have of a particular sandstone, the more samples we collected from that particular unit. In these photos, blue is epoxy (or the empty space between grains), white is quartz or chert, red is calcite and yellow is K-feldspar. *We found angular K-feldspars in virtually every sandstone that we examined*. In the Coconino, this included all around the margins of the formation (top, bottom, edges) and in the middle of the sandstone.

DISCUSSION

In the sandstones that we studied, all have been reported to either be completely or partially deposited by eolian processes by many different authors (see Appendix I). Criteria cited for the eolian origin of many of these sandstones often include (see McKee and Bigarella 1979; Hunter 1977, 1981): 1) large scale cross-strata, 2) high dip angles near the angle of repose, 3) wind ripple marks that are perpendicular to the strike of the foreset beds, 4) slump marks and features, 5) contorted beds, 6) well-sorted sand, 7) fine to medium sized sand grains, 8) predominantly quartz in composition that are usually rounded to some degree, 9) pitted (frosted) sand grains, 10) animal tracks and trails, 11) interdune deposits, 12) non-marine fossil floras and faunas, 13) abrupt boundaries (meaning the sand deposits sharply interfinger with rather than grade into adjacent facies), 14) raindrop imprints, 15) lack of silt and clay in the deposit, 16) various types of characteristic laminae and strata including planebed laminae, rippleform laminae, ripple-foreset cross-laminae, climbing translatent strata, grainfall laminae, and sandflow cross-strata and 17) fine scale stratification associated with dune depositional processes. Often, many authors have not closely examined a sandstone in great detail before they arrive at a conclusion of an eolian origin. There are many examples where only large and steep cross-beds, sorting, rounding and frosting are the only criteria cited. This is especially true in the literature that has criticized creationists for thinking that the Coconino is a subaqueous deposit; albeit these authors are largely not specialists in eolian research (see for example, Hill et al. 2016; Strahler 1999; Weber 1980; Young and Stearley 2008). However, even specialists in eolian research have on occasion used sparingly few criteria in reaching an eolian conclusion for some sandstones (see McKee and Bigarella 1979). It turns out that many of the things that are often cited as "true" for a sandstone are not so after a more detailed examination. We found this to be the case in both the Coconino and Hopeman Sandstones when we examined the most often cited things such as cross-bed dips, sorting, angularity and frosting (Whitmore et al. 2014; Maithel et al. 2015).

It is important to recognize that not all eolian sand grains become well-rounded and there are examples of desert dune sands that have angular grains within them (Pye and Tsoar 2009, p. 82-86). In particular, larger grains tend to get more well-rounded than smaller grains (Khalaf and Gharib 1985) and softer grains more rounded than harder ones (Pye and Tsoar 2009, p. 84). We found angular K-feldspar grains in our survey of small ergs in the western United States (Fig. 11-12). However, local sources for the angular grains could readily be identified from nearby (10's of kilometers) wadis or igneous rock outcrops. In his study of sand grains in the Simpson Desert, Folk (1978) found that there was little appreciable rounding difference in the reg of the desert floor (originating from local streams) compared to the longitudinal dunes. Both quartz (predominant) and K-feldspar were angular to subangular. He attributed this to a short distance of grain transport to accomplish observable abrasion (p. 615, 621) and nearby fluvial origin of the sand (p. 616).

It has been well-known for some time that aqueous transport does not appreciably round quartz *or K-feldspar sand grains* (Kuenen 1960; Russell and Taylor 1937; Twenhofel 1945). These views were confirmed by a noteworthy study of Garzanti et al. (2012; 2015), who investigated sand from the Orange River and Orange River Delta that empties into the Atlantic Ocean in southwestern Africa. Sand from these locations is carried northward along the African coast by continuous longshore currents and tidal activity, some of it for over 1400 km. *After this great distance of transport and mechanical activity, all of the sand is still angular*. The angular beach sand is then blown inland by southwesterly winds where it is deposited in the dunes of the Namibian Erg. They found that aqueous transport of beach sand, along the entire transport distance, fails to become appreciably rounded compared to the original river and delta sands. It is not until the wind picks up the sand and blows it into the erg does any appreciable rounding take place. Thus, in this study, rounding appears to happen *only* by eolian transport and not by any other mechanisms.

Despite these studies, some have suggested K-feldspar can be successfully abraded in aqueous environments. Odom (1975) and Odom et al. (1976) studied a variety of quartz arenites. They observed that K-feldspar content increases with decreasing grain size. In many sandstones with mean grain sizes greater than about 0.177 mm (2.5 ϕ), K-feldspar is often less than 10% of the rock volume (which defines a quartz arenite). With grain sizes less than about 0.125 mm (3.0 ϕ), K-feldspar is often more abundant (10-25%), a rock which is called a feldspathic arenite. The authors suggest that this trend occurs because K-feldspar is abraded more easily in aqueous high energy environments (forming the larger-grained quartz arenites) and conserved in lower energy aqueous environments (forming the smaller-grained feldspathic arenites).

There have been several explanations for how sand grains, especially more resistant quartz grains, become rounded (Chandler 1988; Dott 2003; Goudie and Watson 1981): 1) abrasion of sand grains by wind, 2) selective transport of better-rounded grains (to the dune) with the more angular ones being left behind in aqueous environments, 3) recycling of older deposits containing rounded grains and 4) intense chemical activity causing sharp corners of grains to be removed. Chemical activity can make a sandstone appear more "mature" by removing or altering more soluble grains such as feldspars; leaving quartz behind, especially in wet tropical environments. McBride (1985) referred to these as "diagenetic quartz arenites."

Of the four suggested mechanisms (above) for how sand grains become rounded, the current consensus appears to be *only* eolian transport, especially for the more mechanically and chemically resistant quartz grains (Chandler 1988). In environments like the hyper-arid Namib desert, eolian transport appears to be the *only* explanation because the major source of the sand grains is from

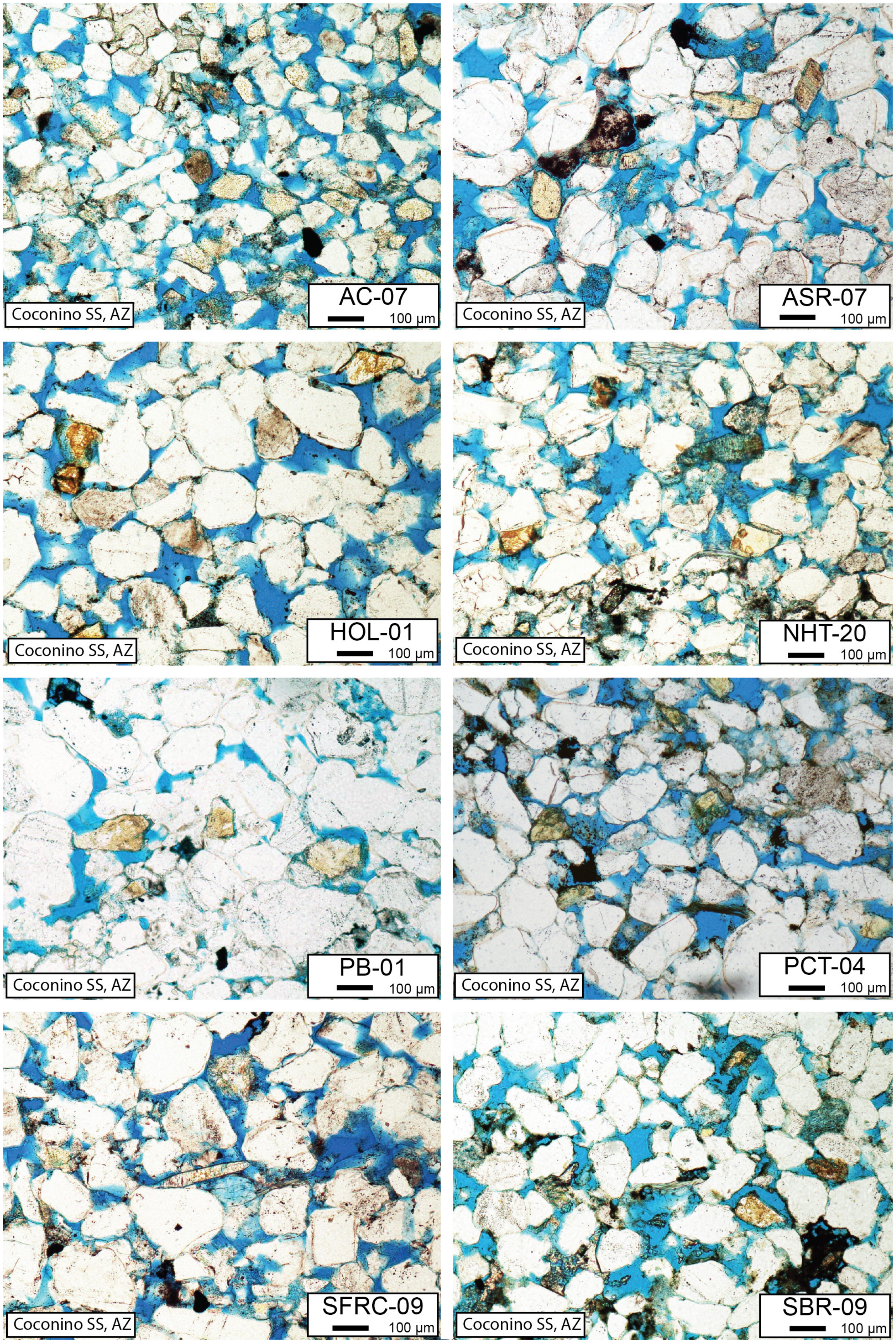

Figure 3. Examples of thin sections from the Coconino Sandstone, Arizona. Both angular and rounded grains can be found in the sandstone. Some of the mineral grains are labeled as follows: (K) K-feldspar, (M) muscovite and (B) biotite. Quartz is white. The blue color is epoxy. The samples have been stained so K-feldspar is yellow.

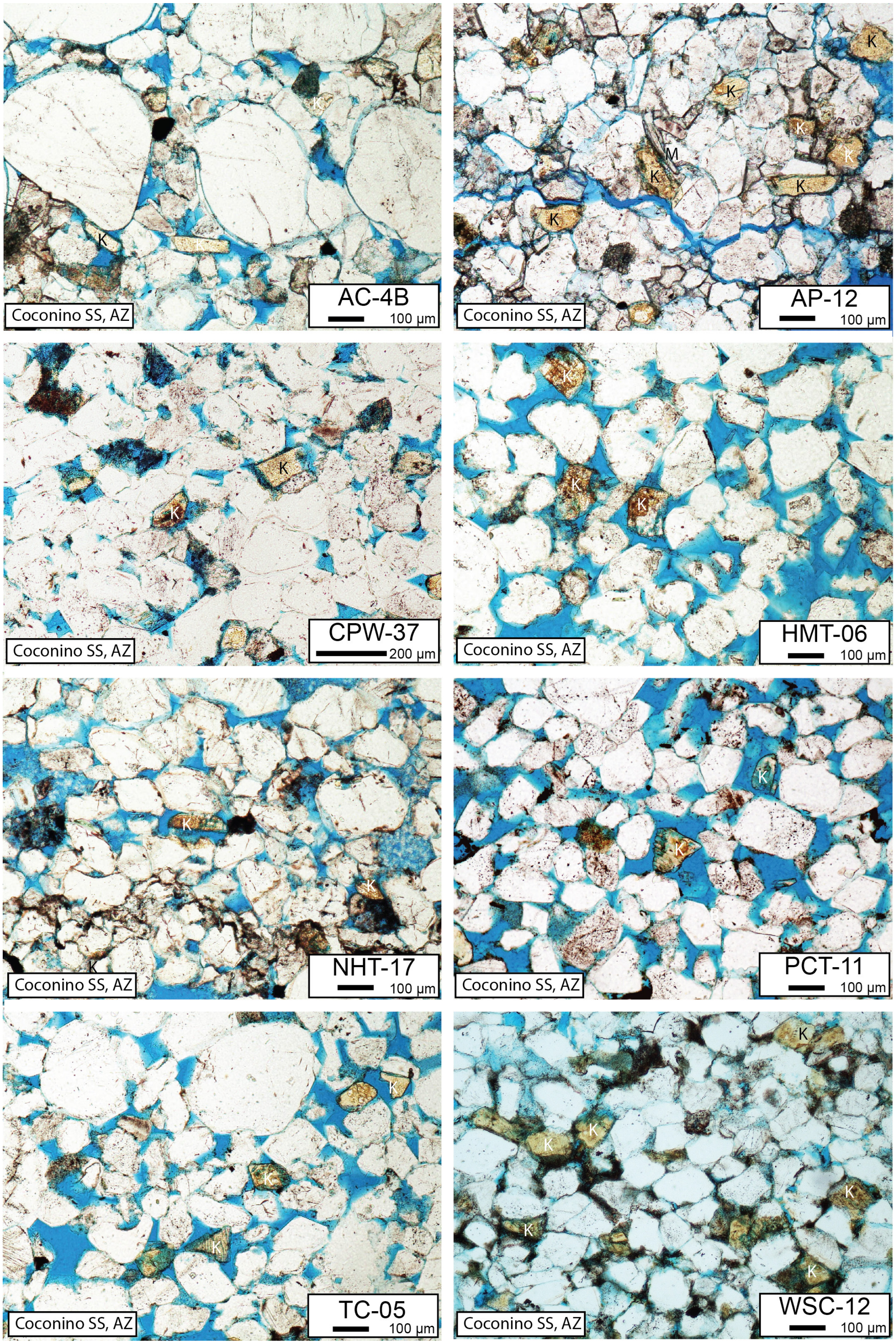

Figure 4. Examples of thin sections from the Coconino Sandstone, Arizona. Both angular and rounded grains can be found in the sandstone. Some of the mineral grains are labeled as follows: (K) K-feldspar and (M) muscovite. Quartz is white. The blue color is epoxy. The samples have been stained so K-feldspar is yellow.

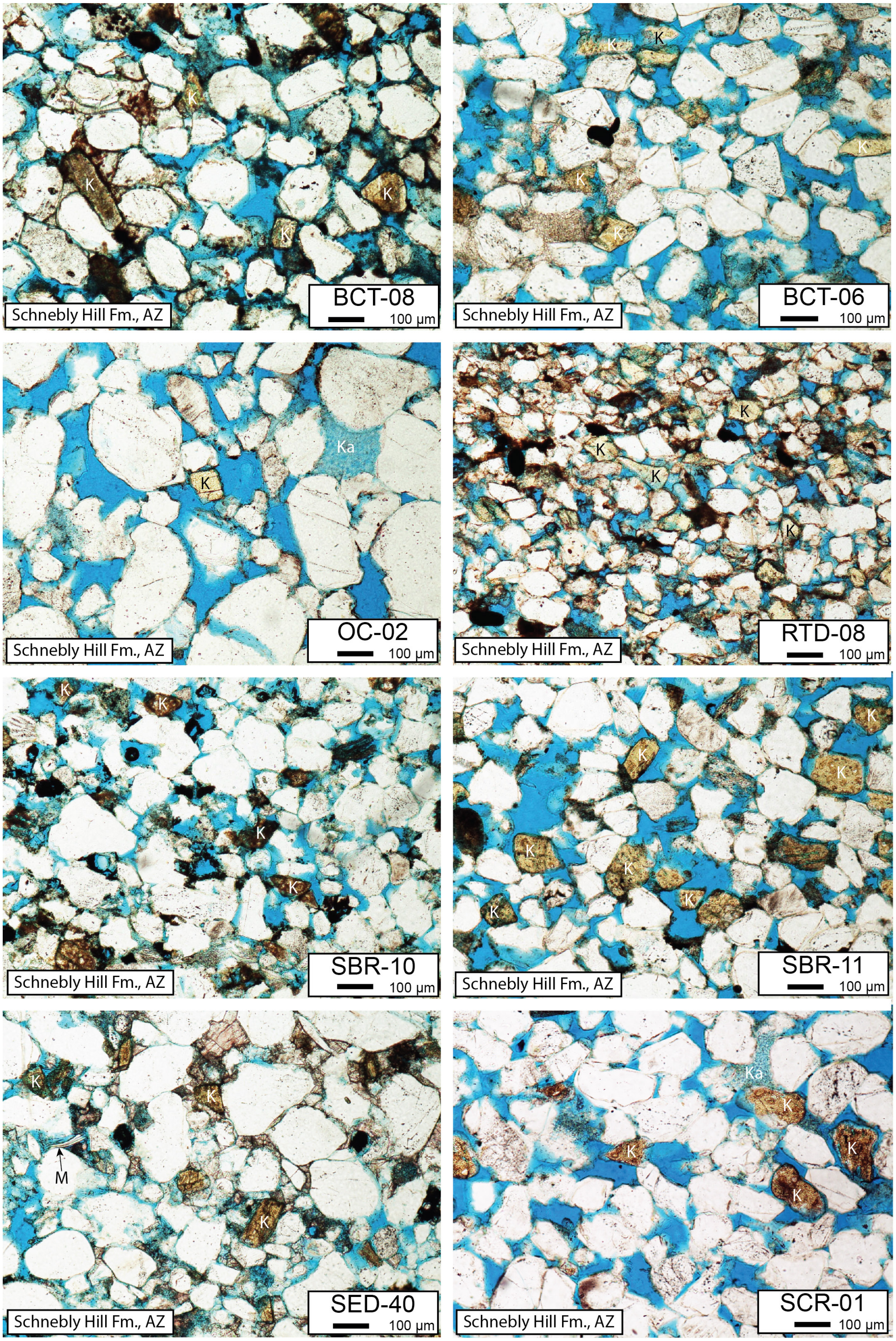

Figure 5. Examples of thin sections from the Schnebly Hill Formation, Arizona (primarily a cross-bedded sandstone). Both angular and rounded grains can be found in the sandstone. Some of the mineral grains are labeled as follows: (K) K-feldspar, (M) muscovite and (Ka) kaolinite. Quartz is white. The blue color is epoxy. The samples have been stained so K-feldspar is yellow.

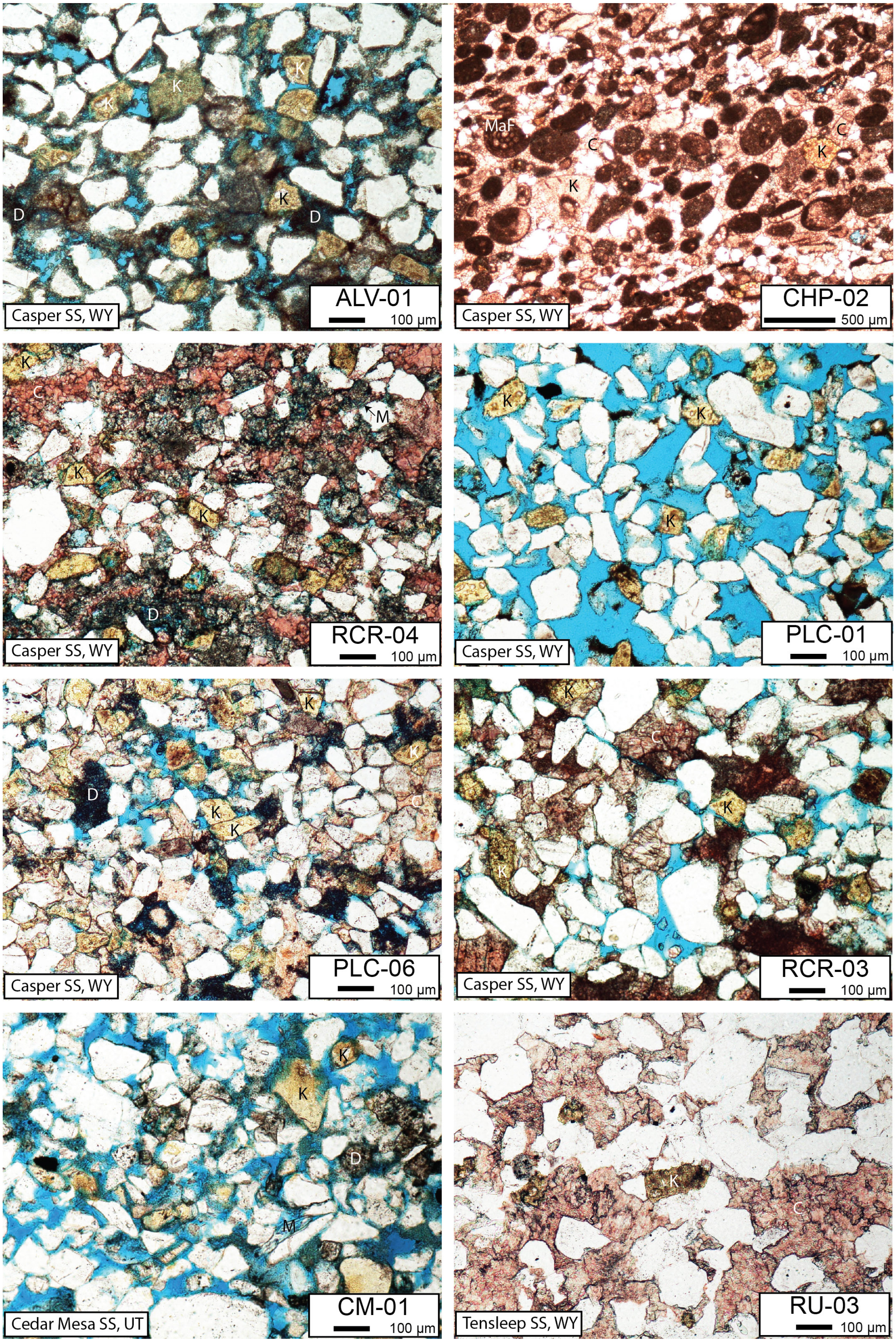

Figure 6. Examples of thin sections from sandstones occurring in Wyoming and Utah. Both angular and rounded grains can be found in the sandstones. Some of the mineral grains are labeled as follows: (K) K-feldspar, (M) muscovite, (D) dolomite, (C) calcite and (MaF) a marine fossil. Quartz is white. The blue color is epoxy. The samples have been stained so K-feldspar is yellow and calcite is red.

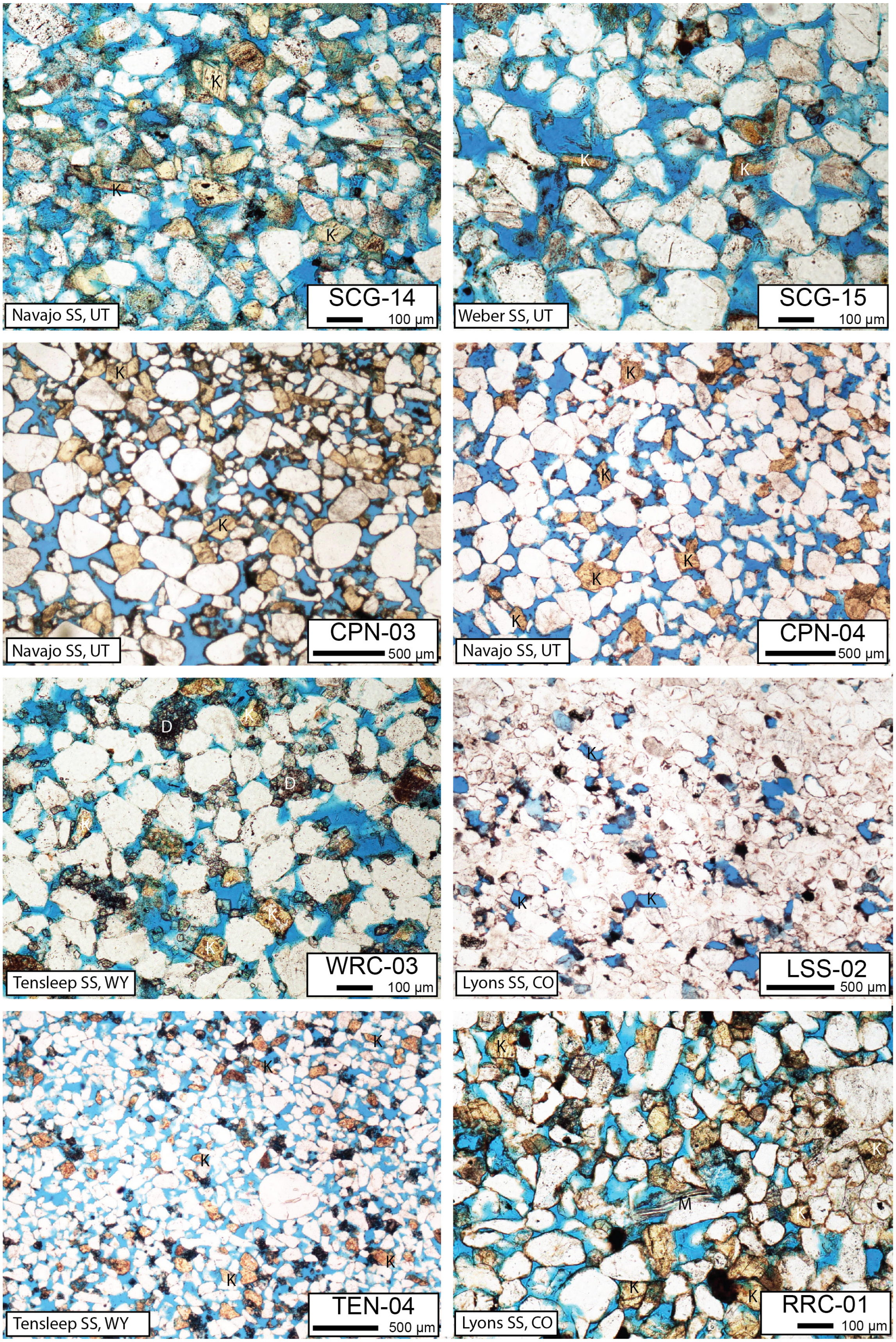

Figure 7. Examples of thin sections from sandstones occurring in Colorado, Wyoming and Utah. Both angular and rounded grains can be found in the sandstones. Some of the mineral grains are labeled as follows: (K) K-feldspar, (M) muscovite and (D) dolomite. Quartz is white. The blue color is epoxy. The samples have been stained so K-feldspar is yellow. The K-feldspar grains in the LLS-02 sample dissolved at some point in the history of the rock, but the angular outline of the grain still remains.

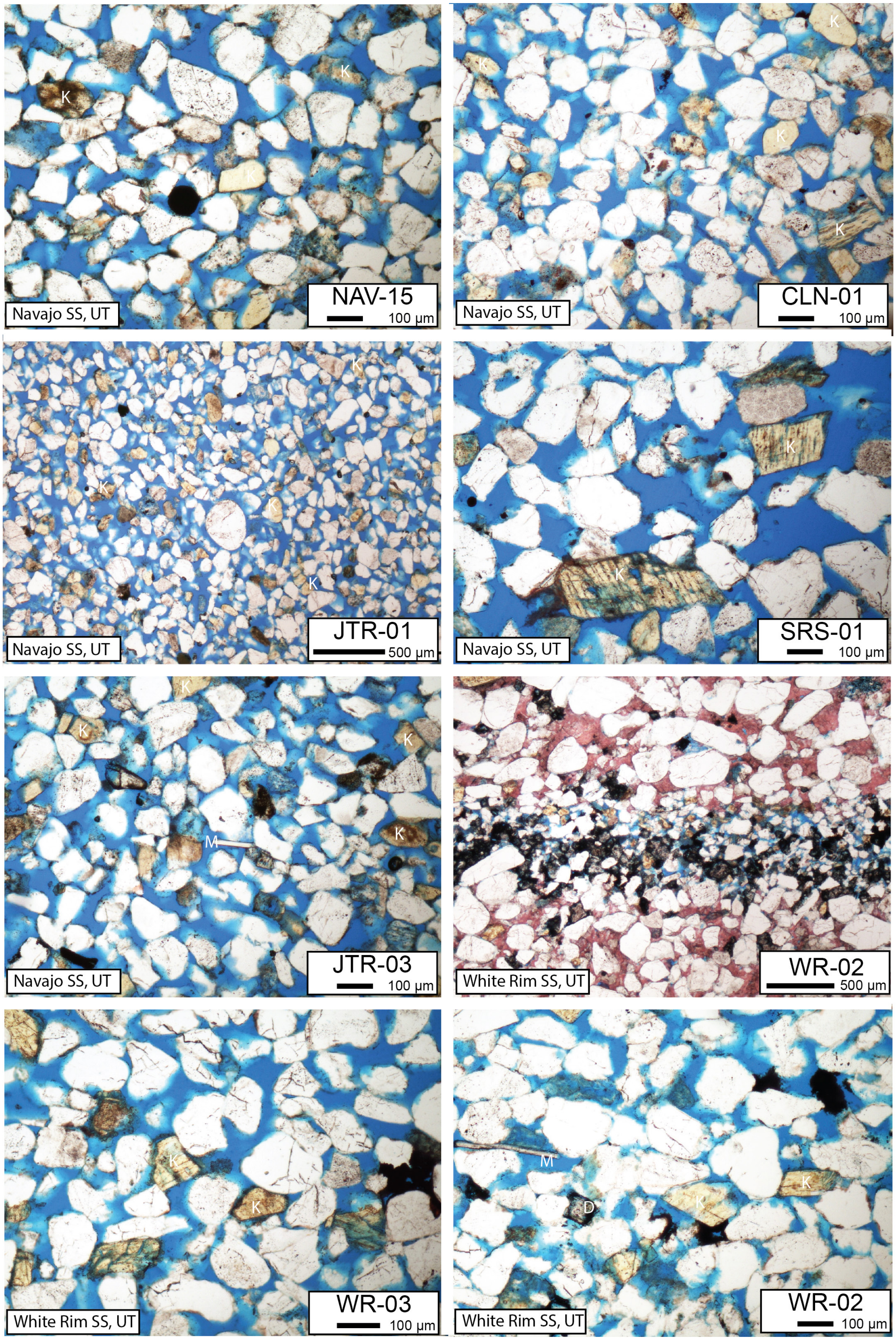

Figure 8. Examples of thin sections from sandstones in Utah. Both angular and rounded grains can be found in the sandstones. Some of the mineral grains are labeled as follows: (K) K-feldspar, (M) muscovite and (D) dolomite. Quartz is white. Calcite is pink. The blue color is epoxy. The samples have been stained so K-feldspar is yellow and calcite is pink.

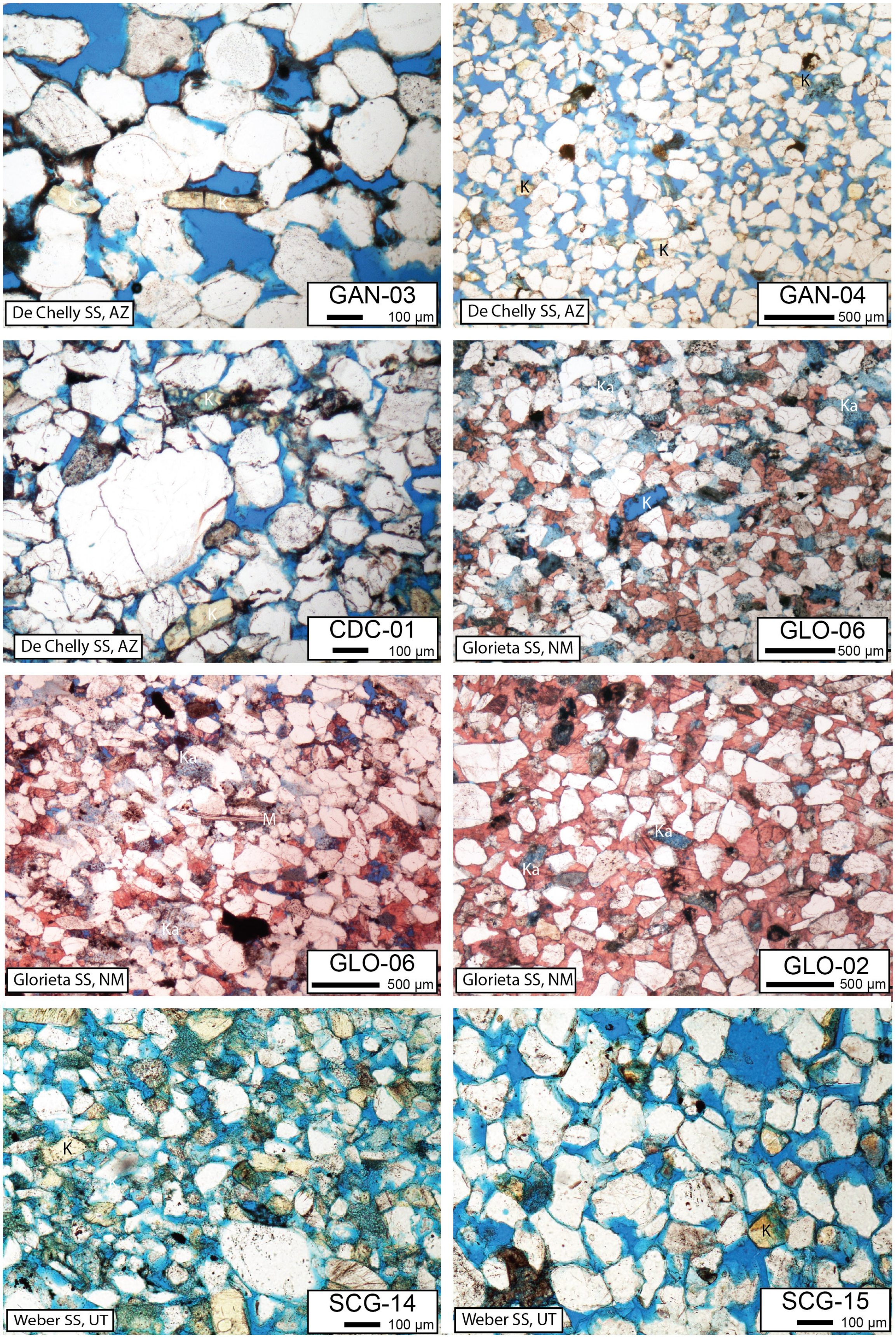

Figure 9. Examples of thin sections from sandstones in Arizona, Utah and New Mexico. Both angular and rounded grains can be found in the sandstones. Some of the mineral grains are labeled as follows: (K) K-feldspar, (Ka) Kaolinite, and (M) muscovite. Quartz is white. Calcite is pink. The blue color is epoxy. The samples have been stained so K-feldspar is yellow and calcite is pink. Note that in GLO-06 the K-feldspar has dissolved, yet its angular outline remains. In GLO-02 and GLO-06 some K-feldspar has been replaced with kaolinite with the angular shape of the K-feldspar remaining.

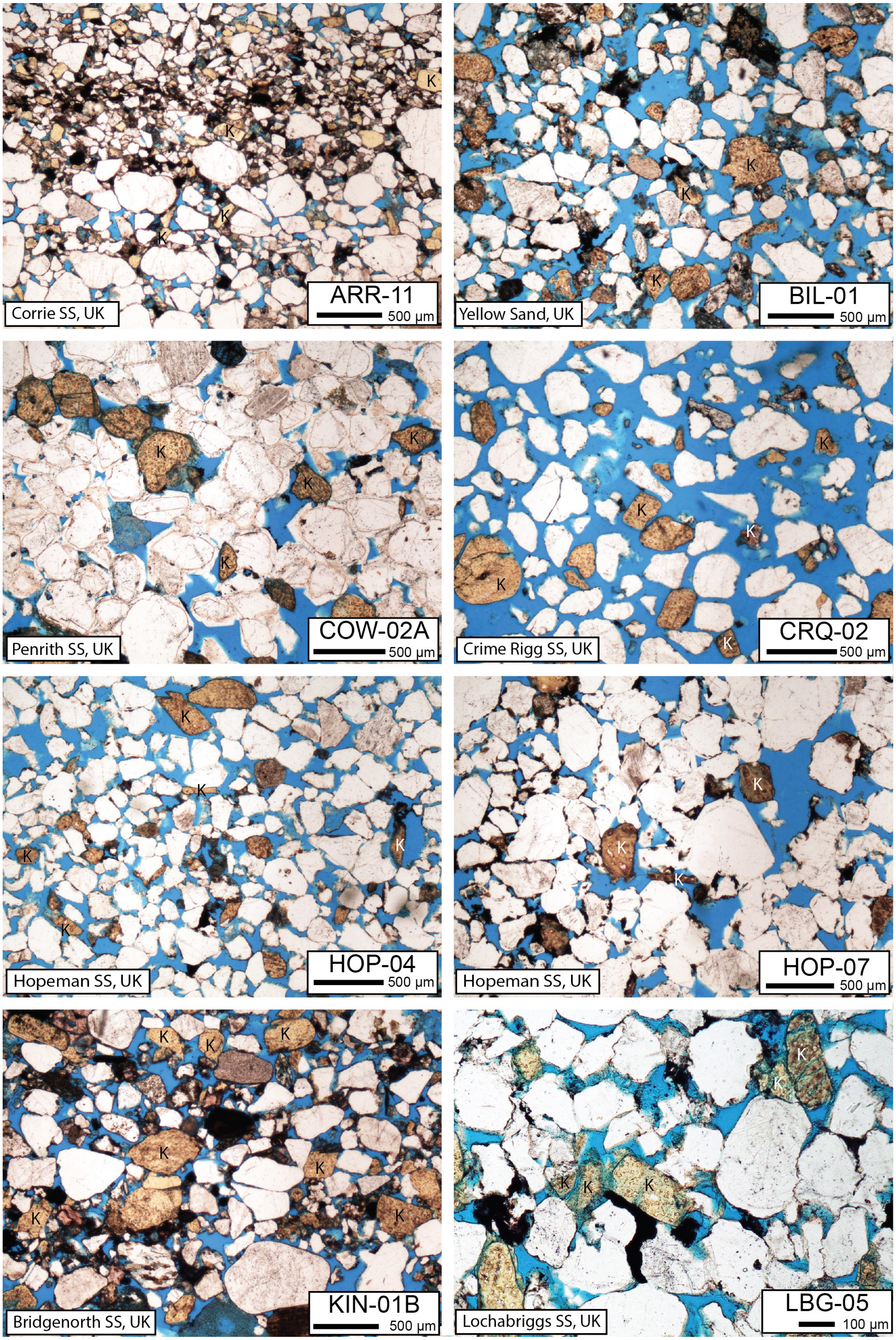

Figure 10. Examples of thin sections from sandstones in the United Kingdom. Both angular and rounded grains can be found in the sandstones. Some of the K-feldspar grains are labeled with a "K." Quartz is white. The blue color is epoxy. The samples have been stained so K-feldspar is yellow.

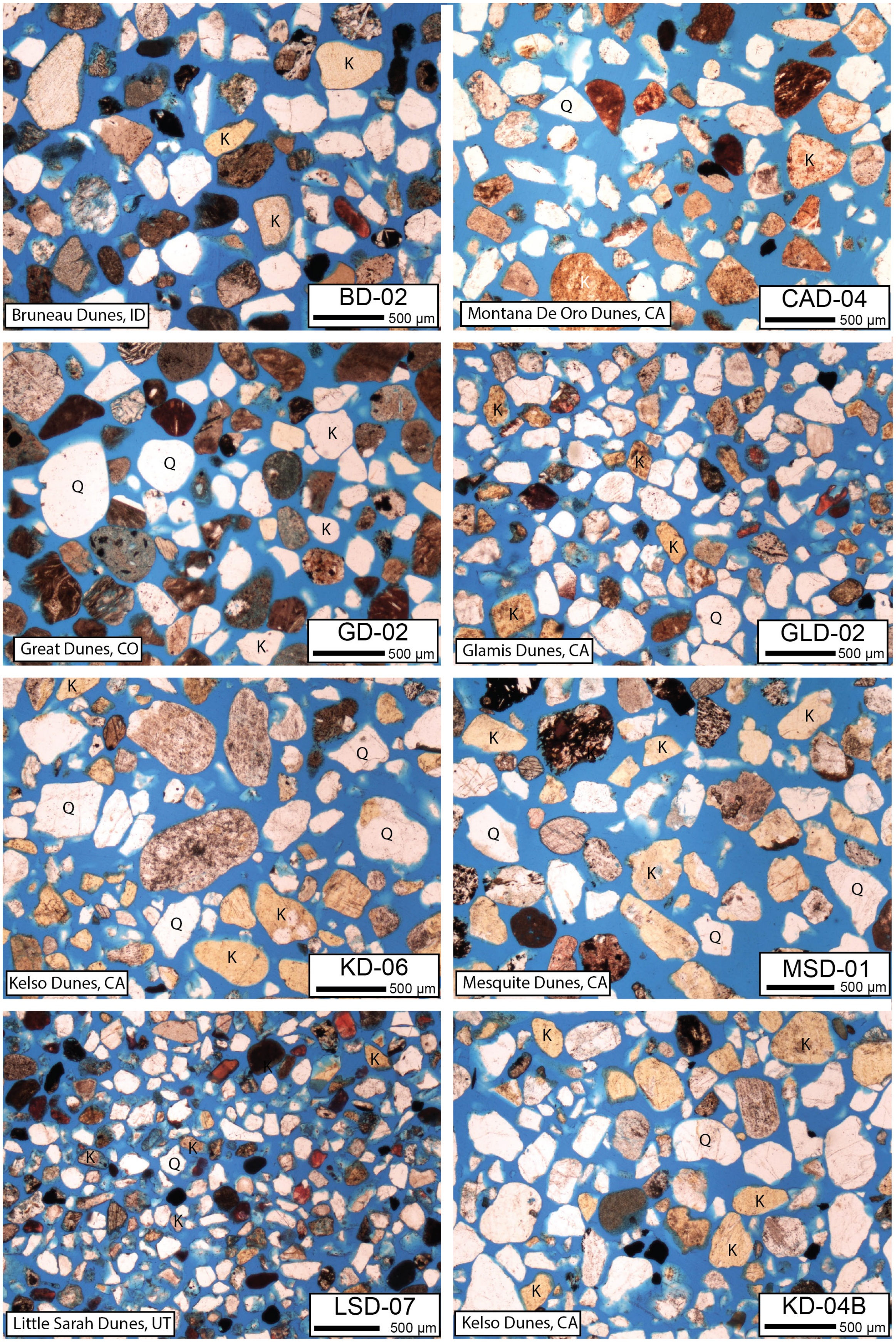

Figure 11. Examples of thin sections from modern dune sands in the western United States. Both angular and rounded grains can be found in sediments. Some of the mineral grains are labeled as follows: (K) K-feldspar and (Q) Quartz. The blue color is epoxy. The samples have been stained so K-feldspar is yellow.

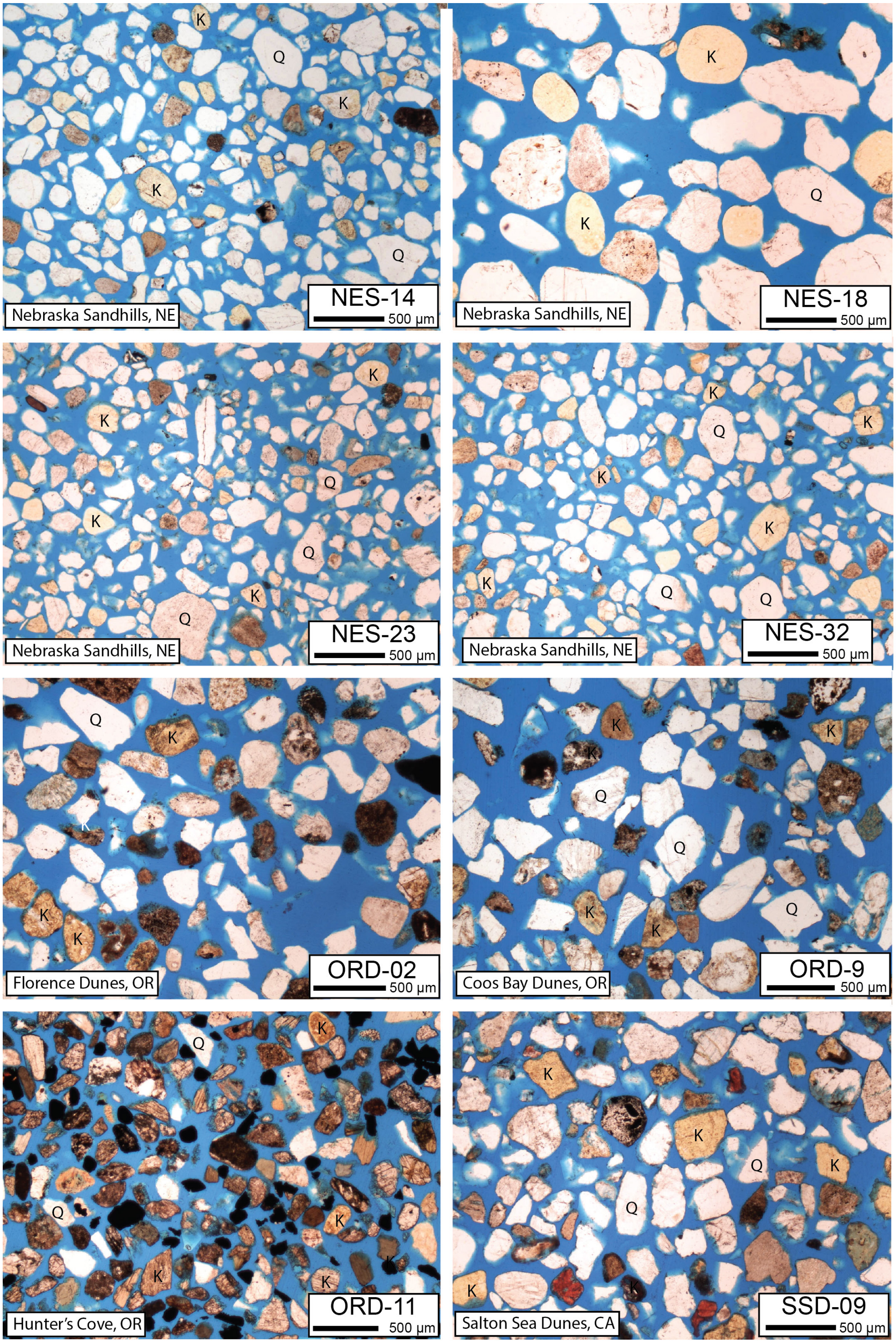

Figure 12. Examples of thin sections from modern dune sands in the western United States. Both angular and rounded grains can be found in the sediments. Some of the mineral grains are labeled as follows: (K) K-feldspar and (Q) Quartz. The blue color is epoxy. The samples have been stained so K-feldspar is yellow.

the angular beach sands (Garzanti et al. 2012; 2015). Although several authors have suggested that round grains are transported more efficiently and are concentrated by eolian processes due to being able to roll easier than angular grains (Folk 1968; MacCarthy and Huddle 1938; Mattox 1955; Mazzullo et al. 1986; Twenhofel 1945) other authors disagree because dunes can be found that have ranges of rounded particles within them and their roundness does not differ from the surrounding desert floor (Folk 1978; Khalaf and Gharib 1985). The lack of consensus is probably because the movement of various shapes, sphericities and sizes of grains is a complex process and is highly dependent on various velocity conditions (Morris 1957; Thomas 1987).

In published discussions of sand dunes and formations that contain an abundance of rounded sand grains (like supermature quartz arenites), the consensus seems to be that textural and compositional maturity is inherited and usually the result of several sedimentary cycles (Dott 2003; Folk 1978). Even though there have been several explanations for how quartz grains become rounded, the most popular and reasonable hypothesis remains eolian abrasion (Dott 2003) that happened in at least in one of the cycles in the history of the sand grains.

The previous discussion on rounding has focused on quartz which is, by far, the most common component of most sandstones. Pye and Tsoar (2009, p. 72) claim that K-feldspar rounds faster than quartz because of its lower hardness. Some theoretical, experimental and observational rounding data has been collected on K-feldspar grains. Marsland and Woodruff (1937) demonstrated experimentally that K-feldspar rounds slightly faster than quartz. Dutta et al. (1993) completed both theoretical and experimental work on eolian abrasion of K-feldspar. These authors theoretically calculated what changes K-feldspar would exhibit from ballistic impacts and then tested the hypothesis in a wind tunnel. They concluded that eolian sands tend to be fine-grained and quartz-rich because of the tendency of K-feldspar to break apart and become smaller due to ballistic impacts (causing rounding and smaller grains). They reasoned that this explained the size reduction and enrichment of quartz in eolian sandstones.

Whitmore and Strom (2017) studied sand along the Pacific coast that was transported into nearby sand dunes. They found that although the K-feldspar was still somewhat angular in the dunes, it had become statistically significantly more rounded even with transport distances of less than 100 m. Garzanti et al. (2015) found that angular sand of all mineral species changes little from marine and fluvial transport but is only significantly altered by eolian abrasion. They state (p. 991):

> Aeolian impacts are unable to change sand composition by selectively destroying labile components, but can spectacularly modify the morphology of detrital grains, which may become nearly as well-rounded as perfect spheres… Most detrital minerals are still angular to subangular after ca 2000 km of transport along the Orange River, confirming that fluvial environments are ineffective in rounding sand grains. Roundness changes little in the marine environment even after 300 to 350 km of high-energy littoral transport along the Atlantic shores of the Sperrgebiet. This condition demonstrates that beach action, as any transport in aqueous media, does not have much influence either (Pettijohn 1957) and disproves the long-held idea that beach sand rounds faster than river sand because the grains are rolled back and forth repeatedly (Folk 1980). Instead, rounding does occur rapidly at the transition to the aeolian environment in the southern Coastal Namib, indicating that abrasion is much more effective during sediment transport in air, where grains hit and round faster because of higher density contrast and lack of cushioning effect by the water film. Roundness reaches maximum in the central Coastal Namib and changes little further north, confirming that the rate of wear is greatest in the early stage of wind transport and declines exponentially with distance (Krumbein 1941).

From their observations they also concluded the “relative toughness” or susceptibility of various minerals to rounding (p. 992):

> Based on the observed compositional trends and differential rates of roundness increase with transport distance, the following sequence of relative toughness and mechanical durability can be established: garnet > quartz > epidote ≥ volcanic rock fragments ≥ feldspars > opaques ≥ pyroxene > amphibole > sedimentary/metasedimentary rock fragments.

It is clear from multiple experiments, theoretical work and field observations from multiple localities that K-feldspar (as well as many other minerals) rounds quickly when subjected to eolian conditions. We argue, based on experimental work and field observations, that supposed ancient ergs should contain an abundance of well-rounded K-feldspar grains (along with other rounded to well-rounded minerals). In field outcrops, it is often easy to establish whether angular K-feldspar grains could have been supplied from nearby crystalline sources or from aqueous sources such as streams or beaches. In the absence of such data, the presence of angular K-feldspar in ancient sandstones should be a reliable indicator of 1) a first-order cycle of at least some of the sediment and 2) aqueous transport and depositional processes of the sandstone being considered. Angular K-feldspar argues strongly against an eolian origin for sandstones especially if it is found centrally located within these ancient sand bodies, 100’s of kilometers from potential sources that could supply angular grains.

In the cases where we found angular K-feldspar in modern desert sand (Figs. 11-12), there was always a nearby source for the angular grains such as an igneous pluton, beach, or wadi. Often these sources were no more than a few kilometers distant. However, when considering whether angular K-feldspar in the Coconino (and its correlatives) were deposited by eolian processes or not, how could angular feldspars reach the center of that giant “erg” without becoming rounded? Angular K-feldspar was not only found along the edges of the Coconino sand body, but *everywhere* we sampled. Samples were collected from the entire exposed breadth and width of the Coconino. Modern observations have shown that angular K-feldspar does not have a reasonable way to be transported to the middle of an erg, except perhaps by fluvial transportation. Observations and experiments show that it is unlikely to be transported more than a few kilometers by known eolian processes without becoming quickly rounded by abrasion. There is no sedimentological evidence within the midst of the Coconino sand body that any of the deposits are beach, nearshore or fluvial in origin, which would be the most reasonable source for the angular K-feldspar.

Many of the Coconino’s correlatives (Fig. 13), and 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 an 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”

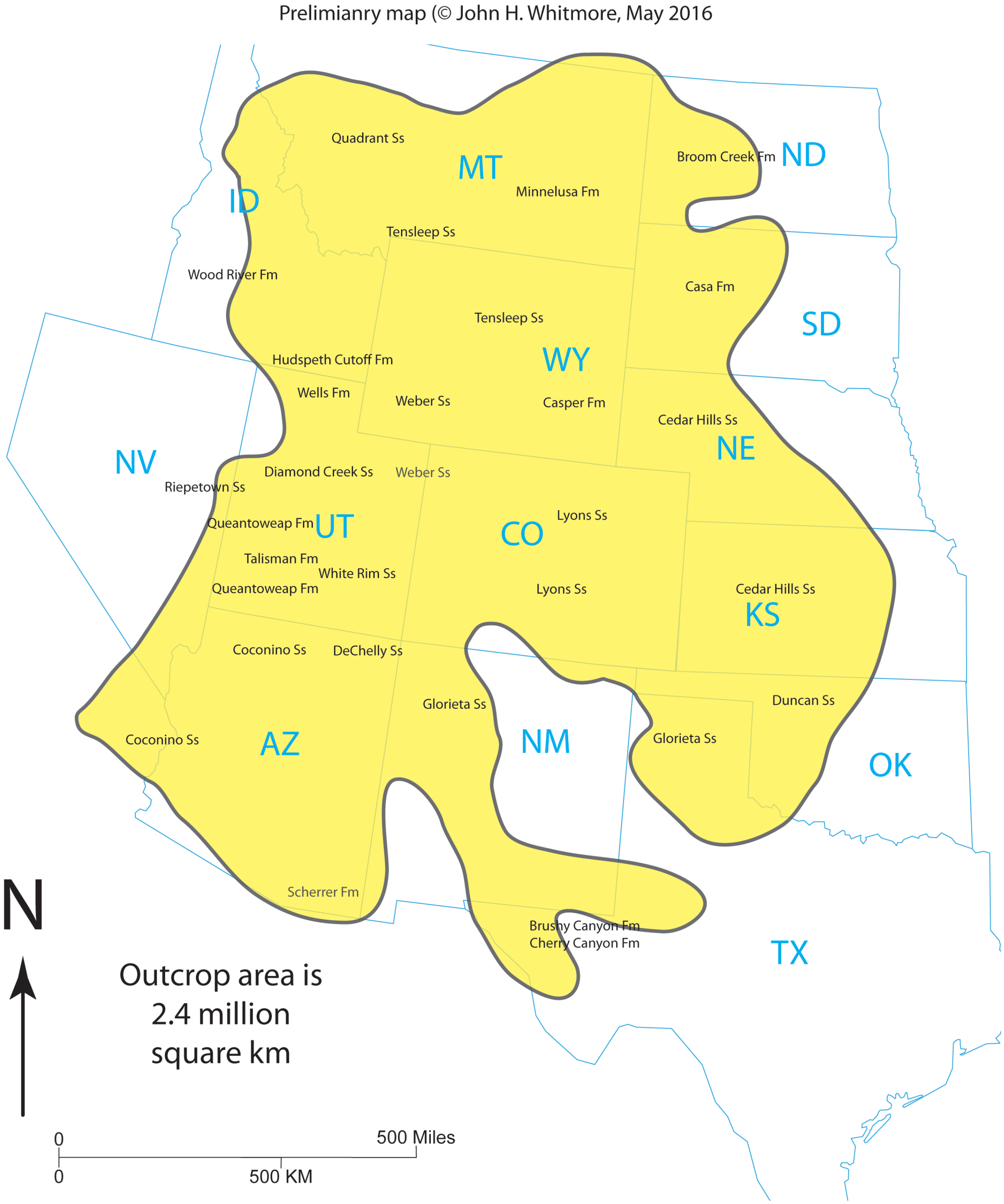

Figure 13. Areal extent of the Pennsylvanian-Permian sandstone sheet that can be correlated as a more or less continuous unit in the western United States that includes the Coconino Sandstone (in Arizona). In general, formations to the north are Pennsylvanian and those to the south are Permian. Preliminary work by Whitmore (2016).

(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. 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, we do not find it surprising that angular K-feldspar grains occur in the Coconino and its equivalents.

It is believed that the source of the Coconino sand, based on analysis of zircons (Gehrels et al. 2011, p. 197), is from the mid-Proterozoic rocks of eastern North America, or possibly, but less likely, from the Ouachita orogen. These authors 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 angular K-feldspar and mica (Borsch et al. 2018), we feel that some type of aqueous transport was primary. Any eolian transport would have quickly rounded the K-feldspars and caused the micas to disappear.

In light of the fact that angular K-feldspars are not expected in eolian sandstones, it is odd that we have these types of grains in so many supposedly eolian sandstones from all over the world, not just the Coconino. Either every one of these sandstones must have had a very nearby K-feldspar source during its deposition, or perhaps they are not eolian. We have not extensively sampled all of the formations in this paper (with the exception of the Coconino). But, with the Coconino in particular, there are no nearby beaches, K-feldspar bearing outcrops or known fluvial deposits within the formation. This might be more likely with some of the other formations mentioned in this report.

Many of the same sandstones that have angular K-feldspars also contain angular grains of quartz, mica flakes (mostly muscovite) and are moderately to poorly sorted (Whitmore et al. 2014; Maithel et al. 2015). In other words, under the microscope these sandstones are not as texturally mature as they might appear to be at the outcrop or assumed to be from their purported eolian origin. As discussed earlier, many criteria for eolian sandstones have been suggested, but very few of the criteria are actually applied except for large scale cross-strata and "high" dip angles.

FURTHER WORK

We encourage further petrographic work on many of the sandstones that we have listed in Appendix I. In the past, detailed microscope work has often been ignored because it can be time consuming to collect, prepare and study the samples. However, this kind of work provides details that are often important for paleoenvironmental interpretations—perhaps even more important than outcrop observations.

Several authors have suggested (Odom 1975; Odom et al. 1976) that K-feldspar is more abundant in sandstones with smaller grain sizes. Work is needed that compares the roundness of similar sized quartz and K-feldspar grains. Similar studies should also be done in modern eolian deposits. This work would be time consuming, but may show some interesting results. We suspect it will show that K-feldspar is often more rounded than similar-sized quartz grains. In ancient sandstones we think it will show that K-feldspar is only slightly more rounded than quartz if not equally rounded as quartz. This could probably be done more easily with modern dunes because those samples can be easily sieved to segregate grain sizes. The process is a bit more difficult with cemented sandstones, but some progress has been made by S. Maithel (2018 personal communication) by using a sonicator to disaggregate sand grains from the Coconino Sandstone as part of her PhD work.

CONCLUSION

K-feldspar sand is often second in abundance to quartz in many ancient cross-bedded sandstones that are often interpreted as partially or completely eolian in origin. On Mohs scale of hardness, K-feldspar has a hardness of 6.0, whereas quartz has a hardness of 7.0. K-feldspar cleaves relatively easily compared to the conchoidal fracture of quartz. Because of these differences, theoretical, experimental, and field observations (in a wide variety of settings) have shown that K-feldspar rounds much easier than quartz in eolian settings. Under aqueous conditions, it is now undisputed that even energetic aqueous conditions (such as longshore currents and daily tidal currents) are insufficient to round any minerals. It is believed that differences in rounding between eolian and aqueous environments are due to the ability of water to cushion impacts between grains; something that air is incapable of accomplishing in the eolian environment, thus causing rapid rounding. In settings where angular sand grains are present on a beach and they are picked up and transported to coastal dunes, rounding has been documented to happen very quickly and over short distances. In fact, many authors now believe that eolian activity is the only reasonable way to round resistant grains such as quartz (see Dott 2003). However, it should be noted that many quartz and K-feldspar grains do not become rounded in eolian settings if a source for angular grains is nearby.

Thus, we argue that when angular K-feldspar sand grains are present in ancient cross-bedded sandstones, especially "blanket sandstones" (Baars 1961), it is a primary criterion that should be considered when determining the origin for a sandstone. We have documented that many supposed eolian sandstones contain angular K-feldspars suggesting that they had an aqueous origin.

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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 data in this table.

Formation	Location and (conventional age)	Selected references and author(s) who made eolian identification (*)	General description and notes about the formation
Aztec Sandstone	California, Nevada (Triassic)	Barca 1960*; Baker et al. 1936*; McKee and Bigarella 1979*; Wilson and Stewart 1967*	Correlative with Navajo Sandstone of Utah. Wilson and Stewart describe as follows (1936, p. 19): "The Navajo or Aztec consists of moderate-orange-pink, yellowish-gray and light-brown fine-grained to very fine grained well-sorted sandstone, typically composed of large wedge-planar sets of high-angle medium- to large-scale cross-laminae." Barca (1960) reports it as 1975 ft. (602 m) thick and identifies it as "eolian." Baker et al. (1936) report a thickness of at least 2100 ft. (640 m) in the Goodsprings Quadrangle (the eroded top of the section is missing). McKee and Bigarella (1979, p. 209) report a thickness of up to 900 m in California.
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 as such 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) thought that it was primarily eolian based on cross-bed spatial variation and architecture. They supposed 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 and Garner 2018 (this volume)	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 Sandstone (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 (Upper Permian) comprises a series of sandstones and conglomerates exposed along the Devon coast of southwest England interpreted 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° (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 Sandstone. It is similar in cross-bed style and appearance to the Coconino Sandstone 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 Sandstone 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 K-feldspar and muscovite in the formation could suggest non-eolian depositional process for these facies.
Locharbriggs 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, beach 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 K-feldspar 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° to 33° (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) interpreted 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. However, 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-07	Coconino Sandstone	Arizona	Permian	36.213	-113.434
AC-04	Coconino Sandstone	Arizona	Permian	36.213	-113.434
ALV-01	Casper Sandstone	Wyoming	Penn-Permian	42.550	-106.723
AP-12	Coconino Sandstone	Arizona	Permian	36.204	-113.379
ARR-11	Corrie Sandstone	Scotland	Permian	55.641	-5.138
ASR-07	Coconino Sandstone	Arizona	Permian	35.041	-112.284
BCT-06	Schnebly Hill Fm.	Arizona	Permian	34.675	-111.664
BCT-08	Schnebly Hill Fm.	Arizona	Permian	34.675	-111.664
BD-02	Bruneau Dunes	Idaho	Modern	42.897	-115.698
BIL-01	Yellow Sand	England	Permian	53.554	-1.265
CAD-04	Montana De Oro Dunes	California	Modern	35.303	-120.875
CDC-01	De Chelly Sandstone	Arizona	Permian	-36.153	-109.539
CHP-02	Casper Sandstone	Wyoming	Penn- Permian	41.046	-105.548
CLN-01	Navajo Sandstone	Utah	Triassic-Jurassic	38.645	-109.736
CM-01	Cedar Mesa Sandstone	Utah	Permian	37.890	-110.370
COW-02A	Penrith Sandstone	England	Permian	54.672	-2.711
CPN-03	Navajo Sandstone	Utah	Triassic-Jurassic	37.102	-112.681
CPN-04	Navajo Sandstone	Utah	Triassic-Jurassic	37.102	-112.681
CPW-37	Coconino Sandstone	Arizona	Permian	35.352	-112.957
CRQ-02	Yellow Sand	England	Permian	54.768	-1.459
GAN-03	De Chelly Sandstone	Arizona	Permian	35.718	-109.464
GAN-04	De Chelly Sandstone	Arizona	Permian	35.718	-109.464
GD-02	Great Sand Dunes	Colorado	Modern	37.743	-105.530
GLD-02	Glamis Dunes	California	Modern	32.993	-115.105
GLO-02	Glorieta Sandstone	Arizona	Permian	35.515	-105.834
GLO-06	Glorieta Sandstone	Arizona	Permian	35.515	-105.834
HMT-06	Coconino Sandstone	Arizona	Permian	36.055	-112.220
HOL-01	Coconino Sandstone	Arizona	Permian	34.834	-110.144
HOP-04	Hopeman Sandstone	Scotland	Permian	57.714	-3.422
HOP-07	Hopeman Sandstone	Scotland	Permian	57.714	-3.422
JTR-01	Navajo Sandstone	Utah	Triassic-Jurassic	37.500	-109.637
JTR-03	Navajo Sandstone	Utah	Triassic-Jurassic	37.500	-109.637
KD-04B	Kelso Dunes	California	Modern	34.735	-115.668
KD-06	Kelso Dunes	California	Modern	34.735	-115.668
KIN-01B	Bridgnorth Sandstone	England	Permo-Triassic	52.448	-2.245
LBG-05	Locharbriggs Sandstone	Scotland	Permian	55.112	-3.582
LSD-07	Little Sahara Dunes	Utah	Modern	39.672	-112.317
LSS-02	Lyons Sandstone	Colorado	Permian	40.220	-105.262
MSD-01	Mesquite Sand Dunes	California	Modern	36.613	-117.117
NAV-15	Navajo Sandstone	Utah	Triassic-Jurassic	38.205	-111.349
NES-14	Nebraska Sand Hills	Nebraska	Modern	42.612	-100.885
NES-18	Nebraska Sand Hills	Nebraska	Modern	42.601	-100.913
NES-23	Nebraska Sand Hills	Nebraska	Modern	42.276	-100.537
NES-32	Nebraska Sand Hills	Nebraska	Modern	41.278	-100.644
NHT-17	Coconino Sandstone	Arizona	Permian	35.997	-111.938
NHT-20	Coconino Sandstone	Arizona	Permian	35.997	-111.938

OC-02	Schnebly Hill Fm.	Arizona	Permian	34.977	-111.746
ORD-02	Florence Dunes	Oregon	Modern	44.013	-124.136
ORD-09	Coos Bay Dunes	Oregon	Modern	43.450	-124.253
ORD-11	Hunter’s Cove Dune	Oregon	Modern	42.312	-124.415
PB-01	Coconino Sandstone	Arizona	Permian	35.236	-112.762
PCT-04	Coconino Sandstone	Arizona	Permian	34.441	-111.423
PCT-11	Coconino Sandstone	Arizona	Permian	34.441	-11.423
PLC-01	Casper Sandstone	Wyoming	Penn-Permian	41.388	-105.484
PLC-06	Casper Sandstone	Wyoming	Penn-Permian	41.388	-105.484
RCR-03	Casper Sandstone	Wyoming	Penn-Permian	41.389	-105.464
RCR-04	Casper Sandstone	Wyoming	Penn-Permian	41.389	-105.464
RRC-01	Lyons Sandstone	Colorado	Permian	38.854	-104.881
RTD-08	Schnebly Hill Fm.	Arizona	Permian	34.680	-111.723
RU-03	Tensleep Sandstone	Wyoming	Pennsylvanian	41.945	-107.332
SBR-09	Coconino Sandstone	Arizona	Permian	34.898	-111.782
SBR-10	Coconino Sandstone	Arizona	Permian	34.898	-111.782
SBR-11	Coconino Sandstone	Arizona	Permian	34.898	-111.782
SCG-14	Navajo Sandstone	Utah	Triassic-Jurassic	40.916	-109.791
SCG-15	Weber Sandstone	Utah	Pennsylvanian	40.916	-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 Sandstone	Arizona	Permian	36.642	-112.053
SRS-01	Navajo Sandstone	Utah	Triassic-Jurassic	38.847	-110.898
SSD-09	Salton Sea Dunes	California	Modern	33.182	-115.853
TC-05	Coconino Sandstone	Arizona	Permian	36.288	-113.330
TEN-04	Tensleep Sandstone	Wyoming	Pennsylvanian	107.352	-44.075
WRC-03	Tensleep Sandstone	Wyoming	Pennsylvanian	43.572	-108.211
WR-02	White Rim Sandstone	Utah	Permian	37.890	-110.411
WR-03	White Rim Sandstone	Utah	Permian	37.890	-110.411
WSC-12	Coconino Sandstone	Arizona	Permian	36.392	-112.301