

Paleoclimate and the Origin of Paleozoic Chert: Time to Re-Examine the Origins of Chert in the Rock Record

C. Blaine Cecil

Scientist Emeritus, U.S. Geological Survey, MS 956, 12201 Sunrise Valley Drive, Reston, VA 20192-0002

INTRODUCTION: THE CHERT PROBLEM

Paradigms regarding the origin of sedimentary chert have remained largely unchanged for decades. Extant paradigms generally focus on some aspect of biogenic extraction and precipitation of silica from seawater without explicitly addressing the primary source of silica (e.g., Gutschick and Sandberg, 1983; Maliva, et al., 1989; Beauchamp and Baud, 2002; Pope and Steffen, 2003). The primary sources of silica in modern oceans have been attributed predominantly to river input with lesser amounts coming from submarine groundwater discharge, dust, seafloor weathering, and hydrothermal vents respectively (Tréguer and De La Rocha, 2013). However, any changes in the order of predominance among these sources through time are unknown. In this paper I reintroduce a rarely discussed paradigm that attributes the predominant source of silica for Paleozoic chert to aeolian deposition of siliceous sediments (hereinafter, dust) (Haught, 1956; Banks, 1970; Cecil, 2004). The dust hypothesis also may help explain chert of nonmarine origin, as will be discussed subsequently. The dust hypothesis is based in part on an apparent empirical correlation between chert occurrence and paleoaridity (Cecil, 2004)*. The empirical correlation between chert occurrence and paleoaridity is further developed herein by comparing multiple depositional environments for Paleozoic chert parent material (CPM) across the conterminous United States (North America craton; NAC) to the paleoclimate maps of Boucot et al., (2013)**. Inferred depositional environments for CPM are derived from the literature (e.g., Hein and Parrish, 1987, Appendix 2-1; among many others), or personal experience. Where applicable, I also present ancillary observations on the relation between arid paleoclimates and the temporal and spatial distribution of quartz arenites whose textural and mineralogical maturity may, in part, be attributed to ancient aeolian processes (e.g., Dott, 2003), regardless of the final depositional environment; such processes could have been major producers of dust.

CPM Depositional Settings

CPM depositional settings discussed herein partially illustrate the myriad of water depths and hydrologic

conditions associated with chert occurrence. Depositional interpretations for Paleozoic CPM examples include the following: a) inferred deep marine along paleo-continental margins, b) shallow shelves and epicontinental seas, c) supratidal environments, and d) nonmarine chert associated with aeolinites. Chert that may have formed on abyssal plains has been lost to subduction. I compare chert examples for each of these settings to paleoclimate interpretations of Boucot et al., (2013).

CHERT: CAMBRIAN TO PERMIAN

Cambrian and Ordovician chert

Examples of CPM in inferred deep water include the Middle and Late Ordovician Bigfork*** and Maravillas cherts in the Ouachita-Marathon structural trend (Goldstein, 1959), and Ordovician chert in the Cordilleran basin margin in Nevada and Idaho (Ketner, 1969). Virtually all these cherts contain dispersed detrital quartz sand and silt (Goldstein, 1959; Ketner, 1969) suggesting aeolian deposition. An arid paleoclimate prevailed across the NAC during the Cambrian and Ordovician (Boucot et al., 2013; Maps 1-4) when CPM was deposited. The source of silica for much of the late Middle and Late Ordovician chert I refer to as deep water has been attributed to upwelling on subtidal ramps (Pope and Steffen, 2003). However, chert is common throughout Cambrian and Ordovician strata across the NAC (Hein and Parrish, 1987) where upwelling does not appear to reasonably account for CPM deposition far removed from inferred zones of upwelling or for detrital quartz in chert.

Both bedded and nodular cherts also occur in Cambrian and Ordovician shallow water carbonates (Hein and Parrish, 1987). In the Appalachian basin (AB), shallow water carbonates contain silicified oolites (Upper Cambrian Mines Dolomite Member, Gatesburg Formation; Early Ordovician Nittany Dolomite, Beekmantown Group; Centre Co. PA), and silicified intraclastic carbonate with pellet structure (Early Ordovician Axemann Limestone of Beekmantown Group, Centre Co., PA) (e.g., Folk and Pittman, 1971) and the Middle Ordovician Lincolnshire Formation in Virginia (Figure 1A). In addition to shallow water chert, Montañez

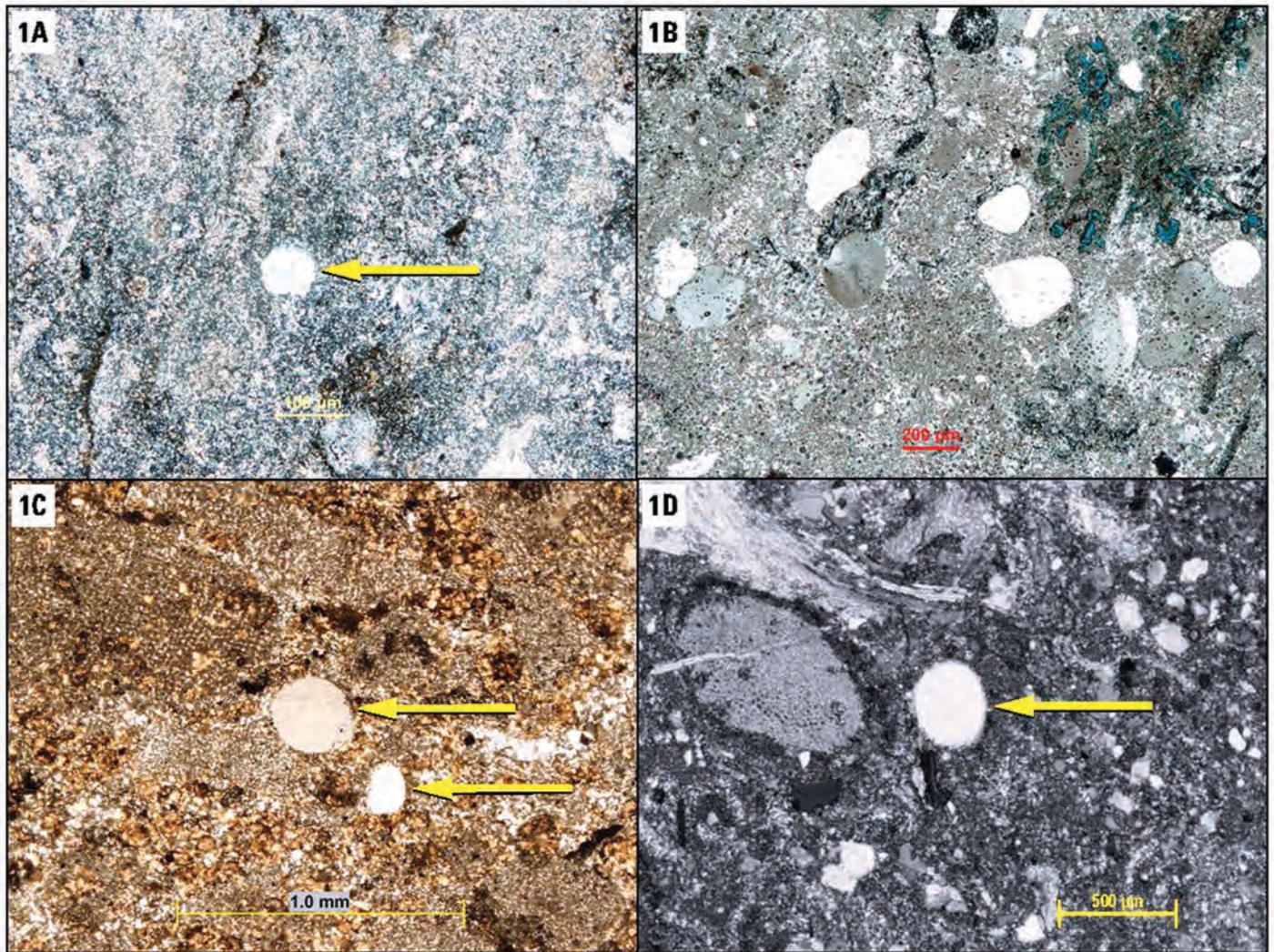


Figure 1: Photomicrographs of chert with quartz detritus floating in chert matrices. The primary source of silica for chert parent material, including detritus, is interpreted to be the result of atmospheric deposition of siliceous dust. 1A. Chert in Middle Ordovician (Blackriveran) Lincolnshire Formation, Rich Patch, VA. Rounded quartz sand grain floating in the chert matrix (arrow). Scale bar is 100 μm . 1B. Devonian (Lochkovian) Shriver Chert, Gosben, VA. Rounded quartz sand grains floating in a chert matrix. Scale bar is 200 μm . Blue color in upper right is light transmitted through mounting medium. 1C. Mississippian (Visean; late Osagean to Meramecian) Warsaw Formation. Sample from road cut, Interstate 55, south of St Louis, MO. Rounded quartz sand grains (arrows) floating in a calcareous chert matrix. Scale bar is 1.0 mm. 1D. Photomicrograph, Permian (Wordian) Rex Chert Member, Phosphoria Formation. Rounded quartz sand grain (arrow) floating in a calcareous chert matrix. Numerous quartz silt grains are also present. Scale bar is 500 μm .

and Read (1992) documented chert replacement of gypsum (cauliflower chert) in supratidal sabkha environments (Late Cambrian to Early Ordovician Upper Knox Group; Maryland, Virginia, and Tennessee). They also noted the presence of quartz silt, and rounded sand grains in the supratidal dolomites (Isabel Montañez, personal communication) consistent with aeolian deposition. The supratidal chert occurrences indicate a probable aeolian source of silica.

ANCILLARY OBSERVATIONS ON ORDOVICIAN SANDSTONES

The origin of Middle to Late Ordovician supermature quartz arenites appears to be related to aeolian processes (e.g., Kelly et al., 2007; Dott, 2003). Well-rounded quartz grains in the St. Peter Sandstone are thought to be indicative of arid aeolian processes (Kelly et al., 2007). Deposition of the St. Peter was approximately coeval with deposition of much of the Simpson Group to the south, including

supermature sandstones in the Arbuckle Mountains, Oklahoma (Dapples, 1955; Ethington, et al., 2012) in settings that were not far removed from the inferred deep water Ordovician chert in the Ouachita-Marathon trend. The sand of the Middle to Late Ordovician Eureka Quartzite (i.e., quartz arenite) in the western NAC is nearly identical to that of the coeval St. Peter and Simpson (Ketner, 1966). These approximately coeval, and morphologically identical supermature sands overlie the sub-Tippicanoe I Sequence boundary of

Sloss (1988), an exposure surface where vast deserts likely existed from the Early Ordovician through most of the Middle Ordovician, a time span of more than 20 myr. Hypothetically, dust derived from Early to Middle Ordovician sand seas may have supplied the CPM in the deep-water settings, as well as shallow water cratonic seas and adjacent sabkhas.

Silurian chert

The Silurian paleoclimate was arid (Boucot et al., 2013; Map 5). Silurian age chert occurrences are relatively minor compared to other time periods (Hein and Parrish, 1987), and will not be discussed further here.

DEVONIAN-EARLY CARBONIFEROUS (MISSISSIPPIAN)

Deep-water chert

Water depth is uncertain in the Ouachita/Marathon structural trend during CPM deposition for the Devonian-Mississippian Arkansas Novaculite (Hass, 1951) and Caballos Novaculite (McBride and Thompson,

1970). McBride and Thompson (1970) suggest water depth in the Marathon basin during Caballos CPM deposition “was probably greater than 300 feet (~90 meters [m]) and may have been several thousand feet (meters) deep”. Hass (1951) recognized three divisions of the Arkansas novaculite; an Early to Middle Devonian lower division, a middle division spanning the Devonian-Carboniferous boundary, and a Mississippian (late Kinderhookian to Osagean) upper division. CPM deposition for the lower division (pure novaculite) was approximately coeval with aridity (Boucot et al., 2013; Maps 6 and 7) and the Early Devonian hiatus that resulted in the sub-Kaskaskia 1 sequence boundary of Sloss (1988). The impure middle division spans the Devonian-Mississippian boundary, when deposition was coeval with the late Famennian and Tournaisian pluvial event in the eastern Laurentia (Appalachian basin) (Cecil, 1990; Cecil, et al., 2004; Brezinski, et al., 2009). Unlike the pure novaculite comprising the lower division when the climate was arid, shale and impure

chert characterizes the middle division when the climate was relatively humid. Relatively pure CPM deposition resumed for the upper novaculite division when the NAC became arid during the Viséan (Osagean).

Deposition of CPM ceased in the Ouachita-Marathon structural trend with the onset of a humid climate over the central and eastern NAC in the Serpukhovian (Mississippian, late Chesterian) (Edgar and Cecil, 2003). CPM deposition in the Ouachita basin was replaced by an influx of siliciclastics (Late Mississippian Stanley Group, the Early Pennsylvanian Jackfork Sandstone, and the early Middle Pennsylvanian Atoka groups respectively). The Caballos Novaculite stratigraphy (Folk and McBride, 1976) is consistent with a similar climatic change interpretation.

Devonian Shallow Water Chert

Early and early Middle Devonian shallow water cherts are widespread across the NAC (Dennison, 1961) when the climate was arid (Boucot et al., 2013, Maps 6, 7, and 8). The examples discussed herein focus on the AB where chert is common from southwestern Virginia into New York. Chert commonly occurs in strata that underlie and overlie the sub-Kaskasia I sequence of Sloss (1988). These accumulations were coeval with the deep-water CPM deposition of the lower division of the Arkansas and Caballos Novaculite. Bedded chert below the sequence boundary in the AB includes the Shriver Chert (Oriskany Group) and the chert-bearing Corriganville Limestone (Helderberg Group) in Maryland and West Virginia, and time equivalent chert in adjacent states. The Huntersville Chert (Figure 2) overlying the sequence boundary consists of relatively pure chert in north central West Virginia (Sheppard and Heald, 1984), grading into chert with minor argillaceous material in southeastern West Virginia. According



Figure 2: Devonian (Eifelian) Huntersville Chert, Frost, WV. Variations in bed thicknesses are interpreted to be the result of fluctuations in dust storm duration and intensity. Person for scale in photo center.

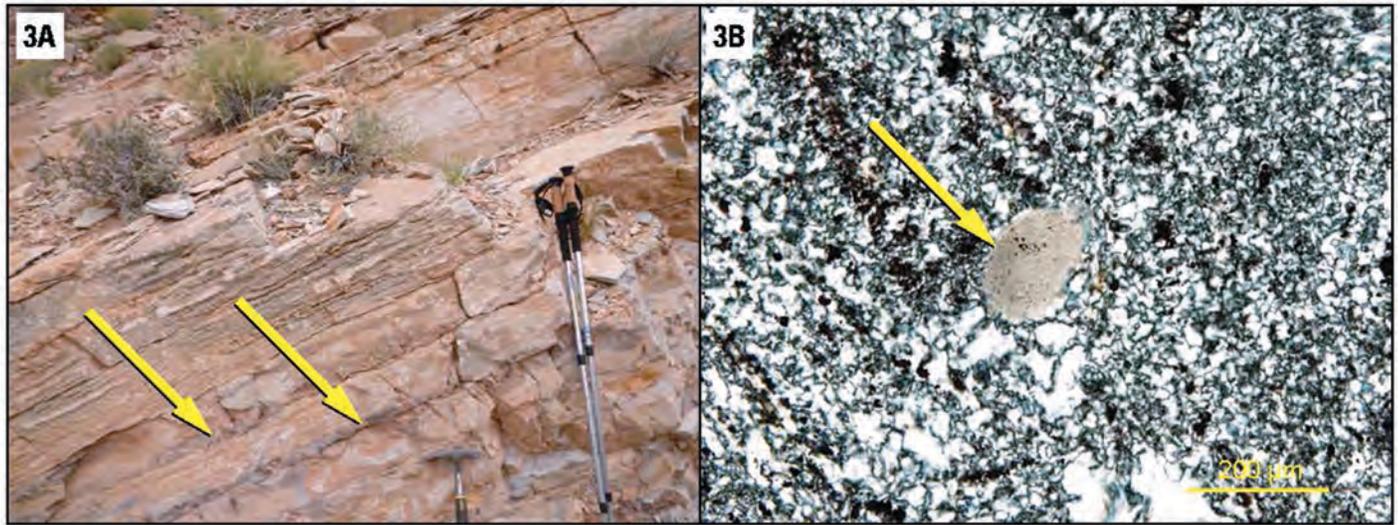


Figure 3: Pennsylvanian (Desmoinesian) Honaker Trail Formation; San Juan River Gorge, Raplee Anticline; Mexican Hat, Utah. **A.** Outcrop photo of cm-scale chert beds (arrows) in peritidal carbonate (walking sticks on right side of photo and hammer, bottom right, for scale). **B.** Round quartz sand grain floating in the chert.

to Sheppard and Heald (1984), “even the cleanest chert in the Huntersville has at least small amounts of dolomite and silt-size (quartz) detritus,” as does the Shriver Chert (Figure 1B). The quartz detritus is consistent with dust as the source of silica.

ANCILLARY OBSERVATIONS ON DEVONIAN SANDSTONES

Devonian quartz arenites (Oriskany, Rocky Gap, and Healing Springs Sandstones, AB; Sylvania Sandstone, Michigan Basin; Dutch Creek and Hoing Sandstones, Illinois basin) underlie and overlie the sub-Kaskaskia I sequence boundary of Sloss (1988). These quartz arenites appear to have been derived from reworking of sand seas during sea level rise (Carman, 1936; Grabau, 1940; Cecil et al., 1991), indicating these sand seas could have supplied quartz-rich dust for chert.

Mississippian shallow water and supratidal chert

The humid climate that developed over the eastern NAC in the late Famennian continued through the Tournaisian (Cecil et al., 2004; Brezinski et al., 2009; Boucot et al., 2013). Chert formation ceased or was

greatly diminished in cratonic seas of eastern Laurentia. With the return of aridity in the Viséan (Osagean, Meramecian, and early Chesterian) (Boucot et al., 2103, Map 10), major CPM deposition resumed across the NAC. CPM deposition sites included the Appalachian basin (Greenbrier Limestone and Fort Payne Formation), mid-continent (Fort Payne, Boone Formation, Burlington, Keokuk, and Warsaw Limestones) and the western U.S. (Redwall, Leadville, and Madison Limestones) (Gutschick and Sandberg, 1983) among many other occurrences. Early Viséan (Osagean) chert is common in environments interpreted as carbonate shelf, shelf edge, and basin/trough (Gutschick and Sandberg, 1983). These authors attributed the primary source of CPM during the late Osagean to upwelling. However, their inferred paleowind direction is not consistent with upwelling. Furthermore, detrital quartz in chert as well as deposition of CPM in epicontinental seas that were far removed from possible upwelling zones also makes upwelling an unlikely source.

Banks (1970) described syngenetic chert in Osagean dolostones within the Leadville Limestone in Colorado and

noted abundant aeolian sand (quartz) in the dolostone members. Banks suggested that the aeolian quartz sand was the most likely, if not the only, source of silica for the syngenetic chert.

Osagean evaporites in subtidal to peritidal carbonates of the Burlington and Keokuk were replaced syngenetically by silica, now in the form of geodes (e.g., Chowns and Elkins, 1974). Chowns and Elkins (1974) noted detrital quartz silt and sand in Fort Payne and Warsaw Formation supratidal dolomites, but they suggested sponge spicules as the source of silica for chert replacement of evaporate nodules. However, detrital quartz sand and silt (Figure 1C), suggests that syngenetic alteration of dust may have been the primary source of silica for biogenic silica as well as chert replacement of evaporites in supratidal, peritidal, and subtidal environments. As with the deep-water chert, CPM deposition ceased in eastern NAC basins with the onset of a humid climate in the late Mississippian (Serpukhovian) (Boucot et al., 2013; Map 11). CPM deposition in cratonic environments (central and eastern NAC) was replaced by accumulations of parent materials for shale, sandstone, and coal.

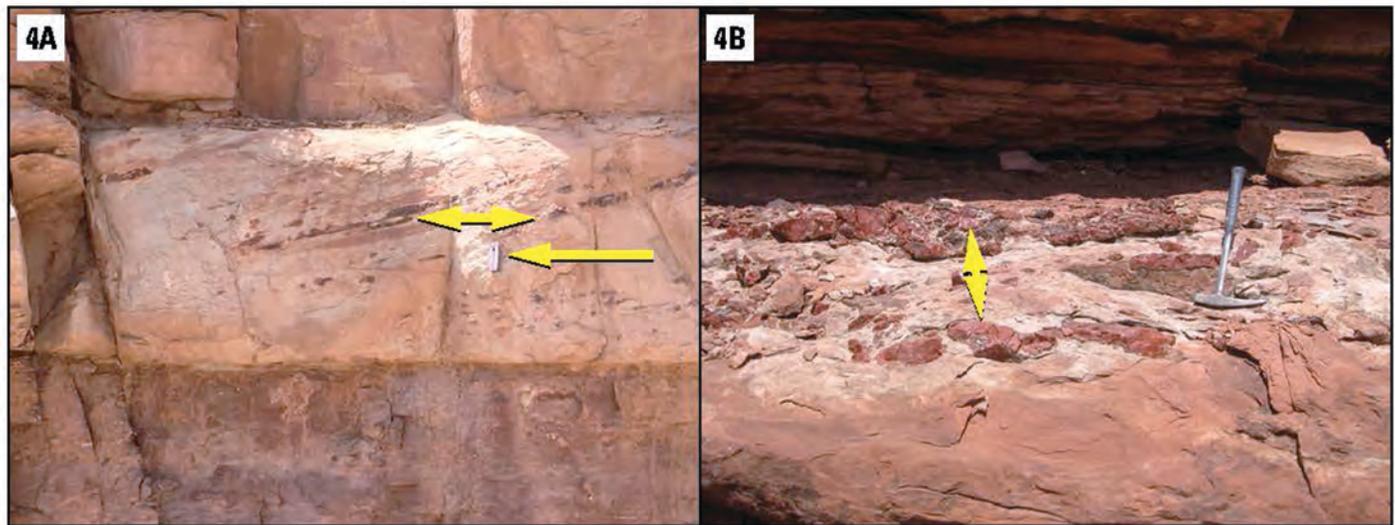


Figure 4: Early Permian, Cutler Group, Cedar Mesa Formation. **A.** Photo of Mokie Dugway road cut (UT RT 261), SE Utah. Dark red bands of chert (jasper) are along interpreted sand sheet facies bedding planes. Two of the chert bands are indicated with double arrow. Knife for scale (single arrow) is 8 cm. **B.** Two beds (double arrow) of red chert (jasper), Indian Creek drainage, SE Utah. Lower chert directly overlies dune facies; upper chert is at or near the top of inter-dune sabkha facies. Hammer, including handle, is 38 cm.

Late Carboniferous (Pennsylvanian) chert

A general perhumid (“everwet”) climate (Boucot et al., 2013, Map 12) prevailed across the eastern and central part of the NAC during most of the Bashkirian and Moscovian (Morrowan, Atokan, and Desmoinesian Series). These humid conditions essentially eliminated low-stand deserts, as evidenced by intense chemical weathering and humid climate paleosols across the NAC (Boucot et al., 2013, p. 113-115). These paleosols delineate the Sub-Absaroka sequence boundary of Sloss (1988).

Pennsylvanian aridity and deserts were restricted to far western Pangea (e.g., Parrish and Peterson, 1988; Soreghan, 1992; Boucot et al., 2013, Map 12) where chert is common in Pennsylvanian marine carbonates. Two examples presented here include the Middle Pennsylvanian Honaker Trail Formation, Paradox Basin, Utah (Condon, 1997), and the Bird Spring Formation, Arrow Canyon Nevada (Cecil et al., 2003; Bishop et al., 2010).

Loope (1985) attributed nonmarine sandstones in marine/nonmarine cycles in the upper part of the Hermosa Formation (Honaker Trail?) in Canyon

Lands National Park, Utah, to aeolian deposition. I observed similar sedimentary cycles in the upper part of the Hermosa Group (Honaker Trail Fm) in exposures along the San Juan River trail near Mexican Hat, Utah, in the Paradox basin. These Missourian (?) age strata contain lowstand nonmarine sandstones (aeolianites) in marine/nonmarine cycles, whereas thin (cm scale) rhythmically bedded red chert occurs in the marine carbonates. The aeolinites in the nonmarine parts of the cycles suggest dust as a possible source of silica for these red chert beds as does detrital quartz in chert matrices (Figure 1D).

Pennsylvanian 4th order sequences in Arrow Canyon, Nevada, are replete with bedded chert, cherty limestones, and decimeter scale fine-grained sandstones interpreted as aeolinites (Bishop et al., 2010; Cecil et al., 2003). Subaerial crusts and microkarst weathering on the unconformity exposure surfaces of marine carbonates suggest a relatively humid weathering during a hiatus in deposition following exposure. Following the weathering interval, fine-grained sandstones and siltstones, interpreted as loessites, were deposited (Cecil et al, 2003). The loessite overlying

the sequence boundary is interpreted to be the result of aeolian sediment delivery initiated by increasing atmospheric high pressure, wind speeds, and climate drying as sea level first began to rise. The loess was ultimately flooded as sea level continued to rise, and is sequentially overlain by peritidal cherty limestone, impure chert, and a cherty open marine limestone capped by an unconformity, the upper 4th order sequence boundary.

Paleowind directions interpreted from aeolian cross-stratification, and paleoclimate modeling (Parrish and Peterson, 1988) indicate that Pennsylvanian strata in Arrow Canyon were deposited down-wind of sand seas in Wyoming, Colorado, and Utah. These sand seas were probable dust sources of proximal loessites (20-80 μm dust size fraction) overlying the 4th order sequence boundaries, as well as chert derived from aeolian dust (< 20 μm fraction) deposition in ever expanding distal marine environments as sea level rose.

ANCILLARY OBSERVATIONS ON PENNSYLVANIAN SANDSTONES

The quartzose sandstones that overlie the Sub-Absaroka sequence boundary

in the Eastern Interior and Appalachian basins are fluvial and relatively immature (Siever, 1957). This textural and mineralogical maturity contrasts sharply with the supermature sandstones associated with older Sloss sequence boundaries that formed under arid paleoclimates. CPM deposition was nearly nil in the humid regions of central and eastern Pangea where there is no evidence for aridity. Sand seas were restricted to western Pangea (e.g., Weber and Tensleep Sandstones) where chert is common in marine carbonates.

Permian chert

CPM for the widespread Permian (Wordian) Rex Chert Member of the Phosphoria Formation (Idaho, Utah, Montana and Wyoming) accumulated in western Pangea under arid conditions when the NAC was situated between 0° and 30 N (Boucot et al., 2013, Map 15). The phosphate, chert, and other constituents in the Phosphoria Formation have been attributed to upwelling (c.f., McKelvey, 1946; Hein et al., 2004). Ketner (2009) suggested that upwelling could not have extended across the broad cratonic expanse of the Rex Chert occurrence. Other workers attribute quartz siltstones in the Phosphoria to aeolian deposition (loess?) in the Phosphoria shelf environments (Carroll et al., 1998). Whether or not there was upwelling in the Phosphoria seaway remains equivocal. Deposition of < 63 µm aeolian dust (siltstones), and in particular the < 20 µm fraction (chert) may have been the primary and predominant source of siliceous sediments in the Phosphoria as well as for the nutrients delivered to the Phosphoria shelf during Late Permian CPM accumulation.

Nonmarine chert

Chert is not restricted to marine environments. Red chert (jasper) occurs in the Early Permian Cedar Mesa Formation in the Paradox Basin,

Utah (Loope, 1985; Mountney and Jagger, 2004). Red chert commonly overlies facies interpreted as inner dune sabkhas or ponds (Mountney and Jagger, 2004) and both underlie and overlie the red dune facies of the Cedar Mesa Formation (sandstone), Utah (Figure 3). Chert also occurs within a facies I interpreted as a sand sheet (Figure 4). The occurrence of chert in this continental setting provides compelling field evidence that dust was the source of silica for CPM rather than upwelling, volcanics, or diagenesis of marine organisms. Dust apparently collected through adhesion to moist silty mud surfaces or was deposited in very shallow saline interdune ponds, as well as the sand sheet facies. It is noteworthy that the dust paradigm is consistent with dust as the source of silica for silcretes (paleosol chert duricrust) that formed under arid to semiarid conditions (Summerfield, 1983).

CONCLUSIONS

When compared to the paleoclimate scenarios included in Boucot et al. (2013), the Cambrian to Permian chert examples herein illustrate that CPM deposition was restricted to regions of paleo-aridity, regardless of age or depositional environment. In contrast, chert is rare or nonexistent when and where the paleoclimate was relatively humid. The empirical correlation between chert occurrence and paleo-aridity is probably not coincidental. The chert-aridity correlation supports the hypothesis that quartz-rich dust might be the primary and predominant source of silica for chert. Furthermore, the enhanced solubility of quartz dust* is a plausible source of silica for silica secreting organisms. Upwelling (e.g., Hein and Parrish, 1987; Maliva et al., 1989) and volcanic processes (e.g., Goldstein 1959) are not as uniformly applicable to the wide variety of CPM depositional models as is dust. Conceivably, CPM dust was deposited

under atmospheric high pressure, which might have driven offshore winds and upwelling along continental margins. Conversely, it seems highly unlikely that upwelling could have supplied silica to the vast cratonic shelves and basins far removed from continental margins. Provenance regions for quartz arenites that owe their textural and mineralogical maturity to aeolian processes are interpreted as probable sources of this quartz rich dust for CPM. Consequently, dust needs to be further considered as a viable source for CPM based on the empirical correlation between paleoaridity and chert occurrences as developed herein.

* Discussion of the importance of enhanced solubility of quartz dust, and dust diagenesis could not be included in this paper because of space limitations (see Cecil, 2004, for a brief overview).

** Paleoclimate maps could not be included in this paper because of space limitations.

*** In so far as possible, geologic names and ages used are in accordance with the US Geological Survey (URL:<http://ngmdb.usgs.gov/Geolex/search>)

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