---

The Importance of Eolian Abrasion in Supermature Quartz Sandstones and the Paradox of Weathering on Vegetation-Free Landscapes
Author(s): R. H. Dott, Jr.
Source: *The Journal of Geology*, Vol. 111, No. 4 (July 2003), pp. 387-405
Published by: The University of Chicago Press
Stable URL: http://www.jstor.org/stable/10.1086/375286
Accessed: 03/12/2013 03:41

---

## ARTICLES

# The Importance of Eolian Abrasion in Supermature Quartz Sandstones and the Paradox of Weathering on Vegetation-Free Landscapes

*R. H. Dott, Jr.*

*Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, U.S.A.*
*(e-mail: rdott@geology.wisc.edu)*

## ABSTRACT

Pure quartz arenites are especially characteristic of lower Paleozoic and Proterozoic strata deposited in nonorogenic settings. A century-long debate over the origin of these remarkably pure sandstones has remained unresolved, largely because they seem nonactualistic. The much greater importance of wind and fluvial processes prior to the Silurian appearance of macroscopic vegetation supported a physical origin, but it is now clear that both multicycling and intense chemical weathering can produce them. Multicycling seemed essential to account for their extreme textural maturity, with the exceptional rounding of many examples pointing to important eolian abrasion. Other attributes such as evidences of mixed sources, upward maturation, association with major unconformities, and an inverse relationship between labile grain content and grain size also were consistent with recycling. A single-cycle origin proven in the modern humid tropics, however, is supported in the ancient record by examples with underlying mature paleosol profiles, chemical etching and lesser rounding of quartz grains, single populations of accessory minerals, downcurrent maturation, dissolution ghosts of labile grains, oversized pores filled with clay, and interstratified pelites composed of only kaolinite or illite. Post-depositional diagenesis also can contribute to maturation either with or without multicycling and may even produce pure, diagenetic quartz arenites in extreme cases. Accounting for the compositional maturity of ancient quartz arenites chemically seems paradoxical without something to stabilize land surface areas long enough to allow intense weathering. Biological crusts or microbial mats composed of complex communities of cyanobacteria, algae, and lichens are here proposed as the likely means of stabilization. Although most familiar today in arid regions, such crusts are known in practically all climatic zones. Apparently they developed early in Precambrian time from marginal marine or lacustrine stromatolites and mats and were the first life forms to invade land long before the advent of vascular land vegetation.

> The man has not yet lived who can adequately describe a grain of sand. (Charles R. Van Hise, 1904)

## Introduction

When I was a student half a century ago, the origin of pure quartz sheet sandstones, then called orthoquartzites, was considered a major puzzle. Together with the origin of dolomite, red beds, black shale, and banded iron formation, they made up a group of seemingly intractable geological problems. Even now, 50-odd years later, their origins are still being debated. Having lived literally upon quartz-rich sandstones for almost 50 years, I have come to regard supermature quartz arenites as nature's finest distillate—almost as remarkable as a pure single malt Scotch whiskey. Can there be anything new of importance to say about such an old problem, which has been reviewed as recently as the 1980s (Dott and Byers 1980; Suttner et al. 1981; Dott et al. 1986; Pettijohn, Potter, and Siever 1987; Chandler 1988)? Rather than new experimental or observational data, I offer some new thoughts about

Manuscript received October 7, 2002; accepted January 9, 2003.

[The Journal of Geology, 2003, volume 111, p. 387–405] © 2003 by The University of Chicago. All rights reserved. 0022-1376/2003/11104-0001$15.00

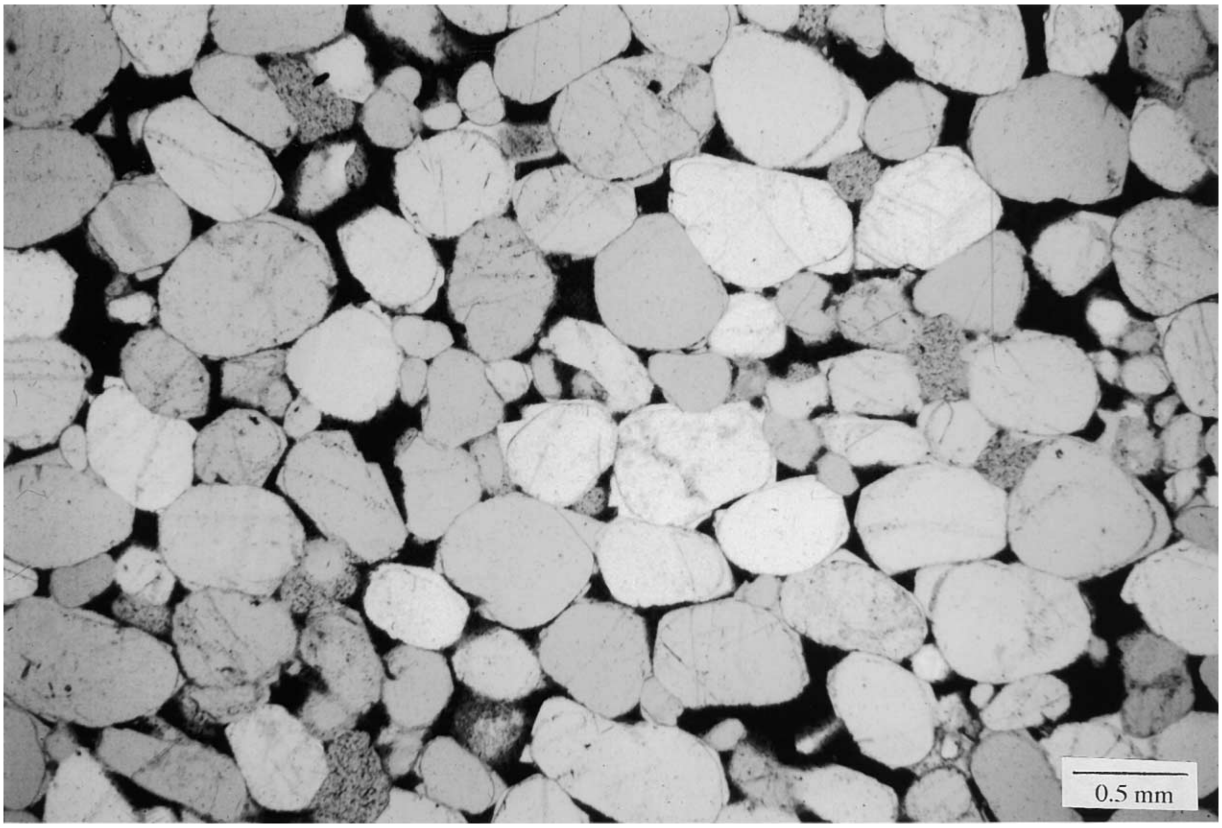

**Figure 1.** Photomicrograph of well-sorted and rounded coarse St. Peter quartz sandstone from Wisconsin, one of the most famous quartz arenites. Incipient quartz overgrowths are visible on many grains (crossed nicols).

the question of single- versus multicycling to explain supermaturity, and I discuss the apparent paradox of very mature chemical weathering on ancient landscapes long thought to be devoid of vegetation.

What is the quartz arenite problem? Foremost is the extreme compositional maturity of sandstones composed of more than 95% quartz. Furthermore, the quartz consists almost exclusively of grains of unstrained, single-crystal units. Very rare lithic fragments consist only of durable polycrystalline quartz types such as chert or vein quartz. In addition, the extremely rare accessory mineral suite (generally <0.05% by weight) is dominated by durable zircon, tourmaline, ilmenite, and leucoxene. Where present, associated conglomerates also consist only of durable clasts of vein quartz, quartzite, or chert. How can we explain the complete disposal of at least 75% of any ultimate parent igneous or metamorphic rock to yield a residue that is at least 95% quartz sand?

Extreme textural maturity is also characteristic of many, but not all, examples. A high degree of sorting has always been emphasized, with high rounding being common but not universal (fig. 1). Both properties imply much abrasion by one or more of nature's most physically vigorous processes, such as surf and strong eolian or aqueous currents. Early writings also emphasized frosting of quartz grain surfaces, which was attributed to an important history of wind abrasion by analogy with sand blasting. Even before 1940, experiments showed the great superiority of wind over water abrasion of sand and showed that for grain sizes smaller than 0.1 mm, little or no significant abrasion of quartz occurs even in wind (Daubrée 1879; Ziegler 1911; Galloway 1922; Knight 1924; Thiel 1940); finer sizes of denser accessory minerals, however, could still become well rounded (fig. 2), grain mass being more important than diameter alone. With new abrasion experiments, Kuenen (1960*a*, 1960*b*) quantified the superiority of wind abrasion by finding that it reduces grain mass 100–1000 times faster than water abrasion (fig. 3).

A thin, tabular geometry was considered another characteristic of pure quartz arenite formations,

**Figure 2.** Photomicrograph of well-rounded accessory minerals from the St. Peter Sandstone, Wisconsin (zircon, tourmaline, garnet, ilmenite; grain mount in plane-polarized light).

which earned the nickname "sheet sands." The originally cited examples were several lower Paleozoic formations in the Great Lakes region of North America. Most are but a few tens of meters thick, but they extend laterally over vast areas encompassing one or several states. A paucity of associated shale in contrast with most other sandstone successions was cited as yet another puzzling characteristic of the sheet sandstones. The original examples are instead interstratified with shallow marine carbonate strata, which prompted F. J. Pettijohn (1957) to coin the term "orthoquartzite-carbonate suite." Clay-sized material was thought to have been winnowed through multicycling by wind and shallow marine processes, and it was thought that much of it escaped from the craton to the deeper continental margins (Dalrymple et al. 1985).

A nonactualistic lack of volumetrically significant analogues forming today was another puzzle, which has invited speculations about different weathering processes in the distant past. It was noted early that the apparent lack of pre-Silurian land vegetation was probably an important factor. Not only might weathering processes have differed but also the influences of wind and rivers might have been orders of magnitude greater than during the past 400 m.yr. since macroscopic land plants appeared (Schumm 1968). The abrasion, sorting, and transport of sand would have been far more efficient without the inhibition of macrovegetation. According to conventional wisdom, physically less durable minerals would be more quickly reduced in size and winnowed away, whereas quartz sand grains would be more quickly rounded, frosted, and sorted on barren landscapes.

Early treatments of the quartz arenite problem attributed a dominant role to wind. C. P. Berkey (1906), the first person to consider the pure quartz sandstone challenge in detail, argued for wind as the most important process on the basis of frosting, rounding, and sorting of grains of the Ordovician St. Peter Sandstone in the upper Mississippi Valley region. Similarly, A. W. Grabau (1913) and Twenhofel and Thwaites (1919) supported an eolian origin for this sandstone, probably the most famous of all orthoquartzites, but they postulated a final transgressive marine reworking. In 1921, C. L. Dake likewise acknowledged initial wind abrasion but posited complete marine reworking for the St. Peter Sandstone on the basis of the presence of some burrows and very rare body fossils. Thiel (1935) concurred with Dake in postulating marine deposition but argued for numerous spasmodic retreats of the shoreline to allow repeated abrasion of the grains by wind.

In 1955, E. C. Dapples reiterated the transgressive marine origin in a regional synthesis of the St. Peter Sandstone. His extrapolation to southern Oklahoma and Arkansas, where the correlative Simpson sands intertongue with the marine Arbuckle Dolomite, doubtless strengthened the overall marine idea of Dake. The marine dogma was not challenged until extensive eolian features were identified 30 yr later in the St. Peter Sandstone as well as in some Cambrian quartz arenites in Wisconsin and northern Illinois (Huazhao and Dott 1985; Dott et al. 1986), Missouri (Lee and Byers

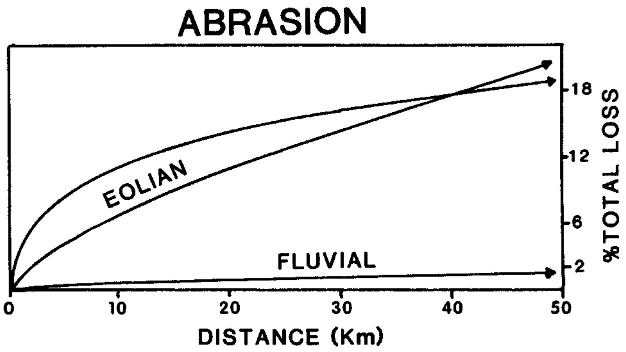

**Figure 3.** Graph showing much more effective abrasion by wind than water based on laboratory experiments by Kuenen (1960*a*). The upper eolian curve is for lithographic limestone; the lower is for quartz grains; the water curve is for quartz. The sand at the beginning of runs averaged 1–2 mm in diameter.

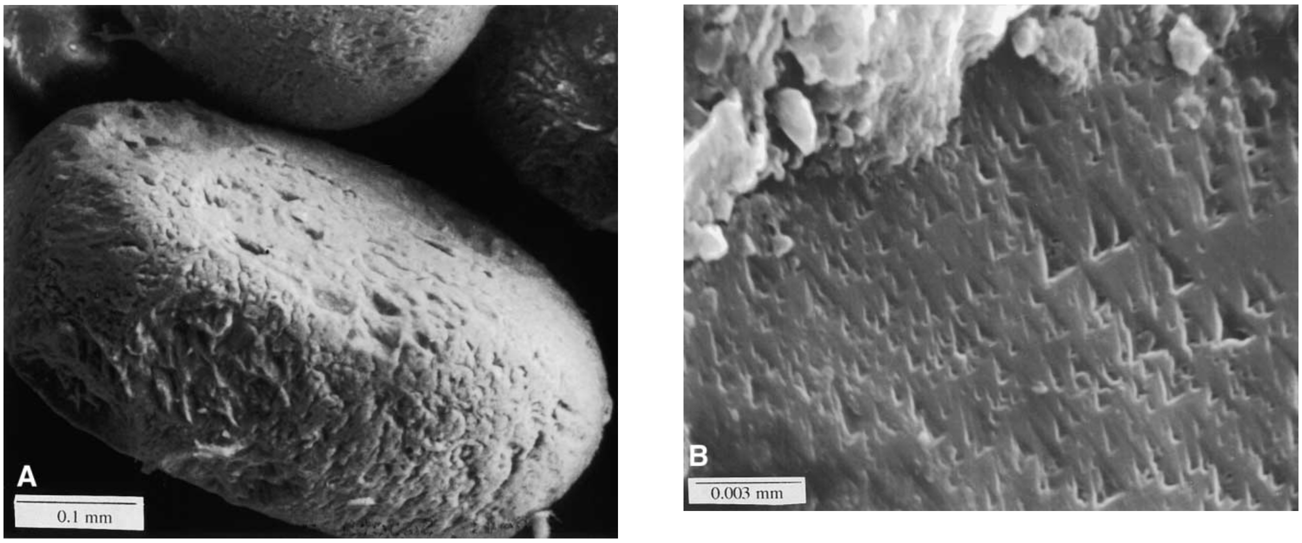

**Figure 4.** Scanning electron microscope images of contrasting grain surface textures. *A*, Well-rounded, wind-abraded quartz grain (0.55 mm long) from the St. Peter Sandstone, Wisconsin, with characteristic surface texture (from Winfree 1983). *B*, Chemically etched quartz sand grain from Padre Island, Texas, showing characteristic V-shaped pits (from Baker 1974).

1992), and western Michigan (Nadon et al. 2000). Cambro-Ordovician eolian components have also been recognized in Ontario (Lewis 1971; Wolf and Dalrymple 1985; MacNaughton et al. 1999, 2002), northwestern Canada (MacNaughton et al. 1997), and Sweden (Wallin 1990).

## Quartz Arenite Myths

Investigations since 1960 have required some reframing of the quartz arenite problem. The most important refinements can be summarized in terms of four myths:

***Compositional Purity.*** Graham (1930) and Odom (1975) showed for the Cambro-Ordovician examples of the Great Lakes region that purity is a function of grain size. Although the medium-grained and coarse-grained sandstones possess more than 95% quartz, interstratified fine-grained sandstones and siltstones contain as much as 50% K feldspar. Doe and Dott independently discovered the same grain-sized dependence in Pennsylvanian and Jurassic sandstones in Utah (Odom et al. 1976). Therefore, obviously, any discussion of the origin of sandstone maturity should specify grain size. The notable absence of plagioclase implies chemical degradation of this less stable species coupled with the more rapid physical breakdown of surviving K feldspar than of quartz.

***Textural Characteristics.*** The frosting or microroughness of sand grains is now known to have several causes besides wind abrasion. Kuenen and Perdok (1962) demonstrated the importance of chemical dissolution as a major cause, which discredited the longstanding myth that frosting proved eolian abrasion. The scanning electron microscope (SEM), while confirming the importance of solution, has also revealed minute precipitates on grains as another cause of a frosted luster. Moreover, the SEM has shown that different processes of abrasion tend to produce distinctive micropatterns and that frosting is not characteristic of eolian sands (fig. 4; Krinsley and Doornkamp 1973). These surface textures coupled with Fourier shape analysis have been used to discriminate changes of process or deposition in seemingly monotonous quartz arenites (Mazzullo and Ehrlich 1980, 1983).

Rounding, like composition, is also a function of grain size in quartz arenites, as was implied by the early abrasion experiments. This was verified empirically by Graham (1930) and subsequent students of the Cambro-Ordovician sandstones of the upper Mississippi Valley region. It may be significant that the lower Paleozoic and Precambrian quartz arenites tend to be coarser and better rounded on average than most younger Phanerozoic examples, which formed after the appearance of macroscopic land plants. Goudie and Watson (1981) found rounded grains to be rare among modern eolian dune sands, but most of these sands fall into the finer sand sizes, which cannot be expected to be well rounded.

Bimodal texture with the coarse mode in the range of 0.5–1 mm mixed with finer grains in the range of 0.09–0.18 mm was suggested by Folk (1968) to be characteristic of eolian dune sands mixed with finer interdune material. Although this is one possible origin for such a texture, it can hardly be the only one. Additional causes of mixing of different-sized populations include thorough bioturbation and infiltration by fines.

***Shale.*** Although most outcropping Cambro-Ordovician examples in the Great Lakes region have remarkably little interstratified shale, their subsurface equivalents are now known from cores to have considerable amounts. This is especially true in Iowa, which was offshore during deposition of the lower Paleozoic sandstones seen in Wisconsin and Minnesota outcrops (Runkel et al. 1998). Considerable shale is also present in cores from the Michigan Basin (Nadon et al. 2000). Clearly, as in younger strata, different depositional environments account for the relative abundance of shale. The original concept of pure quartz sheet sands was biased by their outcrop distribution and the lack of subsurface information when the concept evolved prior to 1960. The shales associated with lower Paleozoic quartz arenites are also compositionally mature, as indicated by their high kaolinite or illite content. (See Medaris et al. 2003 for Precambrian examples and Van Houten and Bhattacharyya 1979 for Paleozoic examples with kaolinite; my deceased colleague, S. W. Bailey, x-rayed many Cambro-Ordovician shales and found only illite.)

***Geometric and Stratigraphic Distributions.*** Dapples (1955) and later Klein (1982) explained the sheetlike geometry of Paleozoic examples by transgressive reworking of sand that had been spread initially by nonmarine processes. In support of this hypothesis, Wolf and Dalrymple (1985) reported Cambrian eolian and fluvial sandstones overlain by marine ones in Ontario, and Dott et al. (1986) found preserved lower eolian overlain by marine sandstones in both Cambrian (Wonewoc) and Ordovician (St. Peter) sandstones in Wisconsin. Runkel (1994), however, showed that simple progradation better explains the sheetlike geometry of the Cambrian Jordan Formation of Minnesota and Wisconsin, proving multiple causes for tabular geometry.

In reality, the importance of sheetlike geometry was biased because the early studies of North American lower Paleozoic cratonic examples were based on outcrops only. The apparently sheetlike St. Peter Sandstone, for example, is now known to be more than 300 m thick in the Michigan Basin. Even thicker is the Cambro-Ordovician quartz-rich succession across North Africa and Arabia (Burke 1999; Burke et al. 2003). There, shale-poor sandstones blanket the northern Gondwana craton. Contemporaneous fine clastics apparently escaped to form sediment wedges on the continental margin, which were later dismembered by the breakup of Pangea (Burke et al. 2003).

Students of the Precambrian sedimentary record have long known of many thick quartz arenites of Proterozoic and even Archean ages (Donaldson and Ojakangas 1977), but most sedimentologists were little aware of these until recently. In reality, there are far greater volumes of pure quartz arenites in the Precambrian than in the Phanerozoic record. They occur on most continents, and many are hardly sheetlike, being hundreds to thousands of meters thick. Pettijohn, Potter, and Siever (1987) and Chandler (1988) have cataloged many examples. Thickness is primarily a function of tectonics because it controls accommodation space. In some cases, enough well-sorted, pure quartz sand was delivered to keep pace with subsidence, resulting in thick, well-sorted quartz arenite deposits. Where subsidence outpaced deposition, however, quartz sand "spilled over the edge into an alien tectonic milieu," as Krumbein and Sloss (1963, p. 551) so aptly put it. In some such cases, resedimentation produced poorly sorted quartz wackes with rounded quartz grains suspended in a fine matrix, which is a rather common Proterozoic sandstone species.

## Multiple Origins

***Multicycle.*** Conventional wisdom of the mid-twentieth century emphasized multicycling to explain both the compositional and textural maturity of pure arenites. Less stable sand-sized minerals were progressively reduced in size through countless cycles of abrasion, leaving only physically and chemically durable quartz and the most stable accessory minerals. Given hundreds of millions of years of subaerial exposure of the craton prior to the Late Cambrian transgression, multicycling seemed inescapable with high degrees of sorting and rounding as inevitable consequences. As Kuenen observed, "There is always the possibility that a sleeping grain will be re-awakened or that a buried one will become the victim of body-snatching" (1960*b*, p. 111).

Long-cited proofs of multicycling are pebbles of older quartz sandstones and sand grains with abraded overgrowths (fig. 5). Also strongly suggestive is an inverse relation between feldspar content and grain size in some quartz arenite–bearing successions (Odom 1975; Odom et al. 1976; Dutta et

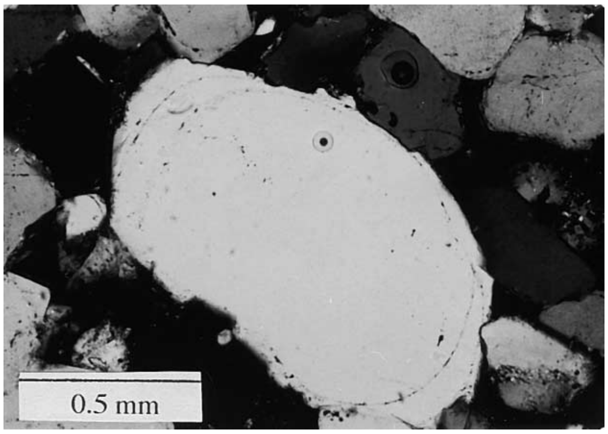

**Figure 5.** Photomicrograph of multiple abraded overgrowths on a coarse quartz sand grain from the Weber Sandstone of northern Utah (Pennsylvanian age), proof of recycling (crossed nicols).

al. 1993). This indicates progressive, selective reduction of feldspar grains and the segregation of distinct beds of finer feldspathic sandstones interstratified with coarser pure quartz ones, which seems to demand multicycling to separate the two so completely. Less diagnostic, but implying probable recycling, are accessory mineral grains and inclusions in quartz grains that show mixing from multiple, distant Precambrian sources but negligible contributions from the immediately underlying basement (Thiel 1935; Tyler 1936; Tyler et al. 1940). Isotopic analyses of U-Pb in detrital accessory zircon and Sm-Nd in quartz from the same formations confirm those early, petrographic arguments about mixed provenance and also imply recycling for Cambro-Ordovician cratonic examples (Johnson and Winter 1999) and for Cambrian sandstones in the Appalachian region (Gaudette et al. 1981; McLennan et al. 2001). Also suggestive of redeposition are the progressive upward increase of maturity from lithic and/or feldspathic basal sandstone to pure quartz arenite in many Proterozoic and some Phanerozoic formations and a common association of quartz arenites with major regional erosional surfaces.

North America's most widespread cratonic supermature sandstones directly overlie the major sequence-bounding surfaces of Sloss (1963). Famous examples include the Cambrian Mount Simon and Wonewoc Sandstones, Ordovician St. Peter Sandstone, the Devonian Oriskany Sandstone, and their equivalents in the north-central United States. Ventifacts also occur widely on the basal Cambrian unconformity (Tank 1970; R. H. Dott, Jr., pers. observ.), which attest to a long history of eolian abrasion and dispersal of quartz-rich sand prior to reworking by the Cambrian transgression. The craton surface had been subaerial for more than 500 m.yr., during which time it acted as a vast sand reservoir that was recycled and purified countless times by fluvial and eolian processes. This also must have happened repeatedly during Precambrian time.

***Single Cycle.*** Even 50 yr ago, an occasional voice asked if first-cycle quartz arenites were possible. Under intense tropical weathering, was it not conceivable that a very pure quartz sandy residual soil might form? Especially if the atmosphere were more corrosive in Early Paleozoic time? The great paucity of feldspar, especially plagioclase, and ferromagnesian minerals implied at least some role for chemical weathering, and some recent studies of modern sands in the humid tropics confirm resoundingly that single-cycle quartz arenites are indeed possible.

First-cycle quartz arenites are forming today in tectonically diverse settings in the Orinoco drainage basin, and some are being delivered to that third-largest river's delta (Johnsson et al. 1988, 1991). Low-lying portions of the Guyana shield with widespread, intensely weathered Precambrian crystalline rocks are drained by tributaries carrying sand so pure that their sand bars "look like they were made of sugar" (R. Meade, written comm. 1988). The higher plateaus of the Gran Sabana are underlain by nearly flat-lying, Late Proterozoic Roraima Group quartz-rich fluvial sandstones (Long 2002). Weathering there is so extreme that quartzites capping many of the buttes, called "tepuis," are extensively karsted by acidic waters with pH 3.5–4.7 (Briceno and Schubert 1990). Tributaries draining this higher terrain also carry quartz-rich sand, but with a few percent feldspar and some lithic plutonic fragments. Thin sections of Roraima sandstones show thorough silica cementation with interlocking boundaries. Although some samples reveal rounded primary grain margins, modern weathering exposes mostly the angular surfaces of syntaxial overgrowths; therefore, rounding of the resulting sands is low. Thus, even recycled Roraima quartz grains, as well as those derived from the low shield now carried by the Orinoco, are poorly rounded.

In contrast with the shield, tributaries draining the northern Andes Mountains of western Venezuela and Colombia, such as the Rio Apure, carry in their upper reaches angular, compositionally immature sands rich in lithic fragments, feldspar, and polycrystalline quartz (Johnsson et al. 1988). As those tributaries cross the foreland llanos, however, their sands become progressively more mature as plagioclase, polycrystalline quartz, and foliated lithic fragments decrease with distance. Much sand is stored in alluvial deposits on the llanos for centuries to millennia, where it undergoes further maturation by chemical solution before being returned to the active river bed by bank erosion. Tributaries that drain only lowland alluvial areas carry pure quartz sand. The accessory mineral suite also experiences selective dissolution during storage, but less so than the bulk mineralogy (Morton and Johnsson 1993).

The Orinoco Basin studies show clearly that first-cycle quartz arenites not only are possible but can form on a large scale and with a reasonable degree of preservation potential. Clearly, humid tropical weathering will produce quartz arenites wherever temporary storage of sediment can occur either in soils or in alluvium. Johnsson et al. (1988, 1991) consider the presence of lithic fragments and abraded syntaxial overgrowths to be the only unambiguous criteria for multicycling. They question rounding as a criterion because the grain surfaces of Orinoco sands are covered with chemical etch pits and larger embayments. In this opinion, they join earlier authors in regarding dissolution to be at least as important as abrasion in rounding quartz sand (Galloway 1919; Crook 1968; Pye and Mazzullo 1994). As noted above, however, the SEM allows one to discriminate between these two modes of rounding (fig. 4). Moreover, the scale of curved grain boundaries is different, with abraded ones typically having larger radii than chemically etched ones.

***Diagenesis.*** Yet another suggestion for making supermature quartz sandstones is diagenesis, whereby all unstable mineral constituents have been dissolved away after deposition to leave only quartz sand grains cemented by carbonate or silica (McBride 1985, 1986). Documentation of chemical purification of sands stored in alluvial plains is one of the most significant results of the Orinoco studies, but should their origin be regarded as first-cycle or diagenetic maturation? Most writers about diagenetic quartz arenites have had in mind a later stage in the history of a sandstone, namely, burial diagenesis. Studies during the past 20 yr have confirmed that labile constituents can be removed chemically from deeply buried sandstones on a significant scale, but there are petrographic and SEM clues to alert us to this phenomenon. These include oversized pores, severely etched skeletal grains, and clay or other postdepositional replacements of grains (Ramaekers 1981; McBride 1985; Anderhalt and Slow 1988; Harris 1989). The most important role of diagenesis is in augmenting the purification of either first-cycle or multicycle sandstones rather than being the dominant agent for their creation.

## Can We Hope to Distinguish Origins?

Granted the validity of all three mechanisms for forming supermature quartz arenites, is there any hope for distinguishing their relative contributions to the rock record? Dake (1921) was pessimistic because extreme maturity provides few clues, and most textural and compositional properties can be inherited through many episodes of recycling by different processes, which compounds the difficulty of interpretation. Similarly, Johnsson et al. (1988) concluded from their Orinoco studies that "the discrimination between first- and multi-cycle quartz arenites is exceedingly difficult" (p. 275).

Diagenetic quartz arenites seem the easiest to recognize using the petrographic criteria noted above. What about first-cycle versus multicycle origins? Together with Kuenen, I believe that the prosaic property of rounding is a more profound criterion than is generally acknowledged. Although most authors since Berkey (1906) have noted the remarkable rounding in the older quartz arenites, just how remarkable it is can only be appreciated by comparisons. Figure 6 provides a visual qualitative comparison of modern Orinoco River sands with Cambro-Ordovician arenites; figure 7 shows a quantitative comparison. Scanning electron microscopic images of grain surfaces from these two regions also indicate a distinction. Many of the Orinoco sand grains show clear chemical etch pits (fig. 4*B*), whereas many of the most rounded Cambro-Ordovician grains show very different surface features characteristic of eolian abrasion (fig. 4*A*). The SEM evidence concurs with the abundant experimental evidence that wind abrasion was the most probable agent for developing the remarkable rounding seen in most ancient quartz arenites. Based upon observations in the Bay of Fundy, Balazs and Klein (1972) suggested that vigorous, frequently repeated abrasion on tidal sand bars might produce extreme rounding equivalent to that by wind. Middleton and Davis (1974), however, showed that the Bay of Fundy examples had inherited their rounding from Jurassic eolian sandstones exposed in nearby cliffs. Rounding once gained is a property that is difficult to reduce, so it may be inherited through many cycles of subsequent deposition by different processes.

Applying the rounding test to some other ancient quartz arenites supports its potential for distin-

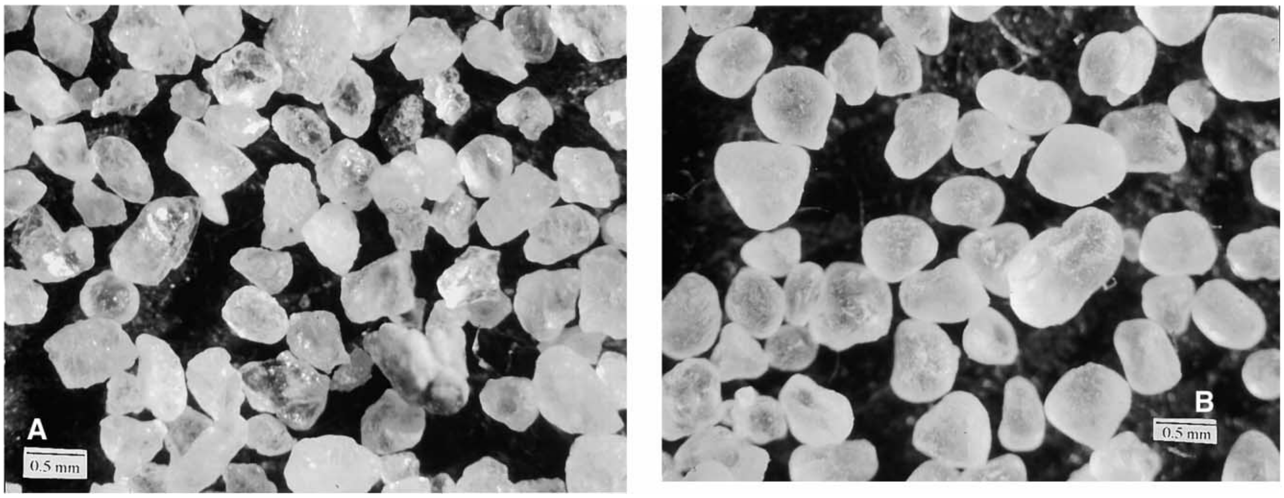

**Figure 6.** Shape contrast between first-cycle and multicycle quartz sands. *A*, Modern, first-cycle Rio Apure (Venezuela) sand showing angular to subangular, unmounted, medium-sized quartz grains. Sample courtesy Robert H. Meade from 15 km above the confluence of Rio Apure with Rio Orinoco (incident light). *B*, St. Peter Sandstone (Wisconsin) multicycle eolian sand showing a high degree of rounding of unmounted medium to coarse quartz grains (incident light).

guishing origin. The vast Nubian sandstone succession, which extends from Arabia across northern Africa to Mauritania, contains pure quartz sandstones of several ages ranging from Carboniferous to Cretaceous. All were deposited on the Afro-Arabian portion of the Gondwana craton, which was equatorial during Mesozoic time. Much of the Cretaceous portion in Egypt and Libya onlapped unconformably over a Precambrian–Early Paleozoic crystalline basement of gneisses, metasediments, and granites. Although there was a small contribution from the old metasediments, most of the sandstone appears to be first-cycle quartz arenite analogous to the modern Orinoco sands. Harms (Klitzsch et al. 1979; Harms et al. 1982; and J. C. Harms, written comm. 1988) interprets them as derived by intense humid, tropical weathering of the underlying crystalline basement. They were transported north across a well-vegetated alluvial plain as attested by the presence of plant remains and paleosols with root traces. Intercalated shales and paleosols contain chemically mature kaolinitic clays (Van Houten and Bhattacharyya 1979). Thanks to slow subsidence, accumulation rates were relatively slow; therefore, sediment could reside for extended periods in the alluvial plain before being reworked by the rivers. As in the Orinoco Basin, this provided ample opportunity for the sands to be further matured by organic acid–rich groundwater passing through them. Although compositionally very mature and well sorted, the Cretaceous sandstones do not display the high degree of rounding typical of the more ancient examples cited earlier; rather, they resemble closely the first-cycle Orinoco sands (cf. fig. 8*A* with figs. 1 and 6).

Another example of an ancient first-cycle quartz arenite is the Late Jurassic Springhill Sandstone of Isla Grande, Tierra del Fuego, in southern South America, which is the principal petroleum reservoir of that region. It overlies unconformably a slightly older, weathered Jurassic silicic volcanic complex (Rocas Verde) and is composed almost entirely of grains of volcanic quartz; feldspar and other labile materials were entirely eliminated by weathering and diagenesis. Like most of the Cretaceous Nubian sandstones, however, the grains are not well rounded (fig. 8*B*). The Springhill Sandstone is cemented largely by well-crystallized kaolinite.

Like the famous lower Paleozoic quartz arenites, many Precambrian examples are dominated by well-rounded quartz grains (fig. 9). Examples in the Lake Superior region include the approximately 1700 Ma Baraboo-Sioux-Barron quartzites. Although these are interpreted as largely braided fluvial grading upward into very shallow marine sands (Dott 1983; Ojakangas and Weber 1984), the presence of scattered well-rounded grains suggests an important earlier eolian history. Several formations in the Canadian Shield still have preserved eolian portions: the 1750 Ma Hornby Bay Group (Ross 1983; Bowring and Ross 1985) and Thelon Formation (Jackson et al. 1984; Miller et al. 1989) as well as the 1750–1780 Ma Athabaska Group (Ramaekers

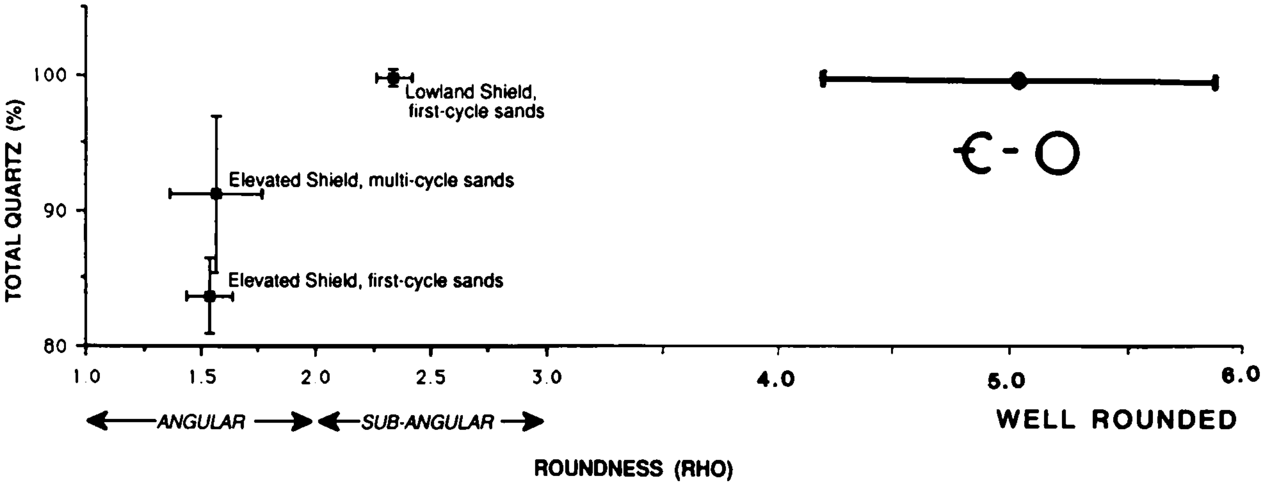

**Figure 7.** Quantitative roundness values for modern Orinoco River medium-grained sands (after Johnsson et al. 1988) compared with Cambro-Ordovician medium-grained and coarse-grained quartz arenites from Wisconsin. Bars for Orinoco values indicate 95% confidence intervals; the bar for Wisconsin samples indicates the total range of values for approximately 500 grains from three formations (rho scale is a logarithmic transformation of the original 0–10 powers roundness scale).

1981; Kotzer et al. 1992). In Scandinavia, the 1635 Ma Dala Sandstone of Sweden has clear eolian stratification (Pulvertaft 1985). The Waterburg Supergroup of South Africa also contains eolian components (Meinster and Tickell 1976; Eriksson et al. 1999), and the Witwatersrand strata have ventifacts (Els 1998). Neoproterozoic eolian deposits are known in the Zambian Copper Belt (Garlick 1981; R. H. Dott, Jr., pers. observ.) and in the Shikaota Formation of India. The latter contains a superbly preserved eolian sand sheet with dune, wind ripple, and adhesion structures (Chakraborty and Chakraborty 2001). In Australia, the Mount Guide Quartzite has adhesion structures (Simpson and Eriksson 1987), and the Neoproterozoic Wyalla Sandstone of South Australia contains well-rounded quartz sand dispersed by wind across a periglacial surface that contained sand-wedge polygons (Williams and Tonkin 1985). This is but a limited catalog; no doubt many more examples of ancient eolian quartz arenites have been recognized already or will be in the future.

## Precambrian Paleosols

Many Precambrian paleosols have been recognized in recent years, and most are surprisingly similar to recent soil profiles (Gay and Grandstaff 1980; Southwick and Mossler 1984; Zbinden et al. 1988; Rainbird et al. 1990; Retallack and Mindszenty 1994; Ohmoto 1996; Driese 2000; Medaris et al. 2003). At least two Precambrian laterites have been identified (Gutzmer and Beukes 1998; Marmo and Ohmoto 2000). According to Ohmoto, practically all of these paleosols show evidence of oxic conditions, with at least 1.5% (Ohmoto 1996), and possibly as much as 10% (Lasaga and Ohmoto 2002), of the present atmospheric oxygen level, even in Late Archean time. The red color of many Proterozoic quartzites, which is due to interstitial hematite cement, is consistent with early atmospheric oxygen.

The most significant difference between ancient and recent soils is the nearly ubiquitous potassium enrichment of the former, which is attributed to postdepositional K metasomatism. In the associated sandstones, diagenetic K feldspar is common, and in many shales, kaolinite has been converted to illite. Fedo et al. (1995) provide a means for evaluating the magnitude of such alterations, which is important for correctly assessing paleoweathering processes.

As an example of extreme Precambrian weathering, the 1700 Ma Baraboo-Barron-Sioux quartzite succession of the southern Lake Superior region has a chemical maturity equivalent to the most mature clastic sediments and associated paleosols in the entire geologic record (Medaris et al. 2003). The Chemical Index of Alteration, which is defined as 100 molar $Al_2O_3/(Al_2O_3 + K_2O + Na_20 + CaO)$, is 95.7 for underlying saprolite and 96.8–98.8 for interstratified pelites that have escaped subsequent

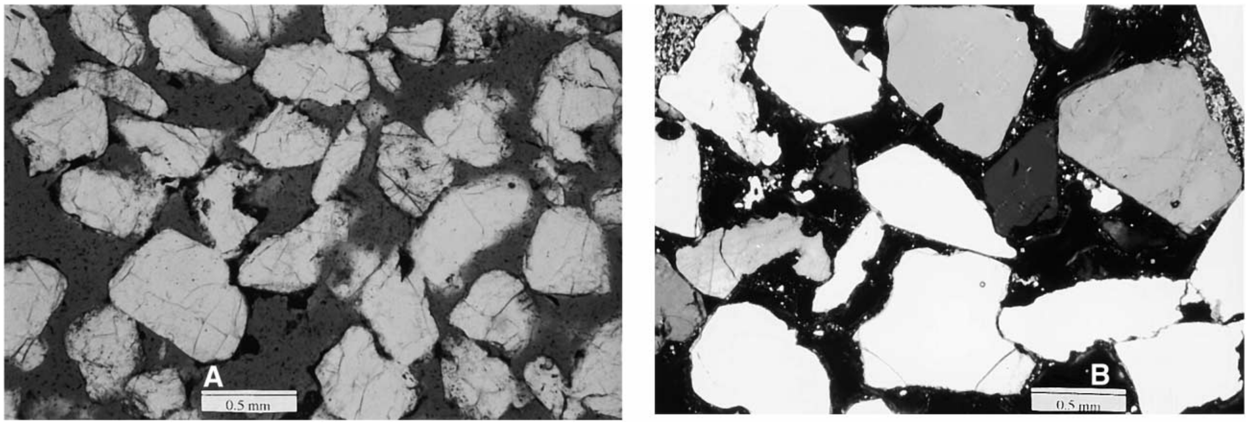

**Figure 8.** Photomicrographs of two angular, first-cycle ancient quartz arenites. *A*, Nubian Sandstone (Cretaceous of Libya) composed of medium-size, angular quartz grains. Photo courtesy of John C. Harms (plane-polarized light; dyed epoxy). *B*, Springhill Sandstone (Jurassic, Tierra del Fuego, Chile) composed of clear, embayed angular, coarse volcanic quartz grains. Sample is courtesy of Chilean National Petroleum Company (crossed nicols).

K metasomatism. Additional elemental comparisons with soils and shales of various ages indicate that this chemical maturity rivals even the most mature soils and sediments that have formed since the appearance of macroscopic plants. K-enrichment is widespread in the Baraboo interval paleosols as well as in many other ancient examples (Medaris et al. 2003).

## The Vegetation Paradox

The exceptional rounding of sand-sized quartz grains provides strong evidence of an important history of eolian abrasion, which is consistent with a multicycling origin. The prevalence of such rounding among lower Paleozoic and Proterozoic quartz arenites, in contrast to a reduced degree of rounding in younger arenites of similar grain size, is also consistent with the absence of pre-Silurian macroscopic land vegetation to inhibit significantly both fluvial and eolian abrasion (Schumm 1968; MacNaughton et al. 1997). The contrast of rounding in younger examples is largely a function of grain size because most Silurian to modern eolian sands fall in the fine grade, which has long been known to experience negligible abrasion by any process. This presumably reflects a reduction of the importance of eolian dispersal of sand after the appearance of macrovegetation. The great compositional maturation of pre-Silurian examples, however, seems to require some additional factor to reconcile geomorphic conditions that could have enhanced the transport and abrasion of enormous volumes of pure quartz sand, on the one hand, but could have allowed exceptional chemical maturation of soils on the other hand, as indicated by profiles beneath, and the composition of pelitic strata interstratified within, many quartz arenites.

Two decades ago I tried to explain the maturity of Baraboo interval strata by postulating a tectonically stable landscape of "very low topographic relief and a warm, humid climate" (Dott 1983, p. 135). However, I have been haunted ever since by the difficulty of rationalizing broad interfluve areas resistant to erosion by either wind or water long enough to accomplish the requisite weathering without something to stabilize the soil profiles. This difficulty is magnified by the fact that large braided stream systems with maximum flow velocities up to a few hundred centimeters per second seem required to disperse the large volumes of quartz-rich sands and rare pebbles up to 2 cm in diameter. To resolve this paradox, I postulated in Medaris et al. (2003) that microbial crusts or mats, such as those that characterize soils in many semiarid and arid regions today (fig. 10), provide a plausible mechanism for physically binding Precambrian surfaces between active fluvial channel complexes to facilitate and also contribute biochemically to weathering (see also Campbell 1979; Monastersky 1989). Meanwhile, Prave (2002) described apparent microbially induced sedimentary structures from the late Precambrian, nonmarine Torridonian succession of Scotland. He inferred microbial crusts living in alluvial, interfluve, and lacustrine margin settings—exactly the circumstances postulated here. Moreover, beneath the Torridonian strata, Retallack and Mindszenty

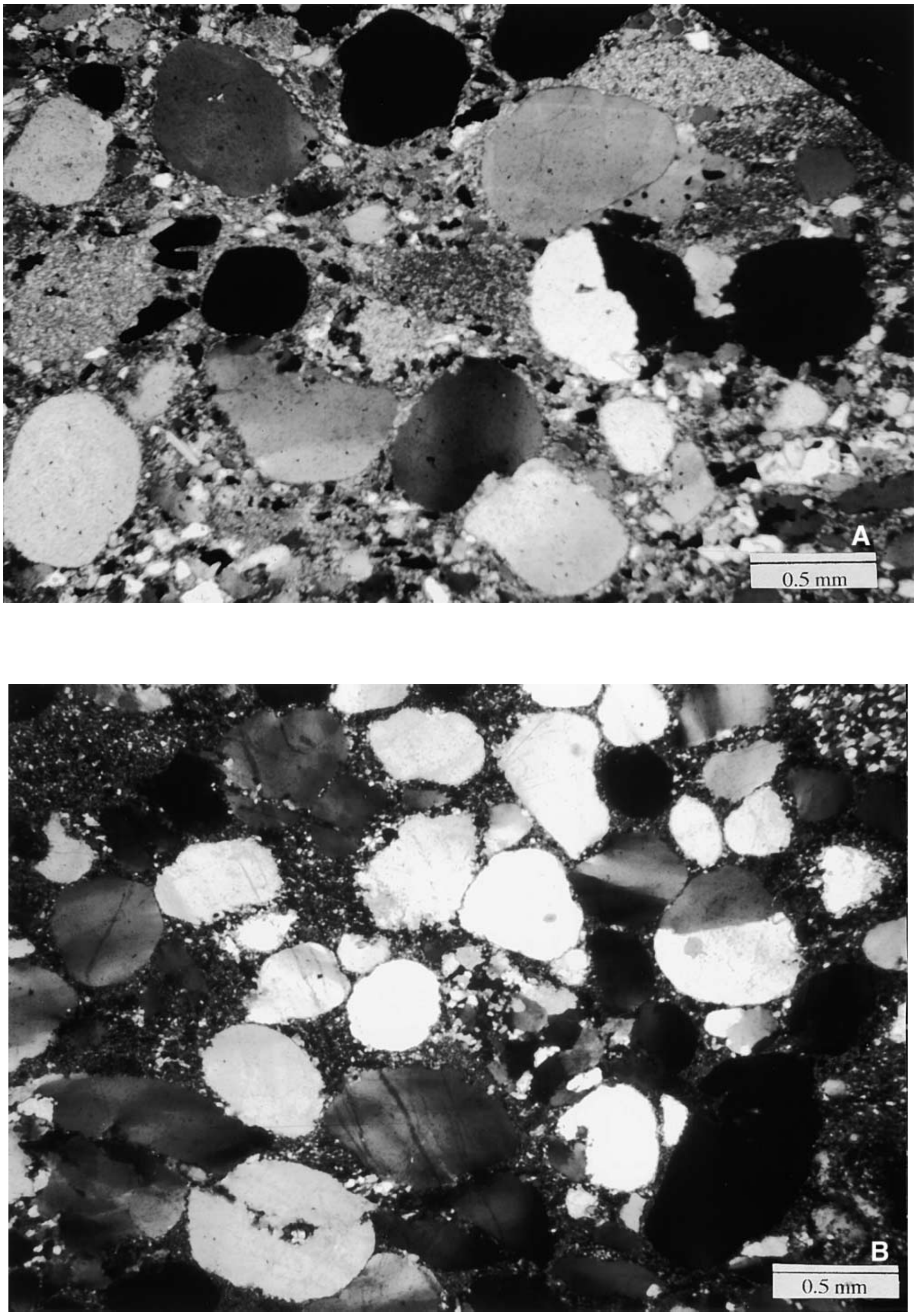

**Figure 9.** Photomicrographs of well-rounded quartz grains in Precambrian sandstones. *A*, Quartzite from the Lower Roan Group (Neoproterozoic), pipeline section at the Roan Antelope Mine, Zambia, with rounded, coarse quartz grains (crossed nicols). *B*, Traders Ferry quartz wacke, Crystal Falls iron district, Michigan (Mesoproterozoic), with rounded, coarse quartz grains (crossed nicols).

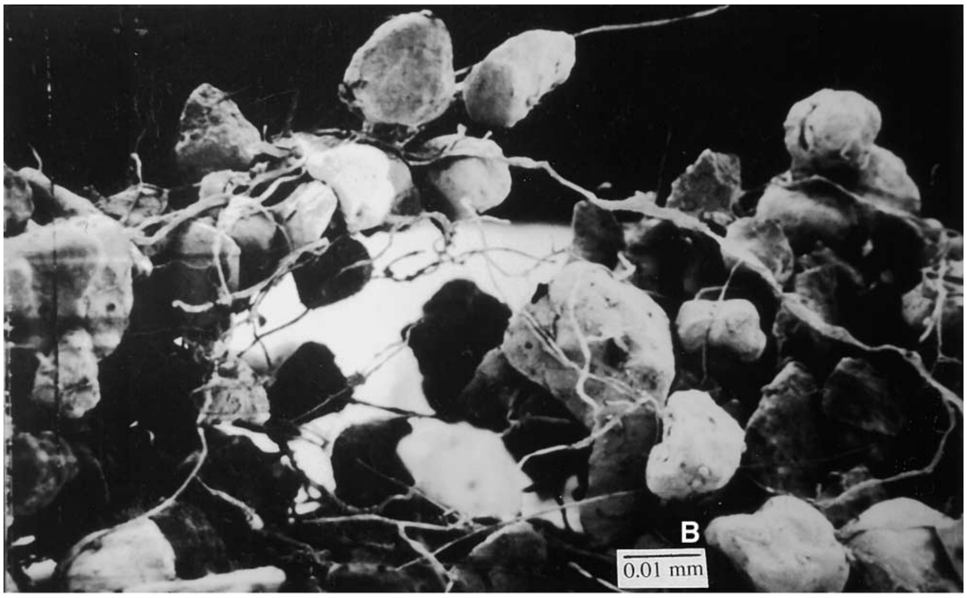

**Figure 10.** Modern microbiotic crusts or mats. *A*, Field view of a typical biological soil crust in Arches National Monument, Utah (width of view approximately 1 m). *B*, Scanning electron microscopic image of microbial filaments around sand grains in a soil crust in Canyonlands National Park, Utah (courtesy of Jayne Belnap).

(1994) found an oxidized soil profile with isotopically light carbon that they attributed to microbial crusts. Eriksson et al. (1999) invoked microbial mats to explain roll-up structures within intermittently wetted interdune deposits of the Proterozoic Waterburg Group in South Africa. Gutzmer and Beukes (1998) also postulated microbial vegetation associated with a Proterozoic laterite.

In my proposed scenario, ground-hugging crusts would not impede wind appreciably, unlike modern macroscopic vegetation but would provide significant stability. In fact, experimental results show that crusts increase up to fourfold the resistance to wind erosion. In wind tunnel experiments, a threshold friction velocity of 50 cm/s entrained sand grains on surfaces lacking crusts, whereas 250–450 cm/s was required to entrain them on surfaces with thick crusts (Belnap 2001). Large eolian dune fields must have formed on ancient braided river plains and occasionally invaded the interfluve areas to bury some microbial crusts; but in the long run, enough of the latter areas survived erosion long enough to create the mature soils necessary to provide kaolinitic clays to the pelitic layers now found interstratified with many Precambrian quartz arenites. Mat stabilization not only would facilitate the compositional maturation of multicycled sands but also might make possible the formation of first-cycle quartz arenites.

Formerly known as cryptogamic soils, biological or microbiotic soil crusts are composed of a complex community of organisms forming layers up to 10 cm thick, which are generally brown in color and feel slightly spongy underfoot (for summaries, see Belnap et al. 2001 and U.S. Geological Survey 1999). Although best known today in semiarid and arid regions, I have observed crusts on a dry, sandy prairie in Wisconsin. Similar microbial communities also occur in tropical savannas and rain forests (Budel 2000), in fact, in practically all climatic zones of the earth, including even polar and alpine areas (Belnap et al. 2001). Crust communities require minimal moisture, but they cannot compete well with a vascular plant canopy; therefore, they thrive where such plants are sparse or absent due to limited water, disturbance, or other environmental restrictions. Component organisms in modern crusts include cyanobacteria, other bacteria, green and brown algae, microfungi, lichens, mosses, and liverworts in varying proportions depending on climate and substrate. They live upon and within the uppermost few millimeters of soil, and sticky sheaths and filaments of some of the organisms, especially cyanobacteria, help to bind particles and stabilize soil surfaces (fig. 10*B*). The crusts can tolerate desiccation for long periods and even develop polygonal cracking similar to that of dried muds, but they revive promptly when wetted. Crusts can also tolerate shallow burial by wind-blown silt or sand because the sheaths and filaments of some taxa can grow up through the cover and also can spread laterally. Microbial crusts are known to elevate substrate pH to as much as 8–10.5, which would greatly enhance the weathering of quartz-bearing rocks (Garcia-Pichel and Belnap 1996; Budel 2000). They also concentrate nutrients such as nitrogen, phosphorous, and potassium. These characteristics led Campbell (1979) and Schwartzman and Volk (1989) to propose biological crusts as the first Precambrian terrestrial organic communities and soil enhancers.

On both taxonomic and evolutionary grounds, botanists have long argued that cyanobacteria (formerly known as blue-green algae) and green algae would have been the first organisms to conquer land. Fungi probably followed soon after and could then combine with algae to form symbiotic lichens (Campbell 1979; Schwartzman and Volk 1989; Gray and Shear 1992; Teske and Stahl 2002). The transition from the aquatic to dry land habitat may not have been as difficult as it might seem. Modern subaerial microbial mats in supratidal and desert environments can survive months of drought and change instantly from a dormant brown to a thriving green carpet with the first drops of water. While the biological probability of this scenario has not been challenged, the timing of that first conquest has long remained in doubt because the fossil record has seemed mute, which is not surprising given the low preservation potential of such simple, microscopic organisms in ephemeral environments (Horodyski and Knauth 1994).

Marine cyanobacterial stromatolites of at least 3000 Ma have been known in southern Africa and Australia for many years (Schopf and Klein 1992). More recently, >2000 Ma freshwater stromatolites have been reported in Africa (Buck 1980), and it is suggested that the cyanobacteria soon spread from ponds to adjacent, intermittently wetted subaerial land surfaces and from there to even drier areas. Garlick has made a similar argument for "algal" mats associated with Late Proterozoic sabkhas in the Katanga Group of Zambia (1981) and also in Montana and Idaho (1988). He suggested that decaying mat organic matter produced anoxic conditions favorable for the precipitation of syngenetic stratiform copper and iron sulfides within sabkha sediments. The approximately 900 Ma nonmarine Copper Harbor Conglomerate of northern Michigan contains small stromatolites and mats that encrusted cobbles and are associated with oolite, oncolite, and intraclast lenses (Elmore 1983). The setting was a lacustrine fan delta in an arid climate, where microbial mats apparently could spread short distances away from lake or pond shorelines.

So far, few localities have yielded Precambrian soil microbe fossils, and the candidates are commonly challenged as to whether they were truly subaerial. In the 2300–2700 Ma Witwatersrand Group in eastern Transvaal, South Africa, carbonaceous material occurs within gold-bearing strata thought to have been deposited at the interface between a shallow lagoon and an arid land surface (Hallbauer and Van Warmelo 1974). Amino acid analyses of this material revealed chemical fossils with a probable photosynthetic algal origin (Prashnowski and Schidlowski 1967). Scanning electron microscopy of the same material showed fungal-like fibers with gold and other heavy metals coating some of them. Fungi absorb and redeposit such metals but algae do not. On the basis of these two different lines of evidence, Hallbauer and Van Warmelo postulated a symbiotic association of a photosynthetic alga with a nonphotosynthetic filamentous organism such as a fungus; modern lichens are just such a symbiont, and all three are components of modern microbial soil crusts.

In the southwestern United States, Horodyski and Knauth (1994) reported microscopic filaments preserved in 800 Ma and 1200 Ma paleokarsts in dolostones with low $\delta^{13}C$ in California and Arizona, respectively. The authors first argued from the carbon isotopic characteristics of modern soil profiles in carbonate rocks that the presence of Precambrian organisms is implied for those ancient karsts. They then described filaments preserved in chert like those of bacteria and cyanobacteria and concluded that microbial mats covered much of the Late Proterozoic landscape and greatly enhanced chemical weathering. Similarly, Golubic and Hoffman (1976) and Golubic and Campbell (1979) argued for ancient subaerial crusts on intermittently wetted rocks on the basis of morphologic similarities between microbial structures in 1900 Ma Belcher Island chert in Canada and a modern subaerial cyanophyte.

Precambrian paleosols are being recognized increasingly (Retallack 1992; Gall 1999), so we may anticipate more evidence of soil microorganisms in the future. Meanwhile, geochemistry can provide indirect support. Upward trends through soil profiles of oxygen and carbon isotopes as well as other elements can test the probability that carbonaceous caps on some of these paleosols were microbial crusts (Schidlowski and Aharon 1992; Ohmoto 1996). Besides the Arizona-California case described previously, Watanabe et al. (2000) reported a 2600 Ma profile from South Africa whose chemical characteristics point to a probable microbial mat at the soil surface.

The oldest known sedimentary rocks with widely accepted chemical fossils are in 3.7–3.8 Ga volcaniclastic strata of the Isua greenstone belt of southwestern Greenland. These contain graphite particles with low $\delta^{13}C$ believed to have originated in pelagic organisms (Schidlowski 1988, 2001; Rosing 1999). Indeed, if marine life appeared that early, then Ohmoto (1996) is probably correct in stating that "terrestrial biomass on the early continents may have been more extensive than previously recognized" (p. 1135).

## Conclusions

It is clear that pure quartz arenites can form in several ways. The venerable multicycling hypothesis is valid for many examples, but single cycling by intense tropical weathering has been shown to be valid as well. Both processes probably contributed to the origin of many examples—either simultaneously or successively—and diagenesis can augment either of the other two mechanisms for maturation. Extreme rounding of medium and coarse sand fractions so common in lower Paleozoic and Proterozoic quartz arenites, together with the widespread presence of ventifacts on the basal Cambrian surface of the North American craton, indicates an important eolian abrasion history. It has long been acknowledged that the importance of wind should have been greatly enhanced by the absence of macroscopic land vegetation prior to Silurian time.

The absence of land vegetation, however, implies a paradox. Unless the ancient land surfaces were perfectly flat, how could they be stable enough to allow the intense chemical weathering indicated by the compositional purity of ancient quartz arenites themselves and by the mature paleosols associated with many of them, as well as by interstratified, mineralogically mature pelites? The abundance of medium-grained to coarse-grained sand and associated pebbles required streams with sufficient gradients to transport such materials, which in turn points to at least moderate topographic relief, which exacerbates the stabilization problem.

Growing evidence for the early appearance of subaerial microbiotic mats or soil crusts offers a resolution of the pre-Silurian landscape paradox. Besides a few examples of preserved Precambrian bacterial and algal filaments from apparently subaerial environments, there is geochemical evidence suggestive of organic caps on Precambrian paleosol profiles, which were probably also microbiotic mats. Although still sparse, the evidence available suggests that lowly microbes greened the dry land at least 2 billion years before macroscopic plants appeared in the fossil record. Moreover, trackways on Cambro-Ordovician eolian foresets in Ontario indicate that some adventuresome arthropod made forays onto land at the edge of the sea at least 40 m.yr. or so before the previously recognized earliest land animals appeared (MacNaughton et al. 1999, 2002). The more we learn, the earlier the appearance of many life forms seems to have been, making "deep time" seem a little less remote.

## ACKNOWLEDGMENTS

I am much indebted to colleagues L. G. Medaris, Jr., and C. W. Byers for their longtime collaborations. J. Valley provided insights about Precambrian chemical fossils. R. H. Meade of the U.S. Geological Survey provided firsthand knowledge and samples of Orinoco River sands. J. Belnap, botanist with the U.S. Geological Survey in Moab, Utah, introduced me to biological soil crusts, and R. Beerbower pointed me to additional references about them. University of Wisconsin botanists P. E. Berry and T. J. Givnesh shared their knowledge of the Gran Sabana of Venezuela. L. G. Medaris, C. W. Byers, J. Belnap, J. Valley, and two anonymous reviewers gave valuable suggestions for improving the manuscript.

## REFERENCES CITED

Anderhalt, R., and Slow, E. S. 1988. Feldspar destruction by diagenetic processes in the Clinton Sandstone—the origin of a diagenetic quartz arenite. Geol. Soc. Am. N. Central Sec. G Abstr. Program 20:332.

Baker, H. W. 1974. Environmental sensitivity of submicroscopic surface textures on quartz sand grains: a statistical evaluation. M.S. thesis, University of Wisconsin—Madison, 66 p.

Balazs, R. J., and Klein, G. D. 1972. Roundness-mineralogical relationships of some intertidal sands. J. Sediment. Petrol. 42:425–433.

Belnap, J. 2001. Biological soil crusts and wind erosion. *In* Belnap, J., and Lange, O. L., eds. Biological soil crusts: structure, function, and management. Berlin, Springer, p. 339–348.

Belnap, J.; Budel, B.; and Lange, O. L. 2001. Biological soil crusts: characteristics and distribution. *In* Belnap, J., and Lange, O. L., eds. Biological soil crusts: structure, function, and management. Berlin, Springer, p. 3–30.

Berkey, C. P. 1906. Paleogeography of St. Peter time. Bull. Geol. Soc. Am. 17:229–250.

Bowring, S., and Ross, G. 1985. Geochronology of the Narakay Volcanic Complex: implications for the age of the Coppermine Homocline and MacKenzie igneous event. Can J. Earth Sci. 22:774–781.

Briceno, H. O., and Schubert, C. 1990. Geomorphology of the Gran Sabana, Guayana Shield, southeastern Venezuela. Geomorphology 3:125–141.

Buck, S. G. 1980. Stromatolite and ooid deposits within the fluvial and lacustrine sediments of the Precambrian Ventersdorp Supergroup of South Africa. Precambrian Res. 12:311–330.

Budel, B. 2000. Ecology and diversity of rock-inhabiting cyanobacteria in tropical regions. Eur. J. Phycol. 34: 361–370.

Burke, K. 1999. Tectonic significance of the accumulation of the voluminous early Paleozoic reservoir-containing quartz-rich sandstones of North Africa and Arabia. Bull. Geol. Soc. Houston (March issue), p. 11–13.

Burke, K.; MacGregor, D. S.; and Cameron, N. R. 2003. Africa's petroleum systems: four tectonic aces in the past 600 million years. *In* Arthur, T. J.; MacGregor, D. S.; and Cameron, N. R., eds. Petroleum geology of Africa: new themes and developing technologies. Geol. Soc. Lond. Spec. Publ. 207 (in press).

Campbell, S. E. 1979. Soil stabilization by a prokaryotic desert crust: implications for Precambrian land biota. Origins Life 9:335–348.

Chakraborty, T., and Chakraborty, D. 2001. Eolian-aqueous interactions in the development of a Proterozoic sand sheet: Shikaoda Formation, Hosangabad, India. J. Sediment. Res., Sec. A, Sediment. Petrol. Processes 71:107–117.

Chandler, F. W. 1988. Quartz arenites: review and interpretation. Sediment. Geol. 58:105–126.

Crook, K. A. W. 1968. Weathering and roundness of quartz sand grains. Sedimentology 11:171–182.

Dake, C. L. 1921. The problem of the St. Peter Sandstone. Univ. Mo. Sch. Mines Bull. 6:228.

Dalrymple, R. W.; Narbonne, G. M.; and Smith, L. 1985. Eolian action and the distribution of Cambrian shales in North America. Geology 13:607–610.

Dapples, E. C. 1955. General lithofacies relationship of St. Peter Sandstone and Simpson Group. Am. Assoc. Pet. Geol. Bull. 39:444–467.

Daubrée, G. A. 1879. Etudes synthetiques de geologie experimentale. Paris, Libraire des Corps des Ponts et Chaussees, des Mines et des Telegraphs, 478 p.

Donaldson, J. A., and Ojakangas, R. W. 1977. Orthoquartzite pebbles in Archean conglomerate, North Spirit Lake, northwestern Ontario. Can. J. Earth Sci. 14:1980–1990.

Dott, R. H., Jr. 1983. The Proterozoic red quartzite enigma in the north-central United States: resolved by plate tectonics? Geol. Soc. Am. Mem. 160: 129–141.

Dott, R. H., Jr., and Byers, C. W. 1980. SEPM research conference on modern shelf and ancient crtaonic sedimentation: the orthoquartzite-carbonate suite revisited. J. Sediment. Petrol. 51:329–347.

Dott, R. H., Jr.; Byers, C. W.; Fielder, G. W.; Stenzel, S. R.; and Winfree, K. E. 1986. Aeolian to marine transition in Cambro-Ordovician cratonic sheet sandstones of the northern Mississippi Valley, U.S.A. Sedimentology 33:345–367.

Driese, S. G. 2000. Mass-balance reinterpretation of the 2.2 Ga Hekpoort (Waterval Onder) Paleosol, South Africa: a Precambrian paleo-vertisol. Geol. Soc. Am. Abstr. Ann. Meeting A-486.

Dutta, P. K.; Zhou, Z.; and dos Santos, P. R. 1993. A theoretical study of mineralogical maturation of eolian sand. Geol. Soc. Am. Spec. Pap. 284:203–209.

Elmore, R. D. 1983. Precambrian non-marine stromatolites in alluvial fan deposits, the Copper Harbor Conglomerate, upper Michigan. Sedimentology 30: 829–842.

Els, B. G. 1998. The auriferous late Archaean sedimentation systems of South Africa: unique palaeoenvironmental conditions? Sediment. Geol. 120: 205–224.

Eriksson, P. G.; Simpson, E. L.; Eriksson, K. A.; Bumby, A. J.; and Steyn, G. L. 1999. Roll-up structures in the 1.8 Ga Waterberg Group, South Africa: evidence for microbial mats in an intracratonic desert setting. Geol. Soc. Am. Abstr. Ann. Meeting A-463–464.

Fedo, C. M.; Nesbitt, H. W.; and Young, G. 1995. Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. Geology 23:921–924.

Folk, R. M. 1968. Bimodal supermature sandstones: product of the desert floor. *In* Genesis and classification of sedimentary rocks. Prague, Int. Geol. Cong., 23d Session 8:9–32.

Gall, Q. 1999. Precambrian paleosols: a view from the Canadian Shield. *In* Thiry, M., and Simon-Coincon, R., eds. Paleoweathering, paleosurfaces and related continental deposits. Int. Assoc. Sediment. Spec. Publ. 27:207–224.

Galloway, J. J. 1919. The rounding of grains by solution. Am. J. Sci. 47:270–280.

———. 1922. Value of the physical characteristics of sand grains in interpretation of the origin of sandstones. Bull. Geol. Soc. Am. 33:104–105.

Garcia-Pichel, F., and Belnap, J. 1996. Microenvironments and microscale productivity of cyanobacterial desert crusts. J. Phycol. 32:774–782.

Garlick, W. G. 1981. Sabkhas, slumping, and compaction at Mufulira, Zambia. Econ. Geol. 76:1817–1847.

———. 1988. Algal mats, load structures, and synsedimentary sulfides in Revett Quartzites of Montana and Idaho. Econ. Geol. 83:1259–1278.

Gaudette, H. E.; Vitrac-Michard, A.; and Allegre, C. J. 1981. North American Precambrian history recorded in a single sample: high resolution U-Pb systematics of the Potsdam Sandstone detrital zircons, New York State. Earth Planet. Sci. Lett. 54:248–260.

Gay, A. L., and Grandstaff, D. E. 1980. Chemistry and mineralogy of Precambrian paleosols at Elliot Lake, Ontario, Canada. Precambrian Res. 112:349–373.

Golubic, S., and Campbell, S. E. 1979. Analogous microbial forms in Recent subaerial habitats and in Precambrian cherts: *Gloeothece coerulea* Geitler and *Eosynechococcus moorei* Hofmann. Precambrian Res. 8: 201–217.

Golubic, S., and Hoffman, H.J. 1976. Comparison of modern and mid-Precambrian Entophysalidaceae (Cyanophyta) in stromatolitic algal mats: cell division and degradation. J. Paleontol. 50:1074–1082.

Goudie, A. S., and Watson, A. 1981. The shape of desert sand dune grains. J. Arid Environ. 4:185–190.

Grabau, A. W. 1913. Principles of stratigraphy. New York, Seiler, 1185 p.

Graham, W. A. P. 1930. A textural and petrographic study of the Cambrian sandstones of Minnesota. J. Geol. 38: 696–716.

Gray, J., and Shear, W. 1992. Early life on land. Am. Sci. 80:444–456.

Gutzmer, J., and Beukes, N. J. 1998. Earliest laterites and possible evidence for terrestrial vegetation in the Early Proterozoic. Geology 26:263–266.

Hallbauer, D. K., and Van Warmelo, K. T. 1974. Fossilized plants in thucholite from Precambrian rocks of the Witwatersrand, South Africa. Precambrian Res. 1: 199–212.

Harms, J. C.; Southard, J. B.; and Walker, R. G. 1982. Unconventional fluvial stratification sequences—the Nubia Sandstone. *In* Structures and sequences in clastic rocks. SEPM Short Course Notes 9:5-15–5-26.

Harris, N. B. 1989. Diagenetic quartzarenite and destruction of secondary porosity: an example from the Middle Jurassic Brent sandstone of northwest Europe. Geology 17:361–364.

Horodyski, R. J., and Knauth, L. P. 1994. Life on land in the Precambrian. Science 263:494–498.

Huazhao, M., and Dott, R. H., Jr. 1985. A subsurface study of the St. Peter Sandstone in southern and eastern Wisconsin. Wis. Geol. Nat. Hist. Surv. Info. Circ. 47, 26 p.

Jackson, M. J.; Pianosi, J. G.; and Donaldson, J. A. 1984. Aeolian dunes in early Proterozoic Thelon Formation near Schultz Lake, Central Keewatin. Curr. Res., Pt. B, Geol. Surv. Can. Pap. 84-1B:53–63.

Johnson, C. M., and Winter, B. L. 1999. Provenance analysis of lower Paleozoic cratonic quartz arenites of the North American midcontinent region: U-Pb and Sm-Nd isotope geochemistry. Bull. Geol. Soc. Am. 111: 1723–1738.

Johnsson, M. J.; Stallard, R. F.; and Lundberg, N. 1991. Controls on the composition of fluvial sands from a tropical weathering environment: sands of the Orinoco River drainage basin, Venezuela and Colombia. Bull. Geol. Soc. Am. 103:1622–1647.

Johnsson, M. J.; Stallard, R. F.; and Meade, R. H. 1988. First-cycle quartz arenites in the Orinoco Basin, Venezuela and Colombia. J. Geol. 96:263–277.

Klein, G. D. 1982. Probable depositional sequential arrangement of depositional systems on cratons. Geology 10:17–22.

Klitzsch, E.; Harms, J. C.; Lejal-Nicol, A.; and List, F. K. 1979. Major subdivisions and depositional environments of Nubia strata, southwestern Egypt. Am. Assoc. Pet. Geol. Bull. 63:967–974.

Knight, S. H. 1924. Eolian abrasion of quartz grains. Bull. Geol. Soc. Am. 35:107–108.

Kotzer, T. G.; Kyser, T. K.; and Irving E. 1992. Paleomagnetism and the evolution of fluids in the Proterozoic Athabaska Basin, northern Saskatchewan, Canada. Can. J. Earth Sci. 29:1474–1491.

Krinsley, D. H., and Doornkamp, J. 1973. Atlas of quartz sand grain textures. Cambridge, Cambridge University Press, 91 p.

Krumbein, W. C., and Sloss, L. L. 1963. Stratigraphy and sedimentation. 2d ed. San Francisco, W. H. Freeman, 660 p.

Kuenen, P. H. 1960*a*. Experimental abrasion. 4. Eolian action. J. Geol. 68:427–449.

———. 1960*b*. Sand. Sci. Am. (April issue) 202:95–111.

Kuenen, P. H., and Perdok, W. G. 1962. Experimental abrasion. 5. Frosting and defrosting of quartz grains. J. Geol. 70:648–658.

Lasaga, A. C., and Ohmoto, H. 2002. The oxygen geochemical cycle: dynamics and stability. Geochim. Cosmochim. Acta. 66:361–381.

Lee, M. A. K., and Byers, C. W. 1992. Eolian-to-marine transition in the St. Peter Sandstone of the Ozark dome, SE Missouri. Geol. Soc. Am. N. Central Sec. G Abstr. Program 24:28.

Lewis, D. W. 1971. Qualitative petrographic interpretation of Potsdam Sandstone (Cambrian), southwestern Quebec. Can. J. Earth Sci. 8:853–882.

Long, D. G. F. 2002. Aspects of Late Paleoproterozoic flucial style: the Uairen Formation, Roraima Supergroup, Venezuela. Spec. Publ. Int. Assoc. Sediment. 33:323–338.

MacNaughton, R. B.; Cole, J. M.; Dalrymple, R. W.; Braddy, S. J.; Briggs, D. E. G.; and Lukie, T. D. 2002. Arthropod trackways in Cambrian-Ordovician aeolian sandstone, southeastern Ontario. Geology 30: 391–394.

MacNaughton, R. B.; Dalrymple, R. W.; and Narbonne, G. M. 1997. Early Cambrian braid-delta deposits, MacKenzie Mountains, north-western Canada. Sedimentology 44:587–609.

MacNaughton, R. B.; Lukie, T. D.; and Cole, J. M. 1999. Arthropod trackways from Cambro-Ordovician aeolian deposits in the Nepean Fromation (Potsdam Group), southeastern Ontario. Geol. Assoc. Canada.–Mineral. Assoc. Can. Joint Ann. Meeting Abstr. 24:76–77.

Marmo, J. S., and Ohmoto, H. 2000. 2.3 Ga paleolaterites in north Karelia, eastern Finland. Geol. Soc. Am. Abstr. Ann. Meeting A-486.

Mazzullo, J. M., and Ehrlich, R. 1980. A vertical pattern of variation in the St. Peter Sandstone—Fourier grain shape analysis. J. Sediment. Petrol. 50:63–70.

———. 1983. Grain-shape variation in the St. Peter Sandstone: a record of eolian and fluvial sedimentation of an early Paleozoic sheet sand. J. Sediment. Petrol. 53: 105–119.

McBride, E. F. 1985. Diagenetic processes that affect provenance determinations in sandstone. *In* Zuffa, G. G., ed. Provenance of arenites. NATO Advanced Science Institutes Ser. C 148:95–113.

———. 1986. Diagenesis of the Maxon Sandstone (Early Cretatceous), Marathon Region, Texas: a diagenetic quartzarenite. J. Sediment. Petrol. 57:98–197.

McLennan, S. M.; Bock, B.; Compston, W.; Hemming, S. R.; and McDaniel, D. K. 2001. Detrital zircon geochronology of Taconian and Acadian foreland sedimentary rocks in New England. J. Sediment. Res. 71: 305–317.

Medaris, L. G., Jr.; Singer, B. S.; Dott, R. H., Jr.; Naymark, A.; Johnson, C. M.; and Schott, R. C. 2003. Late Paleoproterozoic climate, tectonics, and metamorphism in the southern Lake Superior region and Proto-North America: evidence from Baraboo interval quartzites. J. Geol. 111:243–257.

Meinster, B., and Tickell, S. J. 1976. Precambrian eolian deposits in the Waterbug Supergroup. S. African Geol. Soc. Trans. 78:191–199.

Middleton, G. M., and Davis, P. M. 1974. Surface texture and rounding of quartz sand grains on intertidal bars, Bay of Fundy, Nova Scotia. Can. J. Earth Sci. 16: 2071–2085.

Miller, A. R.; Cumming, G. L.; and Krstic, D. 1989. U-Pb, Pb-Pb, and K-Ar isotopic study and petrography of uraniferous phosphate-bearing rocks in the Thelon Formation, Dubawnt Group, Northwest Territories, Canada. Can. J. Earth Sci. 26:867–880.

Monastersky, R. 1989. Supersoil: before grasses and trees emerged, microbial soils may have made Earth more hospitable for life. Sci. News 136:376–377.

Morton, A. C., and Johnsson, M. J. 1993. Factors influencing the composition of detrital heavy mineral suites in Holocene sands of the Apure River drainage basin, Venezuela. Geol. Soc. Am. Spec. Pap. 284: 171–185.

Nadon, G. C.; Simo, J. A.; Dott, R. H., Jr.; and Byers, C. W. 2000. High-resolution sequence stratigraphic analysis of the St. Peter Sandstone and Glenwood Formation (Middle Ordovician), Michigan Basin, U.S.A. Am. Assoc. Pet. Geol. Bull. 84:975–996.

Odom, I. E. 1975. Feldspar-grain size relations in Cambrian arenites, upper Mississippi Valley. J. Sediment. Petrol. 45:636–650.

Odom, I. E.; Doe, T. W.; and Dott, R. H., Jr. 1976. Nature of feldspar-grain size relations in some quartz-rich sandstones. J. Sediment. Petrol. 46:862–870.

Ohmoto, H. 1996. Evidence in pre-2.2 Ga paleosols for the early evolution of atmospheric oxygen and terrestrial biota. Geology 24:1135–1138.

Ojakangas, R. W., and Weber, R. E. 1984. Petrography and paleocurrents of the Lower Proterozoic Sioux Quartzite, Minnesota and South Dakota. Minn. Geol. Surv. Rep. Invest. 32:1–15.

Pettijohn, F. J. 1957. Sedimentary rocks. 2d ed. New York, Harper & Row, 718 p.

Pettijohn, F. J.; Potter, P. E.; and Siever, R. 1987. Sand and sandstone. Berlin, Springer, 553 p.

Prashnowski, A. A., and Schidlowski, M. 1967. Investigation of Pre-Cambrian thucolite. Nature 216: 560–563.

Prave, A. R. 2002. Life on land in the Proterozoic: evidence from the Torridonian rocks of northwest Scotland. Geology 30:811–814.

Pulvertaft, T. C. R. 1985. Aeolian dune and wet interdune sedimentation in the middle Proterozoic Dala Sandstone, Sweden. Sediment. Geol. 44:93–111.

Pye, K., and Mazzullo, J. 1994. Effects of tropical weathering on quartz grain shape: an example from northeastern Australia. J. Sediment. Petrol. A 64: 500–507.

Rainbird, R. H.; Nesbitt, H. W.; and Donaldson, J. A. 1990. Formation and diagenesis of a sub-Huronian saprolith: comparison with a modern weathering profile. J. Geol. 98:801–822.

Ramaekers, P. 1981. Hudsonian and Helikian basins of the Athabasca region, northern Saskatchewan. *In* Campbell, F. H. A., ed. Proterozoic basins of Canada. Geol. Surv. Can. Pap. 81-10:219–233.

Retallack, G. J. 1992. How to find a Precambrian paleosol. *In* Schidlowski, M.; Golubic, S.; Kimberley, M. M.; McKirdy, D. M.; and Trudinger, R. A., eds. Early organic evolution. Berlin, Springer, p. 16–30.

Retallack, G. J., and Mindszenty, A. 1994. Well preserved late Precambrian paleosols from northwest Scotland. J. Sediment. Res. A64:264–281.

Rosing, M. T. 1999. $^{13}$C-depleted carbon microparticles in >3700 Ma sea-floor sediment in rocks from west Greenland. Science 283:674–676.

Ross, G. M. 1983. Proterozoic aeolian quartz arenites from the Hornby Bay Group, Northwest Territories, Canada: implications for Precambrian aeolian processes. Precambrian Res. 20:149–160.

Runkel, A. C. 1994. Deposition of the uppermost Cambrian (Croixan) Jordan Sandstone, and the nature of the Cambrian-Ordovician boundary in the upper Mississippi Valley. Bull. Geol. Soc. Am. 106:492–506.

Runkel, A. C.; McKay, R. M.; and Palmer, A. R. 1998. Origin of a classic cratonic sheet sandstone: stratigraphy across the Sauk II-Sauk III boundary in the upper Mississippi Valley. Bull. Geol. Soc. Am. 110: 188–210.

Schidlowski, M. 1988. A 3,800-million-year isotopic record of life from carbon in sedimentary rocks. Nature 333:313–318.

———. 2001. Carbon isotopes as biogeochemical records of life over 3.8 Ma of Earth history: evolution of a concept. Precambrian Res. 106:117–134.

Schidlowski, M., and Aharon, P. 1992. Carbon cycle and carbon isotope record: geochemical impact of life over 3.8 Ga of earth history. *In* Schidlowski, M.; Golubic, S.; Kimberley, M. M.; McKirdy D. M.; and Trudinger R. A., eds. Early organic evolution. Berlin, Springer, p. 147–175.

Schopf, J. W., and Klein, C. 1992. The Proterozoic biosphere. Cambridge, Cambridge University Press, 1348 p.

Schumm, S. A. 1968. Speculations concerning paleohydrologic controls of terrestrial sedimentation. Bull. Geol. Soc. Am. 79:1573–1588.

Schwartzman, D. W., and Volk, T. 1989. Biotic enhancement of weathering and the habitability of earth. Nature 340:457–460.

Simpson, E. L., and Eriksson, K. A. 1987. Depositional facies and controls on parasequence development in siliciclastic tidal deposits from the Lower Proterozoic, upper Mount Guide Quartzite, Mount Isa Inlier, Australia. Can. Soc. Petrol. Geol. Mem. 16:371–387.

Sloss, L. L. 1963. Sequences in the cratonic interior of North America. Bull. Geol. Soc. Am. 74:73–113.

Southwick, D. L., and Mossler, J. H. 1984. The Sioux Quartzite and subjacent regolith in the Cottonwood Basin, Minnesota. *In* Southwick, D. L., ed. Shorter contributions to the geology of the Sioux Quartzite (Early Proterozoic), southwestern Minnesota. Minn. Geol. Surv. Rep. Investig. 32:17–44.

Suttner, L. J.; Basu, A.; and Mack, G. H. 1981. Climate and the origin of quartz arenites. J. Sediment. Petrol. 51:1235–1246.

Tank, R. W. 1970. Ventifacts associated with the Cambrian-Precambrian unconformity at Nekoosa, Wisconsin. Bull. Wis. Acad. Sci. Arts Lett. 58:147–151.

Teske, A., and Stahl, D. A. 2002. Microbial mats and biofilms: evolution, structure, and function of fixed microbial communities. *In* Staley, J. T., and Reysenbach, A.-L., eds. Biodiversity of microbial life. New York, Wiley-Liss, p. 49–100.

Thiel, C. A. 1935. Sedimentary and petrographic analysis of the St. Peter Sandstone. Bull. Geol. Soc. Am. 46: 559–614.

———. 1940. Relative resistance to abrasion of grains of sand size. J. Sediment. Petrol. 10:103–124.

Twenhofel, W. H., and Thwaites, F. T. 1919. The Paleozoic section of the Tomah and Sparta Quadrangles, Wisconsin. J. Geol. 27:614–633.

Tyler, S. A. 1936. Heavy minerals of the St. Peter Sandstone in Wisconsin. J. Sediment. Petrol. 6:55–84.

Tyler, S. A.; Marsden, R. W.; Grout, F. F.; and Thiel, G. A. 1940. Studies of the Lake Superior Pre-Cambrian by accessory mineral methods. Bull. Geol. Soc. Am. 51:1429–1538.

U.S. Geological Survey. 1999. Biological soil crusts. http://www.soilcrust.org

Van Houten, F. B., and Bhattacharyya, D. P. 1979. Late Cretaceous Nubia Formation at Aswan Southeastern Desert, Egypt. Ann. Geol. Surv. Egypt 9:408–419.

Wallin, B. 1990. Early Cambrian coastal dunes at Vassbo, Sweden. Bull. Geol. Soc. Am. 102:1535–1543.

Watanabe, Y.; Martini, J. E. J.; and Ohmoto, H. 2000. Geochemical evidence for terrestrial ecosystems 2.6 billion years ago. Nature 408:574–577.

Williams, G. E., and Tonkin, D. G. 1985. Periglacial structures and palaeoclimatic significance of a late Precambrian block field in the Cattle Grid copper mine, Mount Gunson, South Australia. Aust. J. Earth Sci. 32:287–300.

Winfree, K. E. 1983. Depositional environments of the

St. Peter Sandstone of the Upper Midwest. M.S. thesis, University of Wisconsin—Madison, 114 p.

Wolf, R. R., and Dalrymple, R. W. 1985. Grant 187: sedimentology of the Cambro-Ordovician sandstones of eastern Ontario. *In* Summary of Research 1984–85. Ont. Geol. Surv. Misc. Pap. 127:112–118.

Zbinden, E. A.; Holland, H. D.; Feakes, C. R.; and Dobos, S. K. 1988. The Sturgeon Falls paleosol and the composition of the atmosphere 1.1 Ga BP. Precambrian Res. 42:141–163.

Ziegler, V. 1911. Factors influencing the rounding of sand grains. J. Geol. 19:645–654.