AUTHIGENIC SILICA FABRICS ASSOCIATED WITH CAMBRO-ORDOVICIAN UNCONFORMITIES IN THE UPPER MIDWEST

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ABSTRACT

Authigenic silica fabrics associated with the Cambro-Ordovician, mid-Lower Ordovician, and Lower-Middle Ordovician unconformities in the Upper Midwest occur to depths of 30 m below unconformities, but are most abundant within 0-5 m of unconformities. Reworked clasts of silicified material above these unconformities indicate that silicification occurred before and/or during unconformity development. Authigenic silica fabrics are most abundant within the outcrop area surrounding the Wisconsin Arch, and diminish in abundance to the west and east. These silica fabrics are important indicators of subaerial exposure because they are easily identified in well cuttings and have not been masked by pervasive, regional dolomitization.

INTRODUCTION

Silica translocation is a common phenomenon in subaerial weathering profiles. Within the central United States the association of authigenic silica with ancient subaerial unconformities was first recognized by Bain and Ulrich (1905), who described a variety of authigenic silica fabrics beneath the Lower-Middle Ordovician Sauk-Tippecanoe unconformity. In "Silicification of Erosion Surfaces" Leith (1925) summarized the association of authigenic silica with subaerial unconformities: (1) Authigenic silica is most abundant immediately beneath the unconformity surface, but (2) fingers of silicified material commonly extend deep beneath unconformities along fractures and paleokarst. (3) A discontinuous layer of reworked silicified material typically occurs above the unconformity. (4) Limestone is more commonly silicified than other rock types.

The term "silcrete" was introduced by Lamplugh (1902, 1907) to describe surficial deposits indurated by authigenic silica by infiltrating groundwater. Woolnough (1927) later introduced the related term "duricrust" to describe surficial crusts in Australia composed of authigenic silica and other diagenetic phases. Wopfner and Twidale (1967), Dury (1969), and Langford-Smith (1978) discuss related terminology. Silcretes and duricrusts are by definition crusts on the upper surface or within the upper horizons of soils. Similar genetic terminology does not exist for authigenic silica types formed 5-30 m beneath unconformities, even in cases where silicification occurred during intervals of subaerial exposure (for example, Leith, 1925).

Authigenic silica fabrics within the Lower Ordovician dolostone of the Mississippi Valley region have long been recognized as markedly different from the familiar nodular chert of many younger carbonate rock successions. Whereas the latter faithfully replace primary carbonate grains with dense, finely crystalline, fairly homogeneous quartz, Lower Ordovician "chert" tends to be very vuggy (with drusy quartz linings), botryoidal, and heterogeneous. Their genesis has been a long-standing mystery for which this paper presents a new hypothetical solution through silcrete formation.

This paper documents the distribution of silica cements and replacement fabrics within Cambro-Ordovician strata of the Upper Midwest (figs. 1 and 2) and demonstrates the association of authigenic silica cements and replacement fabrics with regional subaerial unconformities. By analogy with Cenozoic examples (for example, Alley, 1977; Ambrose and Flint, 1981; Hutton and others, 1972, 1978; Khalaf, 1988; Langford-Smith, 1978; Meyer and Pena dos Reis, 1985; Smale, 1973; Summerfield, 1983a, 1983b; Thiry and Millot, 1987; Thiry and others, 1988; Watts, 1978), this paper proposes that many of the Cambro-Ordovician chert occurrences are the remnants of patchily-distributed, regionally-extensive ancient authigenic silica fabrics formed at the surface and at depths extending 5-30 m beneath subaerial unconformities.

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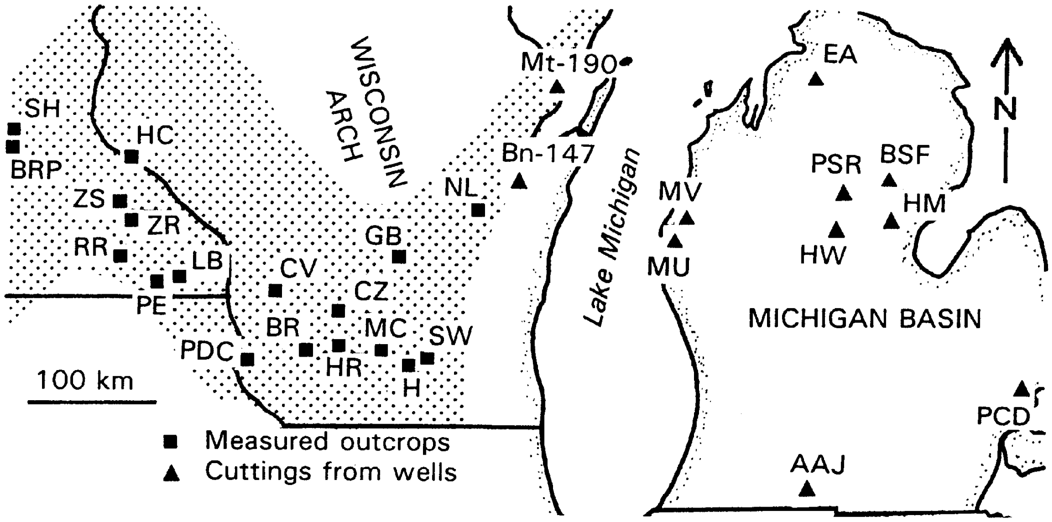


Key to Locations

Outcrops

BR	Blue River, Wisc.
BRP	Bryant Rock Products, Shakopee, Minn.
CV	Coon Valley, Wisc.
CZ	Cazenovia, Wisc.
GB	Glovers Bluff, Wisc.
H	Homburg Quarry, Madison, Wisc.
HC	Hager City, Wisc.
HR	"House on the Rock" Quarry, Wisc.
LB	Lanesboro, Minn.
MC	Millers Curve, Cross Plains, Wisc.
NL	New London, Wisc.
PDC	Prairie du Chien, Wisc.
PE	east of Preston, Minn.
RR	Root River, Minn.
SH	Shakopee, Minn.
SW	Shorewood Hills, Wisc.
ZR	Zumbro River, south of Zumbro, Minn.
ZS	south of Zumbrota, Minn.

Oil and Gas Wells

AAJ	ARCO-ARCO/Johnson 1-3, Branch Co., Mich.
BSF	Brazos-St. Foster 1, Ogemaw Co., Mich.
EA	Energy Acquisition-NML&O, Charlevoix Co., Mich.
HM	Hunt-Martin 1-15, Gladwin Co., Mich.
HW	Hunt-Winterfield A-1, Clare Co., Mich.
MU	Miller-USA 1-26, Mason Co., Mich.
MV	Miller-Victory 2-26, Mason Co., Mich.
PCD	Patrick-Cusumano/Divito 1-22, Macomb Co., Mich.
PSR	Petrostar-St. Roscommon 1-30, Roscommon Co., Mich.

Water Wells

Bn-147	Brown Co., Wisc.
Mt-190	Marinette Co., Wisc.

Figure 1. *Location map of study area. Stippled pattern identifies the outcrop area of the Jordan, Oneota, Shakopee, and St. Peter Formations. Squares indicate the locations of measured outcrop sections. Triangles indicate the locations of wells from which cuttings were examined.*

CONDITIONS OF AUTHIGENIC SILICIFICATION

In general, the prerequisites for near-surface silicification appear to include prolonged subaerial exposure, relatively slow rates of tectonic uplift and erosion, and temperate to tropical climate (for example, Hutton and others, 1972, 1978; Twidale and Hutton, 1986). Based on field and laboratory evidence for the slow rates of silica crystallization (for example, Siever, 1962; Ernst and Calvert, 1969; Maliva and Siever, 1988) long-term stability of the sediment surface may be the single most important factor limiting authigenic silicification in otherwise appropriate settings (for example, Hutton and others, 1978). Petrographic textures indicate that silica precipitates as solid amorphous silica (opal-A), opal-CT, chalcedony, or quartz (for example, Maliva and Siever, 1988, 1989).

Deposits of authigenic silica from a localized geographic area may display a broad range of characteristics related to variations in topography and bedrock composition, and patterns of colluvial transport. Authigenic silica from the Kalahari Basin of southern

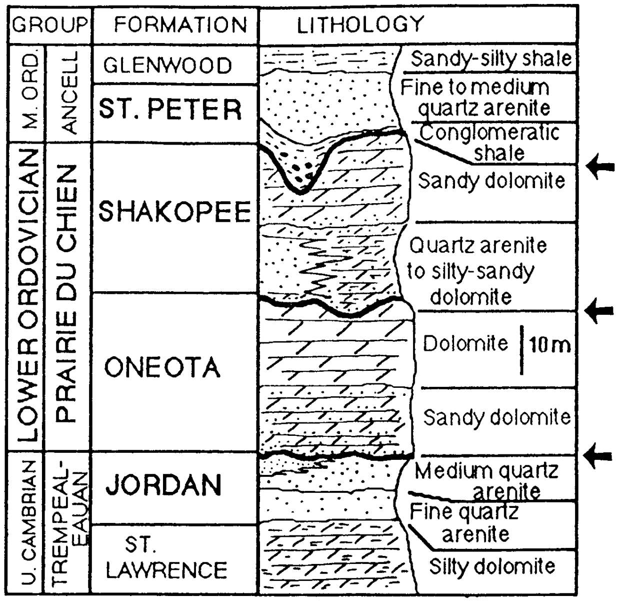


Figure 2. *Generalized stratigraphic column for the Jordan, Oneota, Shakopee, and St. Peter Formations in southwestern Wisconsin. Arrows indicate the positions of major, sequence-bounding unconformities overlying silicified intervals.*

Africa and of valley floors of the Beda Valley region of south-central Australia consists mainly of surficial crusts developed in semi-arid to arid settings on a variety of continental deposits, including fluvio-lacustrine and playa sediments, and calcretes (Hutton and others, 1972, 1978; Smale, 1973; Summerfield, 1983a, 1983b). In contrast, authigenic silica deposits from topographic highs in south-central Australia (Hutton and others, 1972, 1978) and from the relatively humid coastal setting of south Africa (Smale, 1973; Summerfield, 1983a, 1983b) commonly display relatively well-developed weathering profiles up to 10-20 m thick.

Authigenic silica deposits of the Paris Basin described by Thiry and Millot (1987) and Thiry and others (1988) are petrographically similar but not as thick (2-3 m, as opposed to 10-20 m) as weathering-profile deposits of South Africa (Summerfield, 1983a). Unlike authigenic silica deposits formed in the relatively stable geologic setting of South Africa, authigenic silica deposits of the Paris Basin developed through repeated silica dissolution, transport, and reprecipitation within progressively falling water tables associated with Pliocene-recent fluvial downcutting (Thiry and others, 1988; Thiry and Millot, 1987).

Silica in Paris Basin groundwater is typically present at low concentrations (12 mg/l), with Paris Basin silica deposits precipitating from neutral (pH = 7.2-7.4) groundwater (Thiry and others, 1988). In contrast, authigenic silica deposits formed in arid and semi-arid regions precipitate both in evaporative pedogenic settings, and at deeper levels from dilute groundwater (Thiry and Milnes, 1991).

PREVIOUS WORK

Following early work by Ulrich (1924) and Leith (1925), the study of authigenic silica fabrics in the Upper Midwest experienced several decades of neglect. Silica fabrics were first identified as silcrete by Dury and Knox (1971), Habermann and Dury (1974), and Habermann (1978), all of whom attributed the formation of authigenic silica crusts and weathering profiles to deep weathering under humid, tropical conditions during the Mesozoic to mid-Miocene, an interval of subaerial exposure and cratonic stability. Some of these features identified by Dury and Knox (1971) and Habermann (1978) instead may have formed during subaerial exposure associated with development of Cambro-Ordovician unconformities (for example, Smith, 1991, 1992).

METHODS AND GEOLOGIC SETTING

Authigenic silica fabrics were examined in uppermost Cambrian to Middle Ordovician strata within a region encompassing portions of Iowa, Michigan, Minnesota, and Wisconsin (fig. 1). Lithostratigraphic units studied include the uppermost Upper Cambrian Jordan Formation, the Lower Ordovician Oneota and Shakopee Formations (Prairie du Chien Group), and the Middle Ordovician St. Peter Formation (fig. 2). These Cambro-Ordovician strata were primarily deposited in tropical epeiric seas during four relative highstands of sea level that flooded most of the central North American craton (Smith and others, 1993, 1996). Development of the Cambro-Ordovician, mid-Lower Ordovician, and Lower-Middle Ordovician (Sauk-Tippecanoe) unconformities occurred during intervening lowstands of sea level (fig. 2). Measured sections and samples were obtained from 18 outcrops, 2 water wells, and 9 oil and gas wells (fig. 1). Approximately 350 thin sections were examined petrographically.

AUTHIGENIC SILICA IN OUTCROP

Nodular chert

Most nodular chert observed in outcrop is in the form of compact 1- to 10-cm diameter nodules concentrated along individual horizons. Viewed in thin

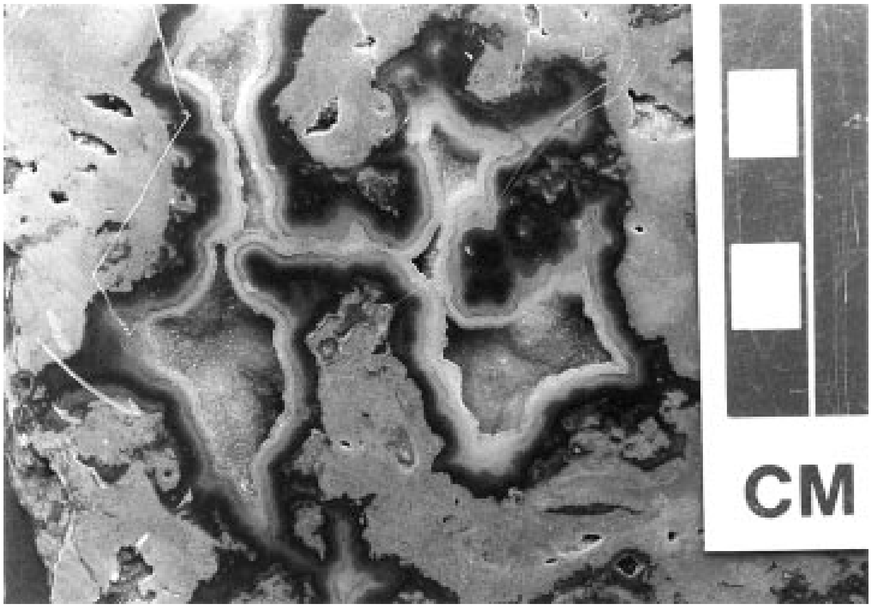


Figure 3. *Polished slab from the upper Oneota Formation near Hager City (HC), Wisconsin. Multiple bands of isopachous length-fast chalcedony and megaquartz are visible. The darker of these cements are distinctively colored purple, black, and reddish brown. Reddish-orange iron oxides and hydroxides superficially coat silica cements and fractures within the host dolomite.*

section, nodular chert from the Cambro-Ordovician section is uniformly microcrystalline and preserves micron-scale textures in exceptional detail. These chert nodules probably formed by the replacement of carbonate sediment by opal-CT, which later recrystallized to quartz, and/or by the direct precipitation of quartz as generally described by Maliva and Siever (1988, 1989).

Chalcedony-quartz aggregates

Unlike finely-microcrystalline nodular chert, most of the authigenic silica observed in Cambro-Ordovician rock of the upper Midwest consists of chalcedony and quartz aggregates displaying complex paragenetic relationships. Most chalcedony-quartz aggregates are irregular centimeter- to meter-scale masses of chalcedony and quartz containing open vugs lined with drusy quartz crystals (fig. 3). Drusy quartz crystals commonly line vugs within adjacent, relatively unaltered nearby dolomite. Chalcedony-quartz aggregates are commonly stained shades of yellow, red, purple, brown, and black by iron oxides and hydroxides. Paragenetic sequences are highly variable between outcrops.

Chert associated with hydrothermal minerals

Non-economic occurrences of Mississippi Valley-type mineral assemblages, mainly marcasite and pyrite, are present throughout the study area in rock of Cambrian to Silurian age (for example, Jenkins, 1968; Heyl and West, 1982; Kutz and Spry, 1989). Mineralizing fluids precipitated chert in addition to a variety of sulfides and carbonates (for example, Jenkins, 1968; McLimans, 1977), but little of the authigenic silica within Cambro-Ordovician strata is associated with Mississippi Valley-type mineral assemblages.

PETROGRAPHIC CHARACTERISTICS OF AUTHIGENIC SILICA

Microquartz (< 0.02 mm)

Replacement microquartz is abundant in Proterozoic-Paleozoic silcrete, where it may represent recrystallization of opal-CT and/or direct precipitation as quartz (for example, Rubin and Friedman, 1981; Ross and Chiarenzelli, 1985; Mustard and Donaldson, 1990). Microquartz (< 0.02 mm crystalline quartz, for example, Folk and Pittman, 1971) is the most abundant authigenic silica type observed in our study. Microquartz occurs as both a replacement phase and as a cement within carbonate rock with high primary permeability and porosity (for example, stromatolitic boundstone, oolitic grainstone, and paleokarst breccia). In thin section microquartz consists of melange of equant to elongate, anhedral to subhedral crystal aggregates containing abundant microdolomite inclusions and ghosts of peloids, ooids, and anhydrite (fig. 4). As a replacement phase, microquartz is typically associated with length-slow, spherulitic chalcedony. As a cement, microquartz forms isopachous pore-linings of isopachous, elongate, subhedral crystals that grade from microquartz into larger, euhedral megaquartz with well-defined

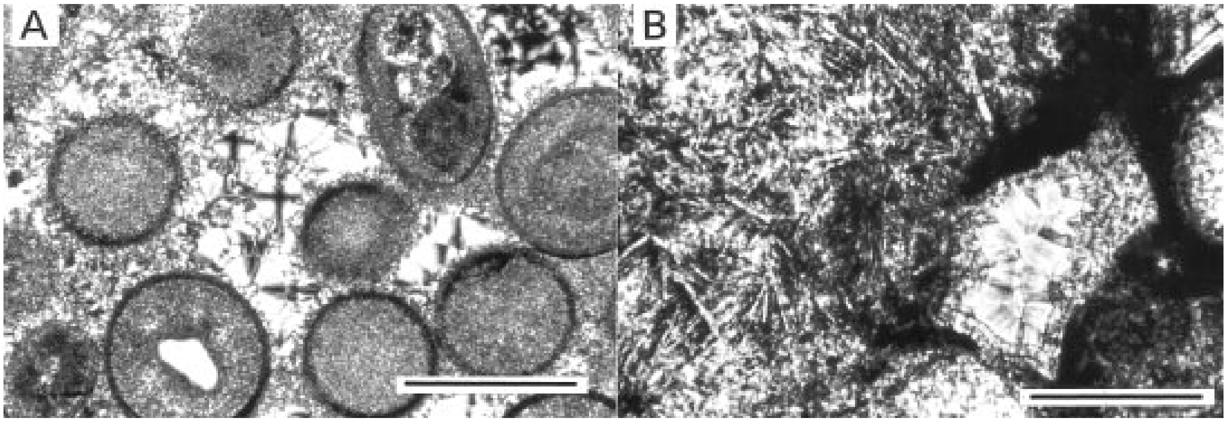


Figure 4. *Microquartz. A) Silicified oolitic grainstone from middle Oneota Formation at Hager City (HC), Wisconsin. Microquartz replaces ooids and occurs as an early pore-lining cement. Remaining porosity is filled by botryoids of length-fast chalcedony. Crossed nicols. Scale bar: 1 mm. B) Silicified anhydrite from basal Oneota Formation at Cazenovia (CZ), Wisconsin. Anhydrite ghosts are present within the lefthand portion of the photomicrograph. The vuggy pore within the righthand portion of the photomicrograph is filled primarily by isopachous, length-fast chalcedony cement. Crossed nicols. Scale bar: 0.5 mm.*

growth bands (fig. 5).

Megaquartz (> 0.02 mm)

Megaquartz (> 0.02 mm, for example, Folk and Pittman, 1971) forms distinctive drusy pore linings of euhedral, equant to slightly-elongate crystals up to 2 mm in length (for example, figs. 3 and 5). Colors range from clear to light orange, red, or purple. Megaquartz is less common as a replacive phase and occurs rarely as equant to elongate, subhedral to euhedral crystals containing needle-like anhydrite inclusions (fig. 6). Replacement of anhydrite by megaquartz is well-documented and is typical of evaporite silicification in shallow-burial diagenetic settings (for example, Milliken, 1979; Friedman and Shukla, 1980).

Syntaxial quartz overgrowths

Within the outcrop area, syntaxial quartz overgrowths are restricted to quartz arenite, sandy grainstone, and the quartz cores of moldic ooids (for example, Austin, 1974; Habermann, 1978). Subhedral to euhedral quartz overgrowths are readily visible in hand sample as tiny, reflective facets on freshly-exposed grain contacts. Simultaneous crystallization of quartz overgrowths and microquartz-megaquartz cements occurred where quartz overgrowths and microquartz-megaquartz overgrowths on carbonate grains meet at pore throats. Quartz overgrowths have been documented in a variety of Cenozoic silcretes (for example, Ambrose and Flint, 1981; Thiry and Millot, 1987; Khalaf, 1988; Thiry and oth-

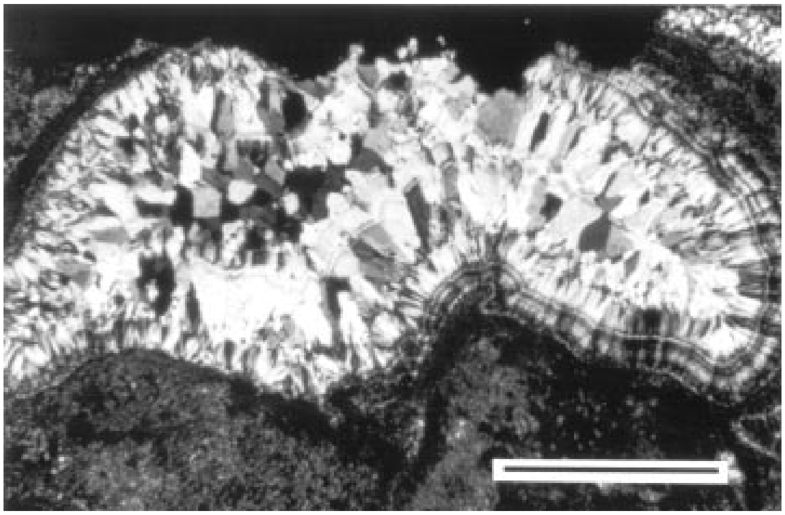


Figure 5. *Multiple generations of silica cements in the basal Shakopee Formation at the HR location: length-fast isopachous chalcedony, microquartz "palisade", and megaquartz (final cement phase). Crossed nicols. Scale bar: 1.5 mm.*

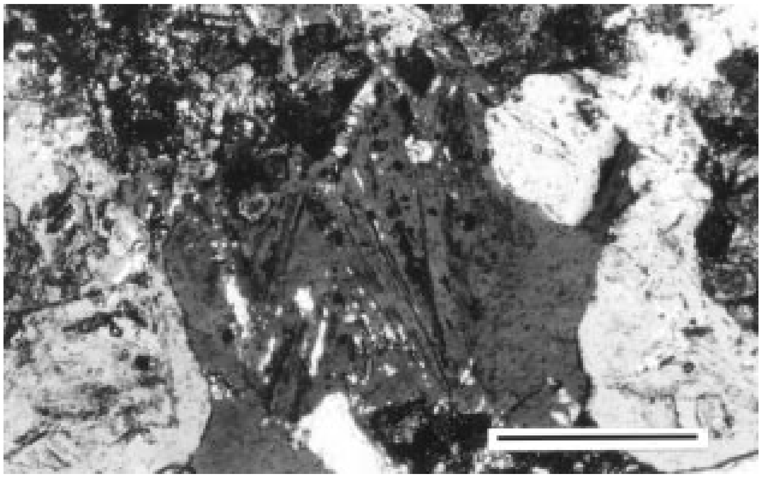


Figure 6. *Megaquartz replacing anhydrite. Silicified anhydrite nodule from basal Shakopee Formation east of Coon Valley (CV), Wisconsin. Silicification has preserved anhydrite texture. Bright needle-shaped patches within megaquartz crystal are anhydrite inclusions. Crossed nicols. Scale bar: 0.1 mm.*

ers, 1988), but are not by themselves necessarily indicative of near-surface weathering conditions.

Length-slow spherulitic chalcedony

Length-slow spherulitic chalcedony consists of irregular spherical masses of clear to brown, radiating-fibrous, length-slow chalcedony (for example, Noble and Van Stempvoort, 1989), displaying undulose extinction and pseudo-uniaxial crosses (fig. 7). Length-slow spherulitic chalcedony occurs as isolated spherules and coalesced masses within all of the studied silicified carbonate rocks. Length-slow spherulitic chalcedony is commonly associated with microquartz, but chalcedony is generally less abundant than microquartz. Length-slow chalcedony commonly replaces evaporite and carbonate (for example, Folk and Pittman, 1971; Jacka, 1974), but is not considered diagnostic of evaporite replacement.

Length-fast chalcedony

Length-fast chalcedony is locally abundant as a cement phase within silicified oolitic grainstone and other rock containing abundant pores. In hand-sample, length-fast chalcedony is isopachous, gray to milky-white in color, and contains millimeter-scale bands. In thin section, length-fast chalcedony is concentrically-banded, inclusion-rich, and yellow-brown in color. Botryoids of length-fast chalcedony commonly coalesce and are overgrown by isopachous length-fast chalcedony, although other sequences occur (figs. 3 and 8). Chalcedony cements are typically overgrown by microquartz and megaquartz cements (for example, fig. 3), a feature sometimes associated with evaporite silicification (for example, Milliken, 1979; Khalaf, 1988; Murray, 1990). Length-fast chalcedony cements growing directly on quartz grains are extremely rare (Austin, 1974).

STRATIGRAPHIC DISTRIBUTION OF AUTHIGENIC SILICA

Silica beneath unconformities

Authigenic silica fabrics are patchily distributed below unconformities. Stratigraphic intervals vary greatly in degree of silicification (for example, figs. 9 and 10). In general, beds with high primary and/or secondary porosity have been preferentially silicified,

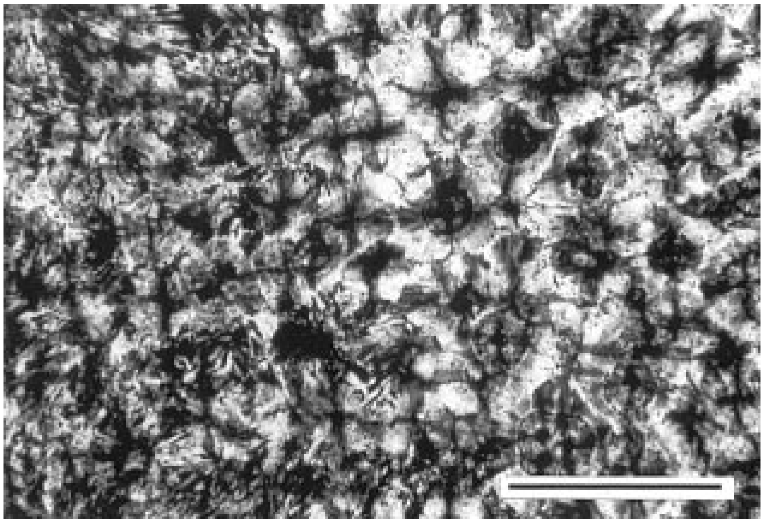
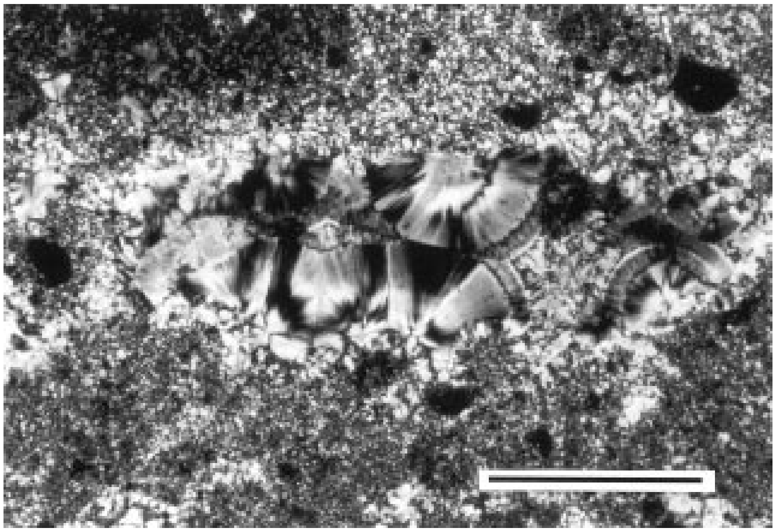


Figure 7. *Length-slow spherulitic chalcedony replacing anhydrite (left) and dolomite (right) in basal Oneota Formation at Cazenovia (CZ), Wisconsin. Note needle-shaped ghosts of anhydrite crystals within lefthand side of photomicrograph. Crossed nicols. Scale bar: 0.5 mm.*

Figure 8. *Length-fast chalcedony from the lower Oneota Formation at Blue River (BR), Wisconsin. A) Botryoids of length-fast chalcedony cement within vuggy pore in silicified peloidal(?) packstone. Crossed nicols. Scale bar: 1 mm.*



as noted by Leith (1925). The largest siliceous masses were observed in a roadcut and quarry east of Prairie du Chien, Wisconsin (figs. 9 and 10), where a 3-m thick stromatolitic layer located 3 to 6 m below the mid-Lower Ordovician unconformity has been altered to a massive cherty rock with abundant decimeter-scale vugs lined with chalcedony and quartz. Within the study area, large chalcedony- and quartz-lined vugs are unique to the Prairie du Chien Group.

Another distinctive silicified rock type occurs within a series of Oneota Formation outcrops within the upper Mississippi River valley (from HC to PDC, fig. 1). This rock type consists of partially-silicified 10- to 20-cm thick beds of 2-cm diameter vertical vugs, secondarily lined with chalcedony and drusy quartz cements (fig. 11). These tubular vugs are the molds of vertically-stacked stromatolites. Similar “piping” textures have been observed within silcrete profiles by Smale (1973) and Watts (1978), although stromatolites are not implicated in these Cenozoic examples.

Anhydrite beds and nodules were preferentially silicified, producing silicified anhydrite nodules and stratiform breccia. Brecciation suggests that volume loss by dissolution and compaction accompanied silicification. In contrast, individual silicified anhydrite nodules do not appear compacted, indicating anhydrite replacement after at least partial lithification.

At several locations (for example, PE, LB, PDC, and CZ, fig. 1), the upper 2-20 cm of the unit beneath the unconformity is pervasively silicified, forming an erosion-resistant cap (for example, fig. 12A). It is not clear whether the silicified layer represents a surface crust or exhumed beds originally silicified some dis-

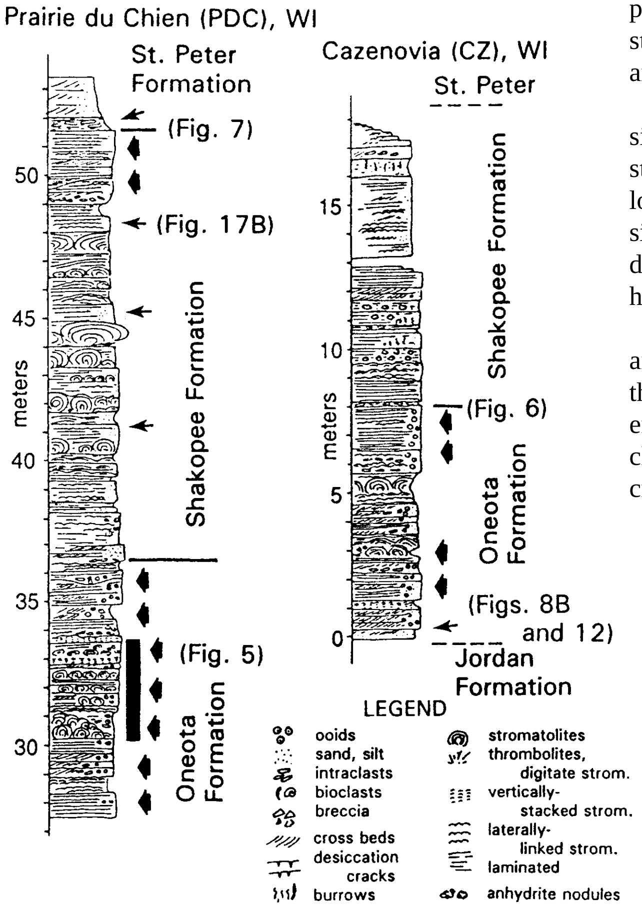


Figure 9. *Measured sections at the Prairie du Chien (PDC) and Cazenovia (CZ), Wisconsin, showing the stratigraphic distribution of diagenetic silica at these two localities. Broad arrows indicate zones of intense silicification. Thin arrows indicate the positions of reworked silcrete lithiclasts. Heavy bar indicates 3 m-thick zone of massive silicification within the upper Oneota Formation at the PDC section.*

tance below the ground surface.

Reworked silicified material

Reworked clasts form patchy, discontinuous breccia and conglomerate. Where silicified material is exposed along an unconformity surface, reworked clasts are abundant above the unconformity (fig. 12B). Reworked sand-sized grains occur up to 10-15 m above unconformities (for example, figs. 9 and 10). Silicified material also occurs within paleokarst, indicating that at least some silicification preceded paleokarst development.

GEOGRAPHIC DISTRIBUTION OF AUTHIGENIC SILICA

In the area of the axis of the Wisconsin Arch (for example, fig. 1., localities MC, SW, CZ, GB, and NL) the Cambro-Ordovician unconformity consists of an irregular surface locally overlain by conglomerates containing silicified clasts (Smith and others, 1993, 1996). Silicified oolitic-grainstone, quartz arenite, and anhydrite nodules underlie the Cambro-Ordovician unconformity surface, which is in turn overlain by reworked clasts (for example, fig. 13). The mid-Lower Ordovician, Oneota-Shakopee unconformity is an eroded paleokarst surface associated with abundant authigenic silica fabrics and reworked clasts (Smith and others, 1993, 1996). Both *in situ* and reworked silicified material are patchily distributed throughout the entire outcrop area and have been identified as far east as western Michigan (for example, fig. 1, locality MU).

The Lower-Middle Ordovician unconformity is another paleokarst surface developed during prolonged subaerial exposure. Both *in situ* and reworked silicified material are patchily distributed throughout the entire outcrop area. Despite recent work by Nadon and Smith (1992) documenting subaerial exposure of the Lower-Middle Ordovician unconformity across the Michigan Basin, silcrete appears restricted to the western margin of the Michigan Basin in eastern Wisconsin (for example, fig. 1, localities Bn-147, Mt-190, and NL). In the outcrop area, post-Early Ordovician dissolution and fluvial erosion produced 60-m-deep sinkholes and valleys in Lower Ordovician carbonate strata (Mai and Dott, 1985). This deep erosion potentially exposed the entire 60 m thickness of Lower Ordovician strata to surficial weathering processes, possibly resulting in

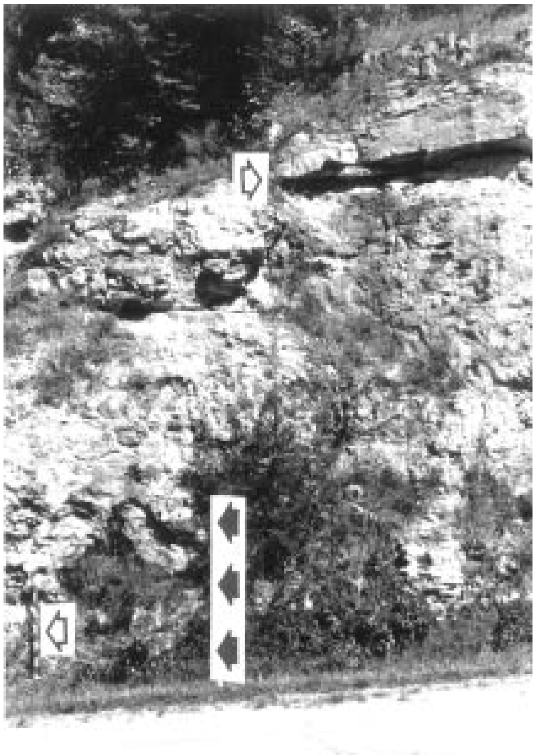


Figure 10. *Roadcut exposure of the upper Oneota Formation at Prairie du Chien (PDC), Wisconsin. Open arrows indicate the positions of the Oneota-Shakopee contact (upper arrow) and a 1.5 m-tall staff (lower arrow). Black arrows indicate the position of the upper end of a massive 3 m-thick zone of chert.*

Figure 11. *Outcrop view of silicified tubular vugs, the molds of vertically-stacked stromatolites, from the upper Oneota Formation near Hager City (HC), Wisconsin.*

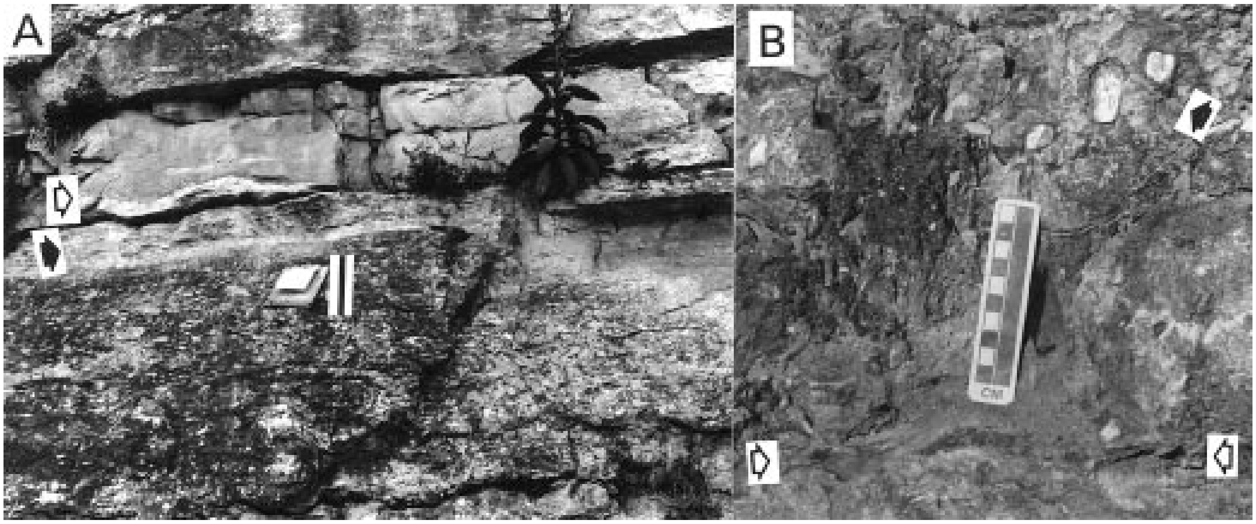


Figure 12. *A) Silicification beneath the Oneota-Shakopee contact east of Preston (PE), Minnesota. Open arrow indicates the position of the contact. Black arrow indicates a 30 cm-thick zone of massive cherty silicification beneath contact. Reworked silcrete lithiclasts (not visible in this photograph) suggest partial erosion of silcrete cap prior to Shakopee deposition. Scale bar: 30 cm. B) Close-up of Oneota-Shakopee contact at Lanesboro (LB), Minnesota. Open arrows indicate the contact. Black arrow indicates chert-pebble conglomerate (reworked silcrete lithiclasts) above contact.*

superimposed authigenic silica fabrics of different ages.

PALEOCLIMATIC INTERPRETATIONS

The most convincing paleoclimatic interpretations based on authigenic silica fabrics are supported by independent criteria, such as the presence of climate-sensitive minerals (for example, Habermann, 1978; Ross and Chiarenzelli, 1985; Khalaf, 1988; Mustard and Donaldson, 1990), fossil evidence (for example, Alley, 1977; Ambrose and Flint, 1981), and records of recent climate (for example, Thiry and others, 1988). Problems of interpretation commonly arise when interpreting fossil Cenozoic silcretes formed in a different climatic regime than the existing one (for example, Hutton and others, 1978).

Cambro-Ordovician strata of the Upper Midwest contain diagenetic features suggestive of both semiarid and humid climates. The mid-Lower and Lower-Middle Ordovician unconformities are associated with extensive paleokarst (Smith, 1989; Smith and others, 1993, 1996) and the Lower-Middle Ordovician unconformity appears to contain some fluvial channels (Mai and Dott, 1985), both of which imply relatively humid conditions. In contrast, nodular and bedded primary anhydrite (now moldic or silicified) within the Prairie du Chien Group suggests relatively arid conditions. The disparate evidence for both arid and humid climatic conditions sug-

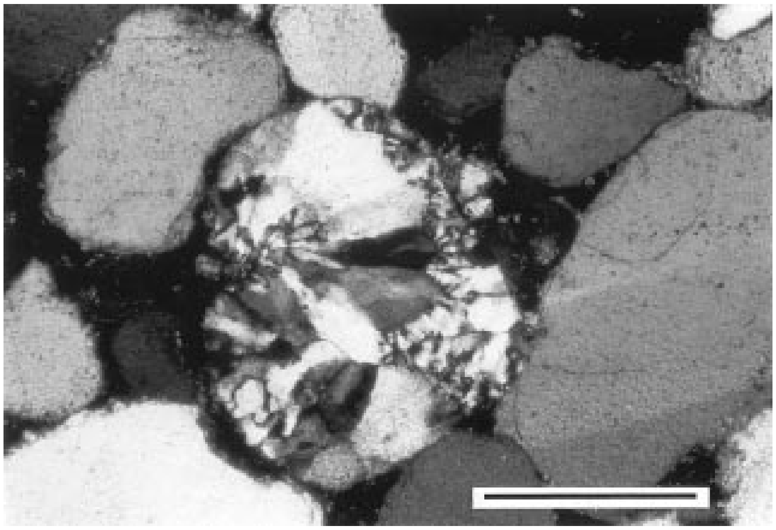


Figure 13. *Reworked silcrete clast containing truncated microquartz and megaquartz cements from the upper Shakopee Formation at Prairie du Chien (PDC), Wisconsin. Crossed nicols. Scale bar: 0.5 m.*

gests that a simple paleoclimate model based on authigenic silica fabrics would be inaccurate, but the climatic conditions inferred for Cenozoic silcretes are no less ambiguous (see Summerfield, 1983b; Twidale and Hutton, 1986).

CONCLUSIONS

Authigenic silica fabrics associated with the Cambro-Ordovician, mid-Lower Ordovician, and Lower-Middle Ordovician unconformities in the Upper Midwest show striking macroscopic and petrographic similarities to Cenozoic silcretes and are thus also interpreted as having formed during subaerial exposure. *In situ* silica is patchily distributed up to 30 m beneath unconformities, but is most abundant within 5 m of unconformities. Reworked clasts of silicified material are present above unconformities. Silica fabrics are best developed in exposures near the Wisconsin Arch axis. Authigenic silica fabrics are valuable indicators of subaerial exposure in carbonate rocks of the Upper Midwest because they are easily identified in well cuttings and are not masked by regional dolomitization.

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