Neoarchean Carbonates - Clues to Early Life and Early Ocean Chemistry

Leader: Dawn Y. Sumner,
Geology Department, University of California, Davis

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This field trip focuses on interesting carbonate facies in the Campbellrand Subgroup, Northern Cape, and interactions between microbial communities and carbonate precipitation. The field stops start in the oldest sediments and work towards younger ones. The guide consists of an overview of the Campbellrand Subgroup geology and the important facies that will be observed on the trip, followed by descriptions of the stops. Detailed descriptions of features at the stops are provided in writing and in stratigraphic sections included as inserts. References are provided at the end of the guide.

2 GEOLOGICAL OVERVIEW

The Neoarchean lower Campbellrand Subgroup contains the best preserved Neoarchean carbonates known. This field trip will focus sites that illustrate diverse aspects of carbonate deposition and the wealth of environmental and biological information that they provide (Fig. 1). The first full day in the field will focus on the Boomplaas Formation (of the underlying Schmidtsdrif Subgroup), a mixed siliciclastic carbonate ramp with ooids that reach up to 5 mm in diameter, commonly in reversely graded beds, and associated with stromatolite reefs. On the second day, we will investigate the Monteville Formation (the basal formation of the Campbellrand Subgroup), which contains diverse carbonate ramp facies, including stromatolites, molar tooth structures, and tsunami-deposited spherules that provide clues to correlations to the contemporaneous Hamersley Basin, Australia. The third day will be spent at the classic section through intertidal to shallow subtidal carbonates at Boetsap (Reivilo Formation). Here, the depositional relationships of abundant aragonite pseudomorphs and diverse stromatolite morphologies can be placed into Neoarchean environmental contexts. The fourth day in the field will be in the Gamoaana Formation at Kuruman Kop, which contains 200 m of well exposed section from lagoonal deposits, across a sequence boundary, followed by deep subtidal microbialites and then banded iron formation. The microbial structures are complex, some with no other known occurrences in the world, and show evidence for microbially influenced calcite precipitation. This site provides numerous insights into Neoarchean microbial ecology. The drive to and from Johannesburg and the field areas will include short stops at several geologically interesting sites, which are not described in this guide book.

The 2600–2520 Ma (Altermann and Nelson, 1998; Barton et al., 1994; Sumner and Bowring, 1996; Walraven et al., 1990) Schmidtsdrif, Campbellrand and Malmani subgroups, Transvaal Supergroup, South Africa, are correlative and compose a ~ 1.5 km-thick carbonate platform that is preserved over 190,000 km² and was probably deposited over > 600,000 km² on the Kaapvaal Craton (Fig. 2, Beukes, 1980; Beukes, 1987; Button, 1973; Eriksson and Truswell, 1974). It represents a transgression across the Kaapvaal Craton, and it is overlain by the thick Kuruman and Penge iron formations, which were deposited after drowning of the carbonate platform. Preservation of the Campbellrand–Malmani platform for 800 km perpendicular to strike, the thickness of the platform, the identification of sequence boundaries with all the associated systems tract architecture, and the presence of basinal facies, indicate that the platform formed in a pericratonic, probably passive-margin setting (Beukes, 1987).

The lithofacies in the transition from a mixed siliciclastic-carbonate ramp to a clean carbonate platform are typically shallowing upward sequences. These cycles are based by shale, which coarsens upward to siltstone in the Boomplaas Formation. The shale becomes calcareous upwards with interbeds of giant ooids abundant in the Boomplaas Formation and grainstones abundant in the Monteville Formation. Diastasis, a type of

Fig. 1: a) Outcrop map of the lower Transvaal Supergroup. We will visit site GE on day 2, MV on day 3, BT on day 4, and KU on day 5. b) Road map of the field area.
Fig. 2: Cross section of the Campbellrand and Schmidtsdrif Subgroups (after Beukes, 1987).

Fig. 3: Cross section of the Monteville and Reivilo formations. Sites are shown in fig. 1a.
synsedimentary deformation (Cowen and James, 1992), may be common in the transitional zone. Upwards, the cycles become cleaner carbonates, both grainstones and stromatolites. The tops of the cycles are dominated by stromatolitic carbonate. Most of the cycles do not shallow to an exposure surface. However, the uppermost cycle in the Monteville Formation is capped by a major sequence boundary marked by an influx of siliciclastic sand in many areas.

Above this sequence boundary, sedimentation is dominated by carbonate with only small proportions of shale and sand deposited during sea level low stands in proximal environments (near and east of Johannesburg), and shale accumulation in deeper basinal environments (near Prieska). The platform starts as a ramp, but develops into a rimmed margin during deposition of the Reivilo Formation (Fig. 2, 3). The margin remains rimmed with stromatolite reefs until drowning during a major sea level rise during deposition of the Gamohaan Formation and subsequent Kuruman Iron Formation. During the growth of this platform, facies tracts are well developed and show a geometry very typical of Phanerozoic rimmed platforms. The 800 km cross-strike extent of this platform demonstrates that the regional distribution of carbonate deposition is controlled by physicochemical conditions as much as by biological control.

2.1 Sedimentary Facies

In the main carbonate platform, eight lithofacies assemblages have been defined (Sumner, 1995). 1) **Slope and basinal lithofacies** include rhythms with interbedded turbidites, chert and dolostone breccias, carbonate shales, iron-formation, and tuffaceous turbidites (Beukes, 1987). 2) The **deep subtidal lithofacies** assemblage consists of a variety of “fenestral microbialites” (Sumner, 1997b; Sumner, 2000). 3) The **subtidal giant stromatolite lithofacies** consists of giant elongate mound stromatolites composed of columnar stromatolites, smooth to peaked laminae, and fanning aragonite pseudomorphs. 4) The **lagoonal lithofacies** assemblage contains fenestral microbial laminites and small domal stromatolites with an abundance of local truncation surfaces. 5) The **intertidal to shallow subtidal lithofacies** assemblage is dominated by columnar stromatolites, oolitic and non-oolitic grainstones, large fanning and fringing aragonite pseudomorphs, abundant erosional unconformities, rare channeling, and ripple, small dune, and low-angle cross-stratification in grainstones. 6) The **supratidal to upper intertidal lithofacies** assemblage consists of domal stromatolites, intraclast and ooid grainstones, intraclast breccias, tepee structures, small fanning pseudomorphs, halite pseudomorphs, and minor micrite. Grainstones contain wave-ripple stratification, desiccation cracks, intraclasts, and channels. 7) The **grainstone-dominated lithofacies** assemblage consists of beds of oolitic grainstones, non-oolitic grainstones, and wavy-laminated dolomite. They commonly are recrystallized to the extent that primary sedimentary features are difficult to identify. However, rare wave, interference, climbing, and current ripples are present. 8) **Quartz sands, siltstones, and siliciclastic shales** are more abundant at the base of the platform and are associated with exposure surfaces. Some aspects of these lithofacies assemblages are characteristics of carbonates of any age, whereas other aspects appear to be characteristic of Neoproterozoic carbonate deposition. This field trip will focus on some of the more unusual characteristics. The following paragraphs describe the facies observed on this field trip in more detail.

2.1.1 SHALE

The siliciclastic shales in the Boomplaas and Monteville formations consist of fine-grained clays and/or micas with an illite/muscovite composition (Bishop and Sumner, unpublished data). They contain rare to abundant interbeds of grainstones. Some of the grainstones fine upward and some are wave rippled. Sedimentary structures in associated grainstones suggest that the shales were deposited in deep water depositional environments. Some shales contain abundant molar-tooth structures.

**A Molar-tooth structures**

Molar tooth structure (MT) is a Precambrian sedimentary fabric consisting of contorted, millimetric- to centimetric-scale veins of microcrystalline calcium carbonate found in fine-grained host rocks. The Monteville Formation contains the only known Archean occurrence of MT. Researchers tend to separate MT formation into three steps: crack genesis, vein filling, and sediment compaction. Cracks did not form at the sediment-water interface, because detrital grains are absent from vein fill (Frank and Lyons, 1998). However, veins commonly are reworked, and sand lenses and mud laminations commonly are differentially compacted around the MT. The model of Furniss et al. (1998) in which ragged, contorted cracks form when gas generated by organic decay rises through firm, fine-grained sediment. Furniss et al. (1998) experimentally modeled this process using aquarium filled with a plaster, clay, sugar, and yeast slurry. The yeast metabolized the sugar to produce gas, which rose through the firm sediment; the rising gas bubbles created contorted cracks, which were filled with water. Furniss et al. (1998) poured plaster of Paris into the cracks to preserve ‘veins’ which showed all of the various morphologies of MT in the Belt Supergroup, Montana.

MT in the Monteville Formation is found in a depositional environment above storm wave base and below areas swept by tidal currents, consistent with the interpretation of James et al. (1998), in which MT is limited to environments above storm wave base. MT appears both in situ and reworked in the Monteville
section. Veins predominantly trend stratigraphically upward when in situ in shale and rarely continue through grainstone lenses. In the grainstone lenses, veins commonly are reworked into clasts and grains. Veins are found in situ in shale drapes and in the troughs of foresets where shale has been winnowed away.

Monteville MT is hosted in a muscovite or illite shale; whereas, most Proterozoic examples are hosted in shaley lime- or dolo-mudstones. Intercalated sand lenses are common in MT sections; in the Proterozoic, sands tend to be reworked MT or ooids. Monteville grainstone, however, is comprised of organic-rich carbonate grains which have been partially replaced/in-filled with MT microsparite. The microsparite also cements many of the grainstone lenses. In addition, the transition from environments with and without MT coincides with a change in grain sizes (i.e., from shale with intercalated silt to shale with intercalated sand). Where silt and sand lenses are found together, MT veins more commonly form beneath sand lenses. With the gas expansion model for MT in mind, these observations suggest that variations in pore pressures may have played a crucial role in determining the formation and orientation of MT.

2.1.2 GRAINSTONES

Diverse grainstone are present in the Campbellrand Subgroup. Most of the grainstones consist of dolomitized grains of unknown origin. These beds are massive, graded, or cross stratified. Stratification styles suggest turbidite deposition, storm wave transport, tidal transport, migrating shoals, shallow wave transport, and current transport in different depositional environments.

Ooids are abundant in the Boomplaas Formation and were deposited in migrating shoals and some inversely graded beds (Beukes, 1979; Beukes, 1983). Ooids in the inversely graded beds reach diameters of up to 5 mm. Beds such as these are common in peritidal facies of the Malmani Subgroup, and have been interpreted as representing times of extended ooid growth with a limited influx of new sediment (Sumner and Grotzinger, 1993).

Spherical grains that appear similar to ooids are also abundant in the Monteville Formation. However, thin sections of these grains show that they are very organic-rich. One possible origin for these grains is spherical balls of organics in which carbonate precipitated, possibly during microbial decay.

Ribbon-rock facies are also present in the Boomplaas and Monteville formations, and are interpreted as fine-grained (silt-sized?) carbonate deposited in moderately quiet water with fluctuating flow speeds. Ribbon-rock facies commonly show evidence for soft sediment deformation.

A Soft Sediment Deformation

Diastasis is synsedimentary deformation that occurs at the sediment-water interface or shallow

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Fig. 4: Model results from Cowan, Bishop and James (2001). Plaster is white, sand is dark; in all photos, white arrows identify larger plaster clasts that were mobile in liquified sand and resemble 'transported' intraclasts (c.f., Bouchette et al., 2001), black arrows identify typical crack configurations that occurred under a range of experimental conditions—these cracks can be either open (sand-filled) or closed (hairline or unfilled), and cut through the plaster from either above or below. Conspicuous recurring features include (A) contorted plaster layers with ragged upper and/or lower surfaces (grey arrows), (B) delamination of plaster at the plaster-sand interface (grey arrow), (C) characteristic crack configurations, (D) delicately cuspate-lobate plaster-sand interfaces (grey arrows), and (E) plaster boudinage.
substratally. It forms when layers of differing competence are subjected to stress (Cowan and James, 1992). Sediment boudinage is a common example of this phenomenon. Diastasis can be created when shear and loading of the sediment pile crack or otherwise deform relatively stiff (competent) layers and liquefy intercalated granular (incompetent) layers. Cracks in the competent layers may be filled with the granular sediment (either passively or through injection), or occluded by cement. In the geologic literature, synsedimentary cracks in sediments layer at the mm-, cm- and dm-scales are commonly attributed to either desiccation or syneresis, but many examples may in fact be diastasis. Cowan et al. (2001) experimentally modeled diastasis by layering water-saturated sand and plaster of Paris in flexible aluminum containers. The containers were subjected variably to simple shear, shear/torque, and loading while the plaster solidified (from a viscous fluid, to a firm material, and ultimately to a hard solid). Cross-sections through models revealed a variety of deformation features that are strikingly similar to those found in ancient sediments (Fig. 4).

Sources of shear and loading in sedimentary environments include storm waves, seismicity, and differential loading. Most common, perhaps, would be the rapid application of stresses induced by the passage of large storm waves through shallow water. Storm waves are of profound interest to coastal and marine engineers, and are known to transmit significant shear and loading 10’s to 100’s of meters into the sediment pile; such wave-induced stresses are common across a range of water depths from the beach to storm wave base. Diastasis can thus be produced in many environments where sediments of contrasting competence are interlayered (e.g., lime mud and sand, siliciclastic clay and sand, bio-stabilized and non-stabilized sand or mud, firm mud and soupy mud, etc.).

Diastasis features are present in the Boomplaas, Monteville, and Gamohaan formations and are best developed at Stop 1, Gewonne Farm. At Gewonne, ribbon-rock facies are substantially deformed in a pattern that reflects the shallowing upward cycles interpretable from facies changes. Deformation may have been caused by storm waves with more intense deformation when the water was shallower. These shallowing-upward cycles include platy breccias in which clasts were repeatedly cracked and displaced through the sediment pile. The relationships among stromatolite, oolitic, and deformation of sediments have yet to be explored. At Kuruman and Monteville, diastasis is associated with, soft-sediment-deformed beds which have competent layers within their folds. At Monteville, shale and carbonate ribbon-rock are deformed, with both lithologies behaving variably competently or plastically. At Kuruman, highly visible black, cherty material was cracked and filled with fine-grained sediment.

2.1.3 "THROMBOLITIC" BIOSTROMS

In the Monteville Formation at Monteville Farm, several large bioherms contain thrombolitic to stromatolitic textures. At outcrop scale, they consist of limestone, dolomite, and chert. Structures include flat-laminated (mm-scale), domed (cm-scale), and irregularly laminated, spar-rich microbial structures. At the hand-sample scale, fabrics range from little lamination or clotting to irregularly laminated and "clotted" textures. The cm-scale ‘clots’ commonly appear to be balled aggregates of laminations. Thus, they are not completely analogous to more typical Phanerozoic thrombolites.

In thin-section, some of these structures contain subtle filamentous forms (~150 µm in diameter) that suggest a microbial origin. Dark, organic matter defines these forms and also coats the walls of primary cavities in which geopedal textures are preserved. Beneath clasts, detrital silt and coarse spar occlude porosity. This texture compares favorable with those of microbial bioherms in the Cambrian Ledger Formation, Pennsylvania (deWet, pers. comm., 2002). It is distinctly different from most stromatolitic textures in the Campbellrand Subgroup, which consist of organic inclusions in fibrous cement-like calcite crystals.

2.1.4 COLUMNAR STROMATOLITES

Columnar stromatolites (Fig. 5a) form beds up to several meters thick and as well as isolated bioherms up to 1 m in diameter. Bioherms commonly are developed on unconformities and are overlain by grainstones. Individual stromatolites, usually 1-20 cm in diameter, show a variety of branching patterns and wall structures. Many of the columnar stromatolites at Boetsap were classified as belonging to the groups Topinamboura, Radiatina, Katernia, Pilbaria, Tibia, and Sapinia (Bertrand-
Sarfati and Eriksson, 1977). The microtexture of many of the columnar stromatolites consists of vertically oriented elongate crystals and fine, filmy laminae defined by organic inclusions (Bertrand-Sarfati and Eriksson, 1977). The crystals are elongate vertically, oriented optically, and contain petrographic characteristics similar to calcite and Mg-calcite cements. Some columns have a herringbone calcite microtexture (Sumner and Grotzinger, 1996a).

At the base of the Boetsap section, irregular decimeter-scale domal stromatolites also are present (Fig. 5b). These domes are dolomitized and contain cm-thick laminae that pinch and swell and are truncated along abundant micro-unconformities. They have low inheritance. Lenses of grainstone are common between and within domes. The pinching, swelling, and truncation of laminae as well as the abundance of associated grainstone suggest that these domes formed by trapping-and-binding of coarse-grained sediment.

2.1.5 GIANT ELONGATE STROMATOLITE MOUNDS

Shallow subtidal elongate stromatolites range from 2 to 10 meters wide and from 5 to >45 meters long (Fig. 10, Truswell and Eriksson, 1973). Synoptic relief ranges from 30 to 200 cm. The mounds contain small columnar stromatolites, smooth to peaked laminae, herringbone calcite encrustations, and aragonite pseudomorph fans. They have rare interbeds of rippled grainstone, breccia, and flat lying beds with aragonite pseudomorph fans.

Columnar stromatolites within the elongate stromatolites are 1-5 cm in diameter and have convex to rectangular laminae with a variety of branching patterns. Some of them are classified as belonging to the groups Radiatina and Katernia (Bertrand-Sarfati and Eriksson, 1977). These stromatolites contain both optically oriented crystals and silt-sized clastic grains, including rare quartz silt (Bertrand-Sarfati and Eriksson, 1977), suggesting a combined precipitated and trapped-and-bound origin for the small columnar stromatolites.

Smooth to peaked laminae in the elongate stromatolites, herein called Boetsap-style lamination, in many elongate stromatolites consist of dark red-brown microcrystalline carbonate lamellae, lighter red-brown to gray finely crystalline lamellae, and light gray coarse sparry layers (Fig. 9). Rare patches of herringbone calcite also are preserved in rocks with the Boetsap-style lamination.

Red-brown microcrystalline carbonate lamellae consist of dolomite and range from 1 to 3 mm thick along a single lamella. Commonly, their upper surfaces are peaked, similar to peaked laminae in peritidal domal stromatolites. They occasionally contain a vertical fabric suggestive of very fine, vertically oriented aragonite pseudomorphs (Fig. 9). Red-brown microcrystalline carbonate laminae make up about 50% of a bed classified as containing the Boetsap-style lamination. Light red-brown to gray, finely crystalline lamellae are uniformly <1 mm in thickness. Gray, finely crystalline lamellae are predominantly calcite whereas red-brown lamellae consist of dolomite. Gray and red-brown lamellae grade laterally into each other suggesting that the red-brown lamellae are dolomitized gray lamellae. A vertical fabric is visible in thicker lamellae, and occasionally

Fig. 6: Giant elongate stromatolites at Boetsap. The cliff is the upper part of Section 2. Geologist for scale in the circle.

Fig. 7: Boetsap style laminae with vertical aragonite pseudomorphs projecting through the layers.
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fibrous crystal pseudomorphs project through lamellae in a fan-like geometry (Fig. 9). Gray and red-brown finely crystalline lamellae compose about 50% of layers with the Boetsap-style lamination. Coarse sparry laminae consist of dolomite and vary laterally in thickness, occasionally pinching out. They are up to 1 cm thick and contain ripple stratification. Coarse sparry laminae do not contain a vertically oriented fabric and make up <1% of laminae.

Red-brown microcrystalline carbonate layers are interpreted as dolomitized fine-grained clastic carbonate with a small proportion of neomorphosed aragonite represented by the vertically oriented fabric. Both red-brown and gray finely crystalline laminae are interpreted as variably altered precipitated laminae. The vertical crystal fibers that project through lamellae were probably originally aragonite (Sumner and Grotzinger, 2000). Rare herringbone calcite demonstrates that Mg-calcite also precipitated in the giant elongate stromatolites. Coarse, sparry laminae are interpreted as recrystallized clastic carbonate deposited from tractional currents.

2.1.6 LAGOONAL FACIES

The lagoonal lithofacies assemblage contains fenestral, microbial laminae and small domal stromatolites. The fenestral microbial laminae consist of dark, finely laminated, 5 mm-thick layers of calcite that alternate with 5 mm-thick white sparry calcite layers to form meter-thick beds of limestone (Fig. 8). Both dark and white layers of calcite are laterally discontinuous and abundant erosional truncation of laminae is apparent. Rare breccias with <1 cm diameter clasts are associated with some of the truncation surfaces. White layers are coarsely crystalline and crystals appear to have grown inward from the top and bottom of the layers. Fine laminae within dark layers are defined by organic inclusions. These laminae are interpreted as having been produced by microbial mats based on the abundance of organic inclusions and the style of the fine laminae (Beukes, 1987). White layers are probably laminoid fenestrae filled with early cements (Beukes, 1987).

Light gray ≤10 cm-diameter domes are interbedded with the fenestral laminite lithofacies (Fig. 8). Typically, these domes formed 5-10 cm-thick beds, but beds up to 1.5 m-thick are present. The hemispherical domes are laterally linked with laminae of even thickness. The domes grew upward with isopachous laminae, a few mm-thick, coating the initial dome. The domes are composed of coarsely crystalline calcite with a rare crystal elongation perpendicular to lamination. The isopachous geometry of the domes and the crystal elongation are consistent with a precipitated origin, either calcite or aragonite.

The fenestral laminite lithofacies alternates with the isopachous dome lithofacies on a decimeter to meter scale. Occasionally, several meter-thick intervals of fenestral laminite lithofacies contain very poorly developed isopachous domes, and the two lithofacies are gradational into each other. The alternation of these two textures may be cyclical.

The abundance of small truncation surfaces and the lack of cross stratification and channeling suggest a shallow subtidal depositional environment with little agitation. The stratigraphic position of these lithofacies platformward of a rimmed margin consisting of the intertidal to shallow subtidal columnar stromatolite-dominated lithofacies assemblage suggests a lagoonal depositional environment (Fig. 2, Beukes, 1987).

2.1.7 SHALLOW SUBTIDAL CEMENT-GRAINSTONE CYCLES

Giant mound stromatolites at the base of the Gamohaan Formation contain 3 to 10 cm thick cyclic beds with basal light tan grainstones that grade upward into 75 to 90% precipitated herringbone calcite crusts that sometimes consist of stromatolites (Fig. 9, Sumner, 1997a). Some grainstones contain centimeter high bedforms showing bi-directional sediment transport. The grainstones grade upward into either herringbone calcite crusts with a laterally uniform thickness or into 3-5 cm diameter columnar stromatolites (Sumner, 1997a). The stromatolites are poorly laminated and often contain a herringbone calcite microtexture. They widen upward leaving tear-drop shaped troughs that are filled with the basal grainstone of the overlying bed. The tops of cycles sometimes are scoured and marked by irregular truncation surfaces (Sumner, 1997a). The origin of cyclicity in this facies is unknown. For grainstone-cement cycles, a long hiatus between influxes of grains could result in cross stratified grainstones followed by thick hardgrounds. However, it is not clear why stromatolites in the stromatolite-cement cycles quit growing to allow the thick layers of cement to form without substantial stromatolitic morphologies.

2.1.8 FENESTRATE MICROBIALITES

Fenestrate microbialites contain three components (Fig. 10, Sumner, 1997b; Sumner, 2000): draping, mat-like laminae; vertically oriented structures called supports; and voids filled with carbonate cements. Mat-
like laminae are 1 to 10’s µm thick, very smooth, and defined by organic inclusions. These laminae were flexible and laterally cohesive during growth as demonstrated by recumbent synsedimentary folding of laminae. Supports are 100 to >300 µm wide and commonly are oriented vertically. They are interlocking surfaces in 3-dimensions and branch in some microbialites (Sumner, 1997b; Sumner, 2000). They are defined by organic inclusions and are interpreted as microbial in origin due to their three-dimensional geometry and their soft, folded character in some microbialites (Sumner, 1997b; Sumner, 2000).

Fenestrate microbialites are classified into seven end-member microbialite morphologies: planar laminae, rolled-up laminae, tented microbialites, net-like microbialites, cuspate microbialites, irregular columnar microbialites, and plumose structures (Sumner, 1997b; Sumner, 2000). Beds of herringbone calcite lacking microbial structures also are present. Five assemblages of microbial structures include: 1) The bedded cuspate microbialite assemblage consisting of interbedded cuspate microbialites, contorted laminated mat, and plumose structures (Sumner, 1997b; Sumner, 2000). Beds of herringbone calcite lacking microbial structures also are present. Five assemblages of microbial structures include: 1) The bedded cuspate microbialite assemblage consisting of interbedded cuspate microbialites, contorted laminated mat, and plumose structures; 2) The planar laminated mat assemblage consisting of planar laminated mat, tented microbialites, and contorted laminated mat; 3) The irregular columnar microbialite assemblage consisting of irregular columnar microbialites, contorted and planar laminated mat, plumose structures, herringbone calcite beds, cuspate microbialites, and tented microbialites, in order of decreasing abundance; 4) The contorted laminated mat assemblage consisting of contorted and planar laminated mat with rare interbeds of shale and cuspate microbialites; and 5) The net-like microbialite assemblage consisting of dcm-thick cycles with net-like microbialites at the base and grainstones or columnar stromatolites at the top.

These microbialite subfacies are distributed in different parts of the platform. Microbialites basinward of the platform margin consist of a mix of the bedded cuspate, irregular columnar, and contorted laminated mat assemblages interbedded with organic-rich shale, slope breccia, and nodular limestone and dolomite. Microbialite units deposited on top of the platform during transgressions consist exclusively of the net-like microbialite assemblage. During final drowning of the platform and deposition of the Gamohaan Formation, fenestrate microbialites with all textures except the net-like microbialites were deposited across the entire platform.

2.1.9 CARBONATE CEMENTS
Calcite and pseudomorphed aragonite cements are abundant in the Campbellrand Subgroup. In some sections, they form up to half of the preserved sedimentary texture, they coat sedimentary surfaces, and form the microtextures of many stromatolites.

A Aragonite Pseudomorphs
Fanning crystal pseudomorphs grew off the sides of columnar stromatolites and upward from bedding surfaces (Fig. 5a, 11, Sumner and Grotzinger, 2000). The pseudomorphs consist of millimeter- to centimeter-wide linear zones of clear calcite, dolomite, and/or recrystallized chert that exclude all surrounding sediment.

Fig. 9: Grainstone-cement (A) and stromatolite-cement (B) cycles. Arrows point to cycle tops.

Fig. 10: Fenestrate microbialites.
They are clumped into bundles of fibrous crystals that grew upward in a radial pattern from a single point and reach heights of over 50 cm. Commonly, the sprays of crystals are draped by sediment and form domes geometrically similar to stromatolites. Rare fan layers contain no clastic carbonate and void space between fans is filled with herringbone calcite and other fibrous precipitated calcite. Neighboring fans commonly intersected each other as they grew, and the most inclined bundles of crystals abut each other (Sumner and Grotzinger, 2000), whereas more vertically oriented crystals continued to grow upward. Beds with a high influx of sediment relative to growth rate of the fans are characterized by small pseudomorph fans and thick layers of draping sediment. Usually, growth of the precursor crystals was terminated by thick layers of sediment, but rarely the most vertically oriented crystals projected above the sediment layer and continued to grow. In beds with lower sediment influx, pseudomorphed crystals that radiated at a low angle to bedding commonly are overlain by a layer of sediment that terminated their growth whereas more vertically oriented crystals continued to grow. Where fans are very closely spaced, only the most upright crystals continued to grow, and a fringe of crystals oriented perpendicular to bedding developed. Similarly, some thinly laminated beds contain crystal pseudomorphs that were elongate perpendicular to bedding without a botryoidal geometry. These pseudomorphs of fine fibrous crystals extend through multiple laminae. They always are oriented perpendicular to bedding and parallel to each other. Laminated sediment fills space between the crystals. These textures are common in the giant elongate stromatolites.

Commonly, crystal fringes grew off the sides of stromatolites in shallow subtidal depositional environments and in the reef-like margin of the platform (Fig. 5a, Bertrand-Sarfati and Eriksson, 1977). These pseudomorphs consist of parallel fine fibers that grew perpendicular to the stromatolite surface. They sometimes coat the entire stromatolite, but more frequently grew as < 1 mm to 10 cm thick lenticular to botryoidal coatings projecting into inter-stromatolite troughs. The fibrous fringes often are coated by later fibrous calcite marine precipitates, including herringbone calcite (a marine cement texture, Sumner and Grotzinger, 1996a), or are overlain by grainstone.

The exclusively upward growth of fanning fibers, their presence in beds lacking detrital carbonate, and the presence of shelter porosity under steeply inclined pseudomorphs all suggest that the fans grew directly on the sea floor and not as diagenetic crystals within the sediment (Sumner, 2001; Sumner and Grotzinger, 2000).

Several of the petrographic characteristics of the fanning pseudomorphs strongly suggest an aragonite precursor mineralogy. First, the relict morphological characteristics of the original crystals are most consistent with an aragonite precursor: the fibrous nature of the primary mineral and the blunt to feathery terminations of the pseudomorphs are typical of aragonite. Gypsum crystals usually have well developed crystal faces, none of which were observed. Second, optically unoriented, equant to elongate calcite crystals with unit extinction are characteristic of the fans as well as of calcite replacement of aragonite (Sumner, 2001; Sumner and Grotzinger, 2000). Gypsum and anhydrite typically are replaced by calcite in a dissolution–precipitation process, so preservation of inclusions defining the internal texture of a gypsum precursor is not expected. Also, secondary calcite mosaics filling gypsum molds would show either a void-filling geometry or an equant neomorphic texture rather than elongation parallel to pseudomorph elongation. Solution-collapse features, which can be associated with replaced gypsum pseudomorphs, are absent. Thus, a combination of the primary crystal morphology and the petrographic textures of the pseudomorphs are inconsistent with gypsum as the precursor mineral.

Marine aragonite commonly contains tens of thousands of ppm strontium initially, and thousands of ppm strontium can be preserved in aragonite pseudomorphs during conversion of aragonite to calcite at low water-to-rock ratios. Concentrations of several thousand ppm are rare in calcite except when it has replaced aragonite. Thus, high preserved [Sr] supports the interpretation of an aragonite precursor to the pseudomorphs. Low [Sr] may reflect either high water-to-rock ratios or a different precursor mineral. Strontium concentrations of calcite cements and pseudomorphs from Boetsap were measured using an electron microprobe. The highest concentrations of strontium are found in pseudomorphs from the lower part of Section 7a and Section 7b. This suggests that these pseudomorphs were formed in a setting with a high water-to-rock ratio, possibly in a shallow subtidal environment. The strontium concentrations in these pseudomorphs are consistent with the interpretation of an aragonite precursor.

Fig. 11: Aragonite pseudomorphs from Boetsap Section 1, 60.5m and Section 2, about 24m. Note the way the fanning pseudomorphs interfere with each other. Sediment drapes the pseudomorphs.
[Sr] were measured in a botryoidal pseudomorph from Boetsap, where concentrations from 1800 to 3700 ± 400 ppm were measured (Sumner and Grotzinger, 2000). Six other pseudomorphs also show local [Sr] of over 900 ppm. The preservation of several thousand ppm Sr in the pseudomorphs supports an aragonitic precursor.

**B Herringbone Calcite**

Herringbone calcite is a serrate calcite cement texture (Fig. 14, Sumner and Grotzinger, 1996a). It consists of alternating light and dark crenulated bands; each light-dark pair is 0.5-1.0 mm thick. Microscopically, each pair of bands consists of a row of elongate crystals with their long axes aligned perpendicular to banding and along the growth direction of the cement. The bases of the crystals are optically unoriented, but upwards in each crystal, the optical axis rotates until it is perpendicular to crystal elongation. The tops of the elongate crystal are thus optically aligned and length slow. The light bands of herringbone calcite correspond to the optically oriented parts of the elongate crystals whereas the dark bands correspond to the optically unoriented, lower parts of the elongate crystals. A Mg-calcite precursor for herringbone calcite, now preserved as low-Mg calcite or dolomite, is supported by the presence of microdolomite inclusions and textural differences between herringbone calcite and textures interpreted as neomorphosed former aragonite.

### 2.2 Focus of Each Stop

**Day 1** will be taken up with travel from Johannesburg to Kimberly. Several short stops are planned, but are not part of the focus of this trip. Thus information on them will be provided on the field trip.

**Day 2:** Stop 1 will focus on the Boomplaas Formation at Gewonne Farm. Here, ooids up to 5 mm are abundant, possible diastasis deformation of ribbon dolomite is abundant, and siliciclastic-carbonate shallowing upward cycles are well exposed. We will focus on discussing the mechanisms for synsedimentary deformation and the roles of physical, chemical, and biological processes in shaping the lithofacies. At stop 2 Suwefontein Farm and along the escarpment, slope facies in the Monteville and Reivilo formations are well exposed. These sediments contain shale to carbonate shallowing upward cycles followed by a thick succession of fenestrate microbialites, similar to those at Kuruman Kop (Day 4). They are temporal equivalents to sediments at stops 3, 4, and 6.

**Day 3:** Stop 3 will focus on a thick shallowing-upward cycle at the top of the Monteville Formation at Monteville Farm. This interval contains the only known Archean occurrence of molar tooth structure. The molar tooth is present in shales near storm wave base. The sediments shallow upward into tidal and stromatolitic facies and then a major sequence boundary. Stop 4 is in the base of the Reivilo Formation and is an introduction to columnar stromatolites with a herringbone calcite microstructure and aragonite pseudomorphs. Stop 5 is at the base of the Monteville Formation (road conditions permitting), and contains an impact spherule layer that may be correlative to one of several in Neoarchean sediments of Western Australia.

**Day 4:** Stop 6 will focus on the Reivilo Formation near Boetsap. This shallow subtidal to intertidal sequence of rocks contains abundant stromatolite types, well preserved aragonite pseudomorphs, and diverse sedimentary structures. These strata were deposited during development of the platform margin farther basinward.

**Day 5:** Stop 7, at Kuruman Kop, contains the transition from lagoonal sediments of the Kogelbeen Formation through a sequence boundary to deep subtidal fenestrate microbialites of the Gamohaan Formation. This site shows the diversity of microbial structures that developed in environments with low sediment influx. The roles of carbonate precipitation and microbial processes will be the focus of much of the stop. Day 6 will be dominated by the return drive to Johannesburg.
3 FIELD SITES

3.1 Day 1
Drive from Johannesburg to Kimberley. We will stay at the Kimberley Holiday Inn.

3.2 Day 2
Today, we will focus on the mixed siliciclastic-carbonate sediments of the ramp at the base of the Campbellrand-Malmani carbonate platform. In the Boomplaas Formation, questions of interest include the origin of deformation of ribbon rocks, the causes of cyclical changes in facies, and the origin of giant ooids (Beukes, 1977; Beukes, 1979; Beukes, 1983). Higher in the section, near the Monteville-Reivilo contact, a change from mixed siliciclastic-carbonate sedimentation to fenestrate microbialite growth reflects the drowning of the entire Kaapvaal Craton. These sediments are distal equivalents to those seen on stops 3 and 5.

3.2.1 STOP 1: BOOMPLAAS FORMATION AT GEWONNE FARM

A Driving Directions:
Please note that the gates to Gewonne Farm commonly are locked. Permission to enter and arrangements for the gates to be unlocked are required a minimum of several days in advance because the owner is not in residence. At all sites, ask permission before walking on a farm and leave gates as you find them, closed or open.

From Kimberley, drive southwest to Douglas on road 357 (Fig. 1). In Douglas, turn north (right) onto road 385 and 370. Immediately after crossing the Vaal River, turn west (left) onto a medium-sized road towards Griquatown (Griqwastaad). Follow this road, which becomes dirt, for about 24 km. Immediately before driving up an escarpment, turn south (left) onto a graded dirt road towards Neikerkshoop. Drive approximately 10 km along the escarpment. After passing Suiwerfonetein on the west, look for the first major track to the east (left) at about 3 km farther (Fig. 14).

Turn east (left) into the tract to Weltevrede Farm and drive through the farm yard and take the track trending slightly west of south (Fig. 14). Continue along the track past Dappersfontein Farm to the Gewonne Farm yard. Keep right and follow the track as it bends to the west. Take the first faint dirt track that trends west and southwest. Park at GPS coordinates of approximately 29°11.47’S, 23° 24.81’E. Walk west along bedding surfaces to a drainage running southwest that is clear of brush (on the east side of a fence line that is not on the map). It should be at about 29° 11.44’S 23° 24.91’E. The field trip follows this drainage downstream to the Orange River.

B Geological Description
Walk from the car to the west to about 29° 11.44’S 23° 24.91’E (Fig. 14). While walking along the bedding surfaces from the car, look for giant ooids and elongate stromatolites. Stromatolite elongation is interpreted as reflecting tidal currents. The stromatolites commonly nucleated on oolitic layers. Many of these stromatolites contain a calcite-cement-like microtexture.

While walking down the drainage into the canyon, note layers of large ooids and abundant platy breccias. Platy breccias commonly are interbedded with siltstones. Below a thick siltstone unit, deformed ribbon-rock facies show a number of interesting features, some of which may be due to diastasis deformation (Cowen and James, 1992). These are particularly well exposed above a pool in the canyon. At the stratigraphic level of the pool, but farther down the canyon, a thick stromatolitic unit is well exposed. These giant elongate stromatolites are surrounded by ribbon-rock facies, and this layer transitions laterally into siltstone-ribbon-rock facies. Both of these relationships suggest that the

Fig 14: Map of Day 2 stops. Taken from topographic map 2923AB (15’).
ribbon-rock was deposited in the moderately deep subtidal depositional environment typical of elongate stromatolites. This contrasts to the typical interpretation of platy breccias as forming dominantly in peritidal depositional environments.

This sequence of beds and similar facies are better exposed farther down the canyon. Giant ooids are commonly visible in the bed(s) below the stromatolites. The best textural exposure of the giant stromatolites is at 29° 11.68’S 23° 24.43’E. They have irregular laminae, some of which have a peaked morphology. Many laminae are truncated. The larger-scale depositional context of the stromatolites is well displayed at 29° 11.75’S 23° 24.36’E. Here and around the next bend, platy breccias and grainstones are exceptionally well exposed at river level. There is abundant soft sediment deformation, including folding of breccia lenses. These facies are organized into cycles (Beukes, 1979; Beukes, 1983) that may reflect either systematic changes in sea level or lateral shifting of facies belts.

Carbonate nodules in the siltstone contain abundant euhedral pyrite. In the larger nodules, pyrite is concentrated near the edges of the nodules. These are interpreted as concretions, possibly promoted by microbial activity within the sediment.

C Issues to Debate
1. What is the origin of the deformation in the ribbon-rocks? Is diastasis, as described by Cowen and James (1992), a reasonable explanation?
2. Are the cycles driven by changes in sea level or are they autocyclical? Could migration of siliciclastic sediment sources and shallow channels explain the cyclicity?
3. What allows the growth of giant ooids and why are they relatively rare in the rock record?

3.2.2 STOP 2: MONTEVILLE & REIVILO FORMATIONS AT SUIWERFONTEIN FARM

A Driving Directions:
Return to the entrance gate for Gewonne Farm and turn right towards Douglas (Fig. 14). The next farm of the west (left) is Suiwerfontein. Turn into the track and drive to the farm house and park. This farm is currently occupied by a retired couple. Walk behind the house to outcrops along the east-facing escarpment.

B Geological Description
Suiwerfontein Farm is located on the Monteville-Reivilo formation contact basinward of the site of future localization of the platform margin. Here, the Monteville Formation consists of shale-to-carbonate shallow-upward cycles, similar to those we will see at stop 3 tomorrow, but deposited in deeper water. One of the issues that James Bishop is researching is the differences in depositional environments between this site and stop 3. Molar tooth structures are abundant in this cycle at stop 3, whereas they are absent from the cycle here. One possible explanation is that molar tooth structure requires specific physical conditions to form, which were absent from this depositional environment.

The transition from the Monteville to the Reivilo formation is marked by a sequence boundary at stop 3. Here, however, the sediments are more distal, and the correlative conformity should be marked by the shallowest facies and, possibly, an increase in siliciclastic sediment because quartz sand is common along the boundary. At Suiwerfontein Farm, a single breccia bed is present, which may represent the shallowest deposition. A tuff is also present in the transitional zone. This tuff was originally interpreted as a siltstone (Beukes, 1980), but has since yielded a number of magmatic-looking zircons. These zircons yield U-Pb ages of about 2.7 Ga (Beukes, pers. comm.), which are much older than zircons from beds lower in the stratigraphy and the expected age of about 2.6 Ga. If the source of siliciclastic sediment was the underlying Ventersdorp Lava, which is 2715 Ma (Armstrong et al., 1991), these zircons and this tuffaceous-looking bed may be the lateral equivalent of the sequence boundary rather than a true tuff.

Above the sequence boundary, fenestrate microbialites dominate the stratigraphy for more than 65 m. These are interpreted as the basinward extension of the lower Reivilo Formation. In this area, they have been heavily dolomitized and are less well preserved than fenestrate microbialites in the Gamohaan Formation (stop 7).

C Issues to Debate
1. What is the depositional environment of the shales with interbedded grainstones?
2. Does the facies change represent a change in water depth or a change in sediment sources?
3. What controls the morphology of the fenestrate microbialites?

D Driving Directions:
Return to the cars and retrace your path to Kimberley.
3.3 Day 3

Today, we will focus on the Monteville Formation. The three stops will include a substantial shallowing upward cycle at the top of the formation, aragonite pseudomorphs and stromatolites at the base of the overlying Reivilo Formation, and an impact spherulite layer at the base of the Monteville Formation. The shallowing upward section at the top of the Monteville Formation contains abundant molar-tooth structures, which are not known from other Archean sediments. Biostromes are also abundant and contain thrombolitic structures. Above the sequence boundary separating the Monteville and Reivilo formations, sedimentation was dominated by the precipitation of calcite and aragonite crystals on the seafloor and on stromatolites. The impact spherulite layer can be used to correlate dispersed sections and may correlate to an impact spherulite layer in the Hamersley Basin, Western Australia (Hassler and Simonson, 2001).

3.3.1 STOP 3: MONTEVILLE FORMATION AT MONTEVILLE FARM

A Driving Directions:

From Kimberley, drive west towards Griqueatown on road R64. At the settlement of Schmidtsdrif, turn north (right) onto a dirt road. At the first main intersection, keep left, traveling west northwest. After the road beds to the north, travel about 3 km to Monteville Farm on the east (right) (Fig. 15). "Monteville" is spelled in white rocks at the top of a cliff to the east. Turn into the farm yard. This farm is currently managed by Derrick and Anthea Shaw. Walk to the south of the farm yard and then east to the base of the cliff. Walk north along the cliff, if necessary, to see good exposures of molar-tooth structures (MT) in shale. Walk up the south side of the cliff to follow stratigraphic column MV1 (Fig. 16, 17). The "thrombolitic" bioherm is located north of the "Monteville" on the hill at 28° 35.84'S 23° 58.06'E.

B Geological Description

The upper cycle of the Monteville Formation shows both shallowing-upward features and a change in lithology from siliciclastic-dominated to carbonate dominated. The base of the section shown in figure 17b consists of ribbon rock with some diastasis deformation. As shale becomes more abundant, MT becomes abundant, but is commonly associated with grainstone lenses. Many of these lenses have hummocky cross stratification (HCS) and wave-rippled tops, suggesting deposition between storm and fair-weather wave base. Grainstone shoals may be represented by several meter-thick sections of organically bound grainstones. Many of the grainstones have spherical grains, which we interpreted as ooids in the field. However, in thin section, well preserved grains do not show concentric laminae and are very organic-rich. Their origin is unknown. Grainstones increase in abundance upward (Fig. 17b), and bi-directional cross stratification becomes common.

Microbially bound sediment also increases in abundance until biostromes dominate the section. The biostroms start small (m-scale) and grade upward into a broad biostrom which appears to extend laterally for at least 500m. In section MV1 (Fig. 17), the biostrom continues upward into a Dm-scale bioherm, which is capped with dm-scale columnar stromatolites. Laterally, the lower bioherms are on-lapped by grainstone beds of cross-stratified and rarely herringbone cross-stratified sands, suggesting environments swept by tidal currents. In sections MV2 and MV3, where the biostrom is not evident, poorly-bedded dolostone strata are laminated at the mm-cm scale.

Above the bioherm, strata consist of mm-cm scale laminated dolomite. Shale and quartz sand become more abundant upward, and mud cracks and small wave ripples are common. Microbial textures are still visible in the dolostone. Overall, features suggest a peritidal depositional environment.

C Issues to Debate

1. What is the origin of molar tooth structure? Why is it present in these Archean facies, but rare in other Archean sediments? Why is it absent from the same shale cycle in deeper water at stop 2?
2. What is the nature of the bioherms? What is the source of the carbonate within them?
Fig. 16: Four sections through the Monteville Formation at Monteville Farm (measured by James Bishop). Note that the biostron is only present in two of the sections. Molar tooth structures were only observed in section MV1, but the shale is poorly exposed in the other sections. Section MV1 is shown in more detail in figure 17.
Fig. 17: Section MV1 of the Monteville Formation measured by James Bishop.
3.3.2 STOP 4: REIVILO FORMATION AT MONTEVILLE FARM

A Driving Directions:
Return to the cars, and turn north (right) on the road that passes the farm house. Drive about 2 km, keeping on the main road to the west north west (left). Look for a strong boundary fence on the west (left) side of the road at right angles to the road-parallel fence. Park and climb over the road-parallel fence to the south of the perpendicular fence. Walk to the south southwest to view precipitated columnar stromatolites at 28° 35.10’S 23° 57.75’E. Continue walking towards the south to the gully at 28° 35.28’S 23° 57.62’E. This is the location of the measured section shown in figure 18.

B Geological Description
This stop is to introduce you to aragonite pseudomorphs and stromatolites with a cement-like, precipitated microtexture. The site is in the lower-most Reivilo Formation in the transgressive to highstand deposits overlying the sequence boundary at the Monteville-Reivilo contact.

At this site, the aragonite pseudomorphs consist of both mm-dcm thick fringes of radiating crystals and cm-dcm tall sprays of crystal pseudomorphs arranged in a botryoidal pattern. They grew off the sides of stromatolites as well as upward from bedding surfaces. Some are draped by sediment and contain shelter porosity filled with calcite cement under blades of crystal pseudomorphs. The petrographic characteristics of the pseudomorphs are most consistent with calcite replacing aragonite (Sumner and Grotzinger, 2000), and residual strontium concentrations in samples from this site are as high as 900 ppm.

Stromatolites range in size from elongate mounds meters in width and length to cm-diameter columns. The larger stromatolites are lower in the section and probably formed in deeper water. Many of the stromatolites at this site contain a herringbone calcite microtextures. In addition, some beds contain alternating units of grainstone and herringbone calcite that precipitated directly on the ocean floor (Fig. 19).

C Issues to Debate
1. Did microbial communities affect calcite and aragonite precipitation? Which aspects of the stromatolites could be considered a biological signature if any?
2. What controls the differences in structure and microtexture between the “thrombolitic” structures in the upper Monteville Formation and the columnar stromatolites in the lower Reivilo Formation?
3. What does the precipitation of dcm-thick coatings of calcite and aragonite directly on the sea floor imply about ocean chemistry and sedimentation rates?

Fig. 18: Reivilo Formation at Stop 4, Monteville Farm.
3.3.3 STOP 5: IMPACT SPHERULE LAYER

A Driving Directions:
Return to the cars. The next stop is down dirt tracks on the Monteville Farm. Driving directions should be obtained from the farmer to the site marked as stop 5 (Fig. 16), or one can walk down the canyon to the site, which is a long hike with abundant thorn trees. The impact spherules are located at about 28°36.55'S 23°59.69'E. Topo map 2824CA will be useful for navigation, although tracks are not mapped entirely accurately.

B Geological Description
Impacts were probably more frequent during Neoarchean time than in Proterozoic and Phanerozoic time, and a number of Neoarchean spherulite layers have been identified in the Hamersley Basin, Western Australia, and at the base of the Monteville Formation (Hassler and Simonson, 2001; Simonson et al., 2000). At Monteville Farm, the layer contains sparse spherules and abundant soft sediment deformation of the sediment (Hassler and Simonson, 2001). I have only seen this layer briefly once, so if the roads are accessible, we will explore this area to search for ripped up layers, possible tsunami wave ripples, and impact spherules.

C Issues to Debate
1. Are impact spherule layers likely to be widely distributed?
2. How can one correlate layers from dispersed sites?
3. How do the Hamersley and Transvaal basins correlate?

D Driving Directions:
Return to the cars and retrace your steps to Kimberley.
3.4 Day 4

3.4.1 STOP 6: REIVILYO FORMATION AT BOETSAP

A Driving Directions:
Travel north from Kimberley on N12 to Warrenton (Fig.1). Take road R49 north through Warrenton. After crossing the river on a one lane bridge, take the dirt road to the west (left). At the major T intersection, turn southwest (left) towards Delporthoop or Ulco (away from Jan Kempdorp). After the dam, turn to the north northwest towards Boetsap, and cross the river. The settlement of Boetsap consists of a well fenced police station and abandoned buildings, many now reoccupied. Proceed through Boetsap and up the hill (Fig. 19). Take the first road to the north (right). The road turns to the northwest and dips slightly; park here, near 27° 57.88'S 24° 27.24'E. Climb the fence and down into the arroyo. The field trip and stratigraphic sections follow the main drainage for approximately 4 km.

B Geological Context
The stratigraphic section at Boetsap is a classic site. Stromatolites and what I now interpret as aragonite pseudomorphs were first described by Young (Young, 1928; Young, 1932; Young, 1934; Young, 1940a; Young, 1940b; Young, 1943). They are some of the first stromatolites in the world to be described. Since then, several others have described and interpreted this section with focus on stromatolite classification (Bertrand-Sarfati and Eriksson, 1977) and depositional environment interpretation (Truswell and Eriksson, 1973). These studies documented that the depositional environment is intertidal to shallow subtidal. Most of the section is in the lower most Reivilo Formation and was deposited during the transition in the platform from ramp to rimmed shelf (Fig. 2, 3).

Two stratigraphic columns for this site are included on oversized inserts at the back of the field guide (and are available online at www-geology.ucdavis.edu/~sumner/IAS). Section 1 represents the lower falls with continuous outcrop, and section 2 represents the upper falls near the parking area. Several 10's m of section are poorly exposed between the two sections. We will walk down and back up both sections. It is almost impossible to look at the rocks on the way down, the following description starts at the top of section 2 and proceeds stratigraphically downward. The stratigraphic columns are very detailed, and one can follow them bed-by-bed on the way back to the cars.

The uppermost part of section 2 consists of domal to columnar stromatolites. Some have irregular, commonly truncated laminae that suggest they grew through the trapping and binding of loose sediment. Others have a sheen to them, which is consistent with a precipitated microtexture. Lower in the section, at the break in slope, giant elongate stromatolites are abundant (Fig. 6). They are longer than 30 m and contain the "Boetsap" style laminae (Fig. 7), which I interpret to consist of a mix of detrital carbonate and calcite and aragonite cements. Look for dcm-diameter domed structures growing upward within the elongate stromatolites (Fig. 11b). Many of these contain cm-wide blades of aragonite pseudomorphs; others contain densely spaced pseudomorphed fibers. The strata between 8 and 14 m is flat bedded and contains abundant aragonite pseudomorphs with both botryoidal and fibrous morphologies. Columnar stromatolites are also common. Below this, giant elongate stromatolites are common again, and exposures of internal textures are poor. Follow the drainage downstream for several kilometers. The sparse shale outcrops are Permian in age and overlie a Permian glacial pavement developed on the Reivilo Formation. Continue down the drainage to a region of nearly bedding-plane outcrops with giant elongate stromatolites. This is at about 67m in section 2.

This part of the section has several interesting features. Look for the recessive shale layers compacted between the elongate stromatolites. The stromatolites underlying one of these layers (65m) were channelized prior to deposition of the shale. Wave ripple marks are preserved in these channels. The drainage directions of the channels are variable, suggesting exposure even though the elongate stromatolites and shales are typically interpreted as being deposited in subtidal depositional environments.

Look for a broadly exposed bedding plane with hemispherical domes on the upper surface (61m). This bed is commonly photographed as a classic example of stromatolites. Look closely at the textures inside the domes, particularly on exposures on the north side of the drainage. Note the closely spaced, radiating aragonite pseudomorphs. Small boyroids of aragonite nucleated off some of the sprays of crystals forming a dense texture. Similar pseudomorphs are more easily seen in the bed immediately underlying the domed bed (Fig. 11a), particularly in exposures on the south side of the drainage. Several meters lower in the section (57m), fringes of fibrous aragonite pseudomorphs grew on the edges of columnar stromatolites (Fig. 5a). Some of these fringes contain more than 3000 ppm Sr. The stromatolites consist mostly of fibrous calcite crystals with organic inclusions and rare grains. Grainstones between the stromatolites were more susceptible to dolomitization.
Below this aragonite pseudomorph-rich zone, there is a thick section with abundant grainstones, some of which contain wave, current, or starved ripples. Irregular columnar stromatolites also are present. Lower, diverse columnar stromatolites are abundant, and rare shale beds are present. The Monteville-Reivilo contact is interpreted as being present in a quartz sand-rich dolomite at 15m. Below this, irregular, dolomitized stromatolites predominate (Fig 5b). They are interpreted as having formed through the trapping and binding of carbonate sediment due to the irregularity and common truncation of their laminae.

C Issues to Debate
1. What controls stromatolite morphology and microtexture? How much of the control is biological and how much is environmental? Why do so many Neoarchean stromatolites have precipitated microtextures?
2. What controls the distribution of stromatolite taxa through time? (The stromatolite forms described by (Bertrand-Sarfati and Eriksson, 1977) are typically considered Paleoproterozoic in age, because the platform has only recently been dated as Neoarchean.)
3. What do the aragonite pseudomorphs imply about Neoarchean seawater chemistry? What controls the distribution of recognizable pseudomorphs in the sediment?

D Driving Directions:
Return to the cars by walking back up the drainage, and drive back through Boetsap to the river crossing. Turn southwest (left) on the road towards Delpourtshoop or Ulco (away from Jan Kempdorp). When the road ends at a paved highway, turn northwest (right) towards Postmasburg. Eventually, the road intersects a north-bound paved road to Danielskuil and Kuruman. Turn north on this road and travel through Danielskuil all the way to Kuruman. The escarpment on the west consists of the Gamohaan Formation capped by the Kuruman Iron Formation. In many places, the contact between the two formations was disrupted by Paleoproterozoic karsting. As the subsurface Gamohaan Formation dissolved, sink holes formed, and the iron-formation collapsed into them. We will see an example of one of these at stop 7. We will spend the night in Kuruman.
3.5 Day 5

3.5.1 STOP 7: GAMOHAAN FORMATION AT KURUMAN KOP

A Driving Directions:
From Kuruman, take the paved road out of town to the north towards Hotazel (Fig. 1, 20). Follow the road for about 17 km. The field stop is on the north end of Kuruman Kop, a distinctive conical hill with a cap of iron-formation. Drive just past the north end of Kuruman Kop and turn south (left) onto a dirt track. There are numerous track branches in this area. Find the main one that runs southwest on the northwest side of Kuruman Kop. Park near the larger acacia trees. The thick, brushy acacias have very sharp thorns, so use caution and take your time. Work your way southeast towards the closest outcrop, where walking is easier. Once you reach more open ground, find the base of the stratigraphic section near 27° 22.82’S 23° 20.82’E. The section (Insert 2) was measured up the north knob of Kuruman Kop, shifting back and forth to avoid dolomitized areas. The tuff at X m was traced from the conical hill to the main hill to the south for the upper part of the section where the transition from carbonate to banded iron-formation deposition is exposed. Soft sediment deformation is abundant at 27° 22.99’S 23° 20.76’E.

B Geological Context
The 2521 ± 3 Ma (Sumner and Bowring, 1996) Gamohaan Formation was deposited during drowning of the Campbellrand carbonate platform (Fig. 2, 21). At Kuruman Kop, the transition from the underlying lagoonal Kogelbeen Formation through a sequence boundary into the drowning sequence, which ends with banded iron-formation deposition, is exceptionally well exposed.

C Kogelbeen Formation and Lower Gamohaan Formation
The base of the section at Kuruman Kop is within the Kogelbeen Formation (Insert 2). These are some of the best exposed lagoonal facies in the platform and show the alternation of laminated and domed structures. Upward in the section, facies shallow with peritidal domal stromatolites at 33 m. Lagoonal facies are again present until development of dm-thick cycles of grainstones and stromatolites capped by calcite cements. Some of these cycles are developed in giant elongate stromatolites suggesting an increase in water depth. Grainstone dominated cycles are cross stratified and show multiple directions of sediment transport. The enigma of these deposits is how thick encrustations of calcite could form in agitated depositional environments. My current interpretation is that carbonate grains were sparse and were introduced in pulses that resulted in deposition of the grainstone bases of the cycles.

Above these cycles, starting at 94 m, a thin interval with abundant clastic carbonate is present. Much of this interval shows soft sediment deformation with nodular carbonates with hints of microbial mats at the top. These sediments grade into the fenestrate microbialites of the bulk of the Gamohaan Formation at 100 m.

D Gamohaan Formation
Much of the Gamohaan Formation consists of fenestrate microbialites and ripped up laminated mat. These structures are complex and some are unique to this formation. The stratigraphy of the Gamohaan Formation is described by Sumner (1997a). Two aspects of the stratigraphy are particularly remarkable: (1) the abundance of calcite cement and (2) the lateral continuity of individual beds. The Gamohaan Formation contains 40 m of deep subtidal carbonates with abundant bladed and herringbone calcite, that precipitated as encrusting beds on the sea floor and as marine cement in primary voids. Facies analysis and integration of the composition of all beds >5 cm thick (see Insert 2) demonstrates that more than 45% of this 40 m section of the Gamohaan Formation precipitated from seawater directly on the sea floor and as marine cement in primary voids. The abundance of precipitated beds and void-filling marine cements demonstrates that ambient seawater was supersaturated with respect to calcite. Despite the extraordinary abundance of sea-floor and void-filling precipitated carbonate, fine-grained carbonate sediments are not present in the Gamohaan Formation: micritic beds, drapes, and geopedal void fills are absent. The delicate nature of the microbialites coated by cements in the Gamohaan Formation, the absence of any tractionally deposited sediment, and the absence of scoured beds indicate that the depositional environment was unaffected by strong currents that may have transported micrite to other sites. Any micrite that precipitated in the overlying water column should have accumulated in the Gamohaan Formation. Thus, the lack of fine sediment suggests that micrite precipitation was rare to absent despite strong evidence for the supersaturation of the oceans at that time. The abundance of calcite cements and the paucity of micrite in the Gamohaan Formation led Sumner and Grotzinger (1996b) to suggest that an inhibitor to calcite nucleation was present in Neoarchean seawater.
Fig. 21: Stratigraphy of the Gamohaan Formation (Sumner, 1997a). “K” beside section KU represent the part of the section for which the proportion of calcite cements was logged. The dated tuff was collected at both KU and AL sites (Sumner and Bowning, 1996). Core BD2 is now interpreted as significantly older than the Gamohaan Formation. Synchronous deposition of the Gamohaan Formation and the lower part of the Kuruman Iron Formation near the site of BD2 is required by recent stratigraphic work near the Griguatown Fault Zone.
The later continuity of specific beds in the Gamohaan Formation is striking (Fig. 21, Sumner, 1997a). Several individual beds of microbialites and encrusting sea-floor precipitates can be identified in all sections within the 7000 km² of good stratigraphic control. The most striking series of continuous beds consists of a two meter-thick interval containing plumose structures and beds of precipitates that show very little textural variation from section KU to section HE (see Sumner, 1997a). The base of this interval consists of a layer of 35 to 65 cm-tall plumose structures encrusted by a several cm-thick coating of herringbone calcite. The herringbone calcite is overlain by a second layer of 15 to 25 cm-tall plumose structures and then contorted microbial mat or massive dolostone that is variable along strike. The next bed is a 22 to 40 cm-thick bed of herringbone calcite with a 2 cm layer plumose structures in the middle. This 2 cm layer is continuous from section KU to HE covering the entire 7000 km² of good stratigraphic control. The herringbone calcite layer is overlain by a variable thickness of contorted mat and then another herringbone calcite bed. This upper herringbone calcite bed is variable along strike, but is recognizable in all sections where outcrop is present. This sequence of beds is unique and its uniformity in all sections demonstrates that depositional conditions were identical across large areas of the platform.

E Transition to the Kuruman Iron Formation

The Gamohaan Formation loses its abundance of calcite cements upwards, the carbonates become more iron-rich, and shales become more abundant. The contact between the Gamohaan Formation and the Kuruman Iron Formation is gradational with interbedding of carbonate, shale, and iron-formation (Beukes and Klein, 1990; Beukes et al., 1990; Klein and Beukes, 1989; Sumner, 1997a). This relationship, in addition to the abundance of iron-formation in deepwater equivalents to the Gamohaan Formation (Fig. 21) demonstrate that carbonate and iron-formation deposition were contemporaneous in different depositional environments.

F Issue to Debate

1. What is the origin of the cycles in the lagoonal deposits?
2. In the grainstone/stromatolite-cement cycles, is sediment influx or calcite precipitation the driving factor?
3. The fenestrate microbialites contain a wealth of information about microbial behavior. How can we interpret that? What were the roles of the microbial communities in carbonate precipitation? How important were environmental conditions to controlling microbialite morphology?
4. What were the chemical changes that accompanied the transition from carbonate sedimentation to iron-formation sedimentation? What implications does this have for the chemistry of Neoarchean sea water?

F Driving Directions:

Return to the cars and retrace your route to Kuruman.

3.6 Day 6: Return to Johannesburg

A Driving Directions:

From Kuruman, take highway N14 to Johannesburg.
4 REFERENCES


BEUKES, N. J. (1977) Transition from siliciclastic to carbonate sedimentation near the base of the Transvaal Supergroup, northern Cape Province, South Africa. Sedimentary Geology, 18, 201-221.


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