Lithofacies and Biofacies of Mid-Paleozoic Thermal Spring Deposits in the Drummond Basin, Queensland, Australia

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PALAIOS, 1996, V. 11, p. 497–518

The Devonian to Carboniferous sinters of the Drummond Basin, Australia, are among the oldest well established examples of fossil subaerial hot springs. Numerous subaerial and subaqueous spring deposits are known from the geological record as a result of the occurrence of economic mineral deposits in many of them. Some are reported to contain fossils, but very few have been studied by paleobiologists; they represent an untapped source of paleobiological information on the history of hydrothermal ecosystems. Such systems are of special interest, given the molecular biological evidence that thermophilic bacteria lie near the root of the tree of extant life.

The Drummond Basin sinters are very closely comparable with modern examples in Yellowstone National Park and elsewhere. Thirteen microfacies are recognisable in the field, ranging from high temperature apparently abiotic geyserite through various forms of stromatolitic sinter probably of cyanobacterial origin to ambient temperature marsh deposits. Microfossils in the stromatolites are interpreted as cyanobacterial sheaths. Herbaceous lycopsids occur in the lower temperature deposits.

INTRODUCTION

Hydrothermal ecosystems can be expected to have existed on Earth since life arose. A thermophilic lifestyle has been proposed for the common ancestor of life (Woese, 1987; Stetter, 1994) and submarine hydrothermal vents are a candidate site for the origin of life (Baross and Hoffman, 1985). Similar springs occur in lakes (Remsen et al., 1990; Crane et al., 1991; Tiercelin et al., 1993). The biology of subaqueous springs, particularly those in deep water, is difficult to study; in contrast, the biology of the more accessible subaerial thermal springs has been studied in great detail (e.g., Castenholz, 1969; Brock, 1978). In subaerial springs, diverse communities of archaebacteria, eubacteria and cyanobacteria (e.g., Ward et al., 1989, 1992) give way at progressively lower temperatures to algal, animal and plant populations. The chemical and thermal gradients associated with springs sort organisms into different, sharply delineated communities, so that diverse organisms are concentrated into relatively small areas in a predictable and informative fashion; an enormously wide range of metabolic strategies is concentrated into small areas, thus furnishing a significant sampling of the existing biota.

Our interest in these ecosystems is to develop strategies for the search for fossil life on Mars (Walter, 1988; Walter and DesMarais, 1993; Farmer and DesMarais, 1994), and also results from our involvement in research on early life on Earth (e.g., Schopf, 1983; Schopf and Klein, 1992). We have advocated focussing on thermal spring deposits as part of the search for fossil life on Mars (Walter and DesMarais, 1993). As well as being sites of diverse life, thermal springs are also characterised by abundant deposition of minerals such as opaline silica and calcite which entomb and fossilise the microorganisms. In searching for analogous fossil systems on Earth we have found that the paleobiology of ancient hydrothermal systems is almost completely unknown. This is because of lack of research on this topic, not absence of deposits on which to work. As a

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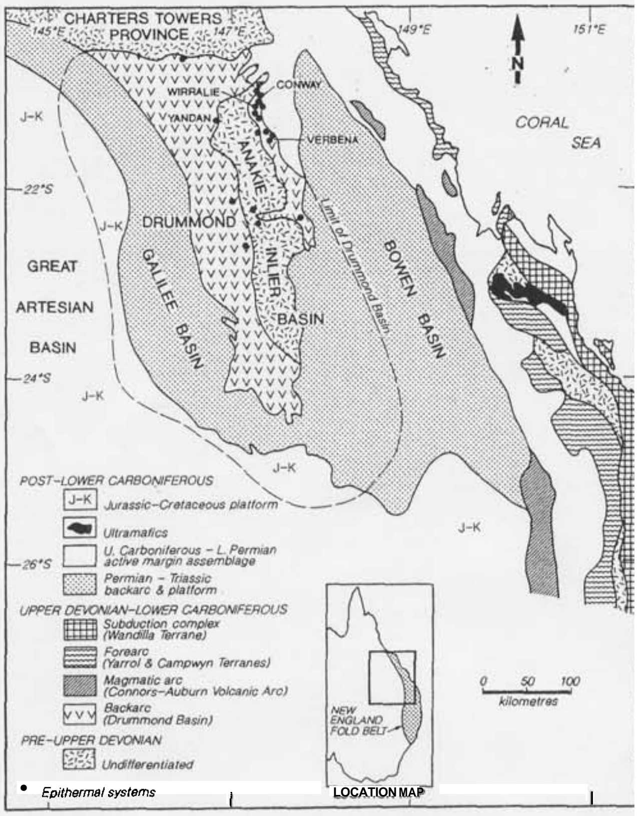


FIGURE 1—Geological setting of the Drummond Basin, and location of epithermal mineralization (after Johnson and Henderson, 1991).

result of mineral exploration, large numbers of fossil subaqueous and subaerial spring systems are known: numerous gold and base metal deposits of all ages back to Archean are in such "exhalative," "volcanogenic massive sulfide," "epithermal" and "Kuroko-style" systems.

There is growing interest in the paleobiology of submarine low-temperature springs and seeps (for instance, see the recent special issue of Palaios, v. 7, number 4, 1992). Comparable studies of the paleobiology of fossil subaqueous thermal springs are rare, though the potential exists (Walter, 1996): Oudin and Constantinou (1984) report fossil "worm tubes" and Juniper and Fouquet (1988) probable fossil microbial filaments in the Cretaceous age Troodos deposit of Cyprus, and fossil microbial filaments occur in Cambrian submarine vent deposits in Australia (Duhig et al., 1992a, b). The literature on epithermal gold deposits has occasional references to fossils in the cherts and volcaniclastic deposits associated with these deposits (e.g., Casaceli et al., 1986; Wood, 1991).

The Devonian Rhynie Chert of Scotland is at least partially a subaerial thermal spring deposit (Rice and Trewin, 1988; Trewin, 1994, Rice et al., 1995), and is the only example that has been extensively studied by paleobiologists (starting with Kidston and Lang, 1917–1921; recent references include Edwards, 1986, and Taylor et al., 1992). The Rhynie Chert does not outcrop; the paleontological studies are on float specimens, supplemented with the results of recent drilling.

Apart from the Rhynie Chert, the oldest well established examples of fossil subaerial hot springs for which there is published documentation are those first described from Queensland, Australia, by Cunneen and Sillitoe (1989) and White et al. (1989). These were discovered in the course of exploration for epithermal gold deposits in a subaerial felsic volcanic terrain. They were recognised as sinters because of their volcanic setting, siliceous mineralogy and morphological similarity to the sinters of New Zealand and Yellowstone National Park, Wyoming. They are well exposed in at least seven sites, and are interbedded with volcaniclastic sediments, lava, and marsh sediments containing silicified plants. After a reconnaissance of the known sinters, the two which are best exposed and show the greatest range of microfacies were selected for study: these are Verbena, and Wobegong in the Conway hydrothermal system.

REGIONAL GEOLOGY

The Drummond Basin is a north-south trending backarc basin of Late Devonian to Early Carboniferous age that covers an area of some 25,000 km^2 in northeast Queensland (Olgers, 1972; Fig. 1). It lies within the northern part of the Tasman Orogenic Belt and is the largest of several Late Devonian to Early Carboniferous basins that formed during plate margin convergence (Henderson, 1980; Day et al., 1983; Johnson and Henderson, 1991). Early work on the tectonic setting of the Drummond Basin suggested a thrust-related foreland basin origin. However, recent work integrating geological data with regional magnetic, gravity, and seismic reflection data indicates an extensional, back-arc basin environment (McPhie et al., 1990; Johnson and Henderson, 1991).

The Drummond Basin is divided by a north-south trending ridge known as the Anakie Inlier (Fig. 1) which consists of igneous and metasedimentary basement rocks ranging in age from mid-Paleozoic possibly to Proterozoic (Ewers et al., 1993).

With gold discoveries at Mount Coolon in 1913, the Drummond Basin became the focus of an intense exploration effort (Ingram, 1989). The potential for widespread sediment-hosted epithermal mineralization was not fully realized, however, until 1983 with the discovery of gold deposits at Pajingo (Porter, 1988). Since that time, numerous prospects have been identified along a regional north-south trend lying adjacent to the eastern margin of the Anakie Inlier (Fig. 1).

West of the Anakie Inlier, Olgers (1972) recognized three disconformity-bounded, tectono-sedimentary cycles. The basal sequence, Cycle 1, consists of predominantly intermediate to acid lavas and pyroclastics, and volcaniclastic sediments containing a Late Devonian to Carboniferous fossil flora. Sediments and fossils of Cycle 1 indicate terrestrial deposition proximal to volcanic sources. This sequence is overlain by fluvial successions comprising Cy-

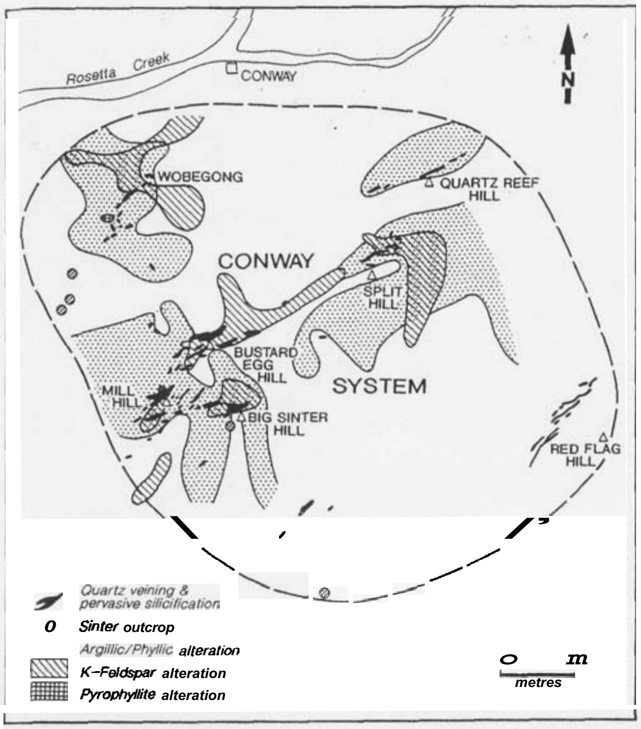


FIGURE 2—Map of the Conway hydrothermal system, with the locations of sinter, quartz veins and alteration zones (from Ewers et al., 1993).

cle *2* which in turn is overlain by volcanic and fluvial-lacustrine successions of Cycle 3 that indicate a period of renewed volcanism. Cycles 2 and 3 sediments are fairly continuous over the entire basin, and were apparently deposited during a period of broad basinal subsidence. In contrast, Cycle 1 sediments are less continuous over the basin, having accumulated primarily within rapidly subsiding subbasins mostly associated with eruptive centers in the northeastern part of the basin (Hutton, 1989).

In the northern and eastern portions of the basin, stratigraphic relationships are obscured by rapid lateral facies changes, disconformities, and poor age control (McPhie et al., 1990), and basin-wide stratigraphic correlations remain controversial. Tectono-sedimentary cycles identified west of the Anakie Inlier are not apparent in the northern and eastern parts of the basin, where magmatism was more or less continuous. However, five major igneous episodes, spanning the interval from Late Devonian to Permian, have been documented in the eastern Drummond Basin (Hutton, 1989). The sinters described here apparently occur within the products of the earliest episode, variously called the Bimurra Volcanics, the "DCv unit," the Silver Hills Volcanics, and other names (Law et al., 1989; McPhie et al., 1990; Ewers et al., 1993).

Between 305 and 290 Ma, subaerial volcanism was widespread over the basin, resulting in subaerial eruptions of rhyolitic lavas and ignimbrites which comprise the Bulgonunna Volcanic Group. This Late Carboniferous succession has been deeply eroded, exposing high level plutons over large areas of the northeastern part of the basin. The plutons cluster into two groups, an older high-K granitoid group that is overlain non-conformably by Late Carboniferous volcanics, and a younger group consisting primarily of monzogranites. Regional compostional trends of the Carboniferous granitoids suggest northward-directed subduction (McPhie et al., 1990; Silver and Chappell, 1988).

Well preserved siliceous sinters and associated shallow epithermal mineral deposits occur predominantly in the eastern part of the basin within volcanic successions marginal to the Anakie Inlier. Age constraints are poor in these sedimentary successions, but thin, discontinuous marine units present in this area suggest a Late Devonian to Carboniferous age.

TIMING OF HYDROTHERMAL ACTIVITY

Sericite from fractures and intensely altered volcanic rocks associated with the epithermal mineralization yields K/Ar dates of 298–342Ma (Late Carboniferous to Early Permian), with error limits of up to 15Ma. This correlates with a major period of igneous activity dated by U/Pb techniques on single zircon grains at 290–305Ma, expressed as the Bulgonunna Volcanic Group and intrusive granites (Ewers et al., 1993).

Because of limited outcrop and very poor paleontological control it has proven difficult to correlate the volcanic units (McPhie et al., 1990). Partly as a result of this, the literature is replete with confusing and contradictory comments about the timing of mineralization and the age of the sinters. The stratigraphy at the Conway locality is given in Table 1, from Ewers et al. (1993) who state that the mineral deposits are "hosted predominantly by a sequence of massive trachyte, rhyolitic to andesitic lavas and volcaniclastic rocks which belong to the Bimurra Volcanics at the base of the Drummond Basin sequence". The sinters described here from both Conway and Verbena contain abundant fossils of what is identified from elsewhere in the basin as the herbaceous lycopsid *Oxroadia gracilis* (Alvin, 1965; Olgers, 1972; Cunneen and Sillitoe, 1989; White et al., 1989; Ewers et al., 1993). This taxon is considered to be restricted to the Early Carboniferous (Bateman, 1992); however, a study of our specimens has not been able to confirm this identification, and additional work is continuing (S. McLoughlin and A. Drinnan, written comm., 1994).

Thus the paleontological dating of the sinters as Late Devonian to Early Carboniferous contrasts with the radiometric dating of the mineralization as Late Carboniferous to Early Permian. Numerous detailed studies of individual deposits indicate a complex history of mineralization possibly spanning a long time interval (e.g., Porter, 1988; Hine et al., 1989; Hopf, 1992; Ewers et al., 1993). In summary it seems that the significant gold mineralization and associated coarse grained quartz phases post-date the sinters by 50Ma or more; their occurrence together indicates repeated hydrothermal fluid movement through the same conduits. By comparison with better known Tertiary

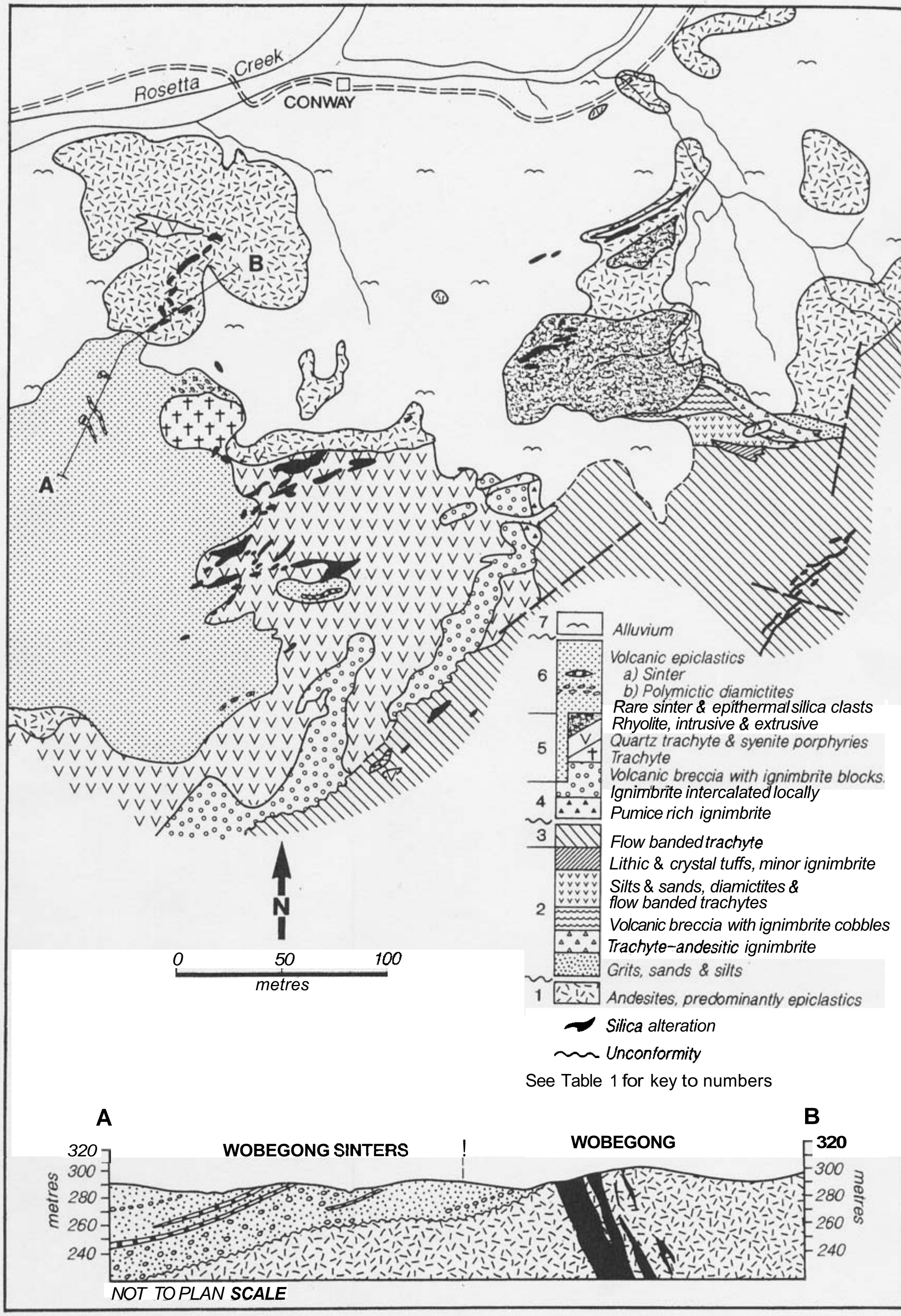


FIGURE 3—Geological map and section of the Wobegong area, Conway hydrothermal system (after Newcrest Mining Ltd., unpublished).

TABLE 1—Lithological units from the Conway hydrothermal system (from Ewers et al., 1993).

Unit	Lithological description	Thickness	Remarks
7	Alluvium	>350 meters	
6	Epiclastic volcanic sandstone & mudstone with rare sinter	Variable	Partly sourced from lower units, contains *interbedded siliceous sinters* with combined thickness up to **3** meters
5	Quartz trachyte, syenite & rhyolite	Variable	Mineralization related to emplacement of this unit
4	Quartz-rich trachyte & andesitic ignimbrite and volcanic breccia	>130 meters	Several undifferentiated facies, pumice-rich in places; angular unconformity with unit *3*
3	Massive flow-banded trachyte	>1200 meters	Very minor volcaniclastic rocks
2	Volcanic breccia, sandstone & mudstone	~230 meters	Minor flow-banded trachyte, lapilli-rich ignimbrite, disconformably overlies unit 1
1	Andesitic volcaniclastic rocks & lavas	>1000 meters	

and Quaternary age hydrothermal systems it can be inferred that each major period of hydrothermal activity lasted 1–3 Ma (Silberman et al., 1979).

DESCRIPTION OF SINTER DEPOSITS

Conway Hydrothermal System

This system occupies an area of about 15 km^2, is subcircular, and 4–5 km wide (Fig. **2).** The host rocks are massive trachyte, rhyolitic to andesitic lavas, and volcaniclastic rocks (Fig. 3) which belong to the Bimurra Volcanics at the base of the Drummond Basin succession. Two unconformities within the volcanics at Conway were recognised during detailed mapping for mineral exploration (Fig. 3, Table 1). Hopf (1992) has suggested that there was local erosion and redeposition of the volcanic and volcaniclastic succession.

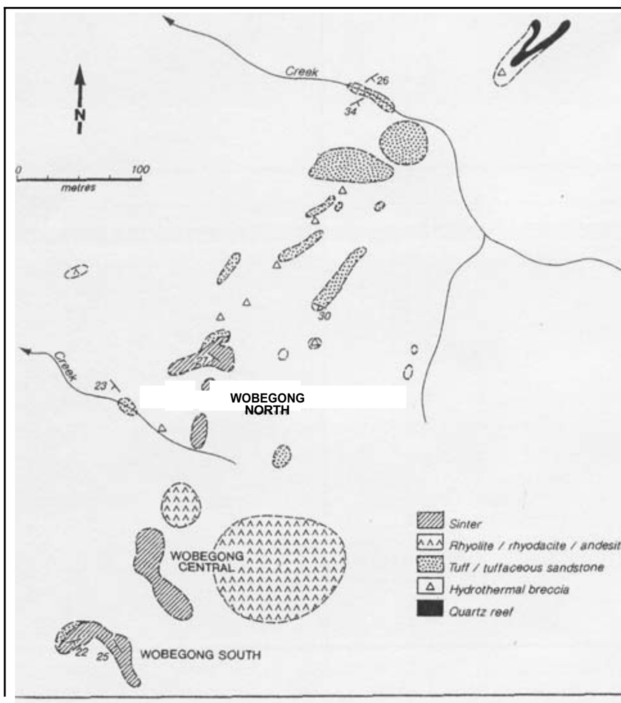


FIGURE 4—Distribution of the Wobegong sinters and associated volcanic rocks (extensively modified after Newcrest Mining Ltd., unpublished).

At Wobegong (Figs. 4–8), thin sinters are interbedded in tuffs, arenaceous tuffs and polymictic diamictites (?lahars), in a NE-SW trending 100 m wide zone which includes hydrothermal breccias and areas of abundant, anastomosing coarse-grained quartz veins ("quartz reefs"). Within the Conway system there are extensive areas with hydraulic fractures and breccias, and with quartz veining and pervasive silicification (Figs. 3–4, Fig. 14c–e). These and large areas with secondary mineral assemblages indicative of hydrothermal alteration (Fig. *3)* define the system. "Silicic alteration includes colloform-banded and comb-textured quartz veins, fine-grained quartz after chalcedony in veins, and silica-cemented breccias. Weak to intense argillic-phyllic ([clay-mica] mainly sericite and mixed layer illite/smectite) and propylitic [carbonate-epidote-quartz-chlorite] alteration are common. . .Secondary K-feldspar alteration, minor kaolinite, alunite, pyrophyllite, and jarosite have also been recognised" (Ewers et al., 1993). Calcite and zeolites fill tension fractures and occur as veins. The calcite veins cross-cut breccias and the alteration zones; in places the calcite is bladed, and rarely is replaced by quartz. There is some hematite associated with fractures. Gold and silver occur with the quartz veins and in silica-rich areas. The alteration mineralogy, geochemistry and rare earth element systematics of this system are the subjects of a doctoral research thesis by Hopf (1992).

The Conway system has been reported to include sinters at Wobegong and possibly also Big Sinter Hill (White et al., 1989; Ewers et al., 1993). We were unable to locate the latter example. Three outcrops of sinter occur at Wobegong (Figs. 4, 5). They all occur in the same stratigraphic unit (Fig. 3, Table 1), but the poor quality of the outcrop of the volcaniclastics in which they are interbedded prevented us from determining whether they are at the same or different stratigraphic levels. Each outcrop was mapped (Figs. 3–4, 6–8), and where possi-

FIGURE 5—Outcrop of the "Wobegong North" *sinter.*

ble, sections were measured (Figs. 9–10). Thirteen microfacies were distinguished in the field; their distribution, relationships, thicknesses and abundances are shown in Figures 4–10. Much of the outcrop is rubbly, preventing the precise determination of microfacies thicknesses and relationships.

The Wobegong sinters are characterised by their small size (less than 100 m maximum extent and mostly less than 1 m thick) and a high diversity of microfacies. Each is considered to represent one or more small spring systems (see below). Each microfacies is briefly described below after the field description of the Verbena locality.

Verbena Hydrothermal System

The sinters at Verbena are interbedded in the Late Devonian to Early Carboniferous Silver Hills Volcanics (Cunneen and Sillitoe, 1989). The host rocks are tuffaceous sandstone, tuff and ignimbrite. A flow-banded rhyolite plug occurs 2 km southeast of Verbena, at a somewhat higher stratigraphic level. Quartz veins, stockworks and sinter are exposed (Fig. 11) along a northwest-trending zone 400–600 m wide and 1500 m long (both ends are concealed by Tertiary and Quaternary alluvium). Some of the stockworks grade into hydrothermal breccias. Cunneen and Sillitoe (1989) consider that stockworks are cut by later chalcedonic veins with replacement textures after bladed calcite.

Three sinters were reported by Cunneen and Sillitoe (1989); we could not locate their westernmost example, and we found an additional two sinter beds in the main outcrop area (Fig. 11), part of which we mapped in detail (Fig. 12). By our measurements the thickness of the sinters (Fig. 13) is substantially less than the estimates made by Cunneen and Sillitoe (1989). Ten microfacies of sinter were recognised in the field, and are described in the following section.

The main Verbena sinters are characterised by their considerable lateral extent (up to 600 m) and the predominance of finely laminated lithologies. A diverse assemblage of microfacies occurs at the northwestern end of the main outcrop, interpreted as having been an area of spring vents (see below).

Microfacies

A total of thirteen different microfacies was distinguished in the field at the two localities. Each is briefly described here. All but two are homologous with microfacies distinguished in modern sinters (e.g., Weed, 1889a, b, c; White et al., 1964; Walter, 1972, 1976a, b; Walter et al., 1972, 1976; recent unpublished observations of the authors). All consist of micro-crystalline quartz (chert).

Massive/Mottled/Diffusely Layered

Massive white to grey chert commonly with weak, discontinuous, subhorizontal laminae and color mottling (Fig. 14b). At Verbena this microfacies frequently contains centimeter-sized, empty vugs lined with drusy quartz.

Brecciated With Angular Equant Clasts

This occurs as irregular, discordant bodies from millimeters to centimeters wide with equant to tabular angular clasts of chert themselves millimeters to centimeters wide cemented by microgranular quartz (Fig. 14c). Most

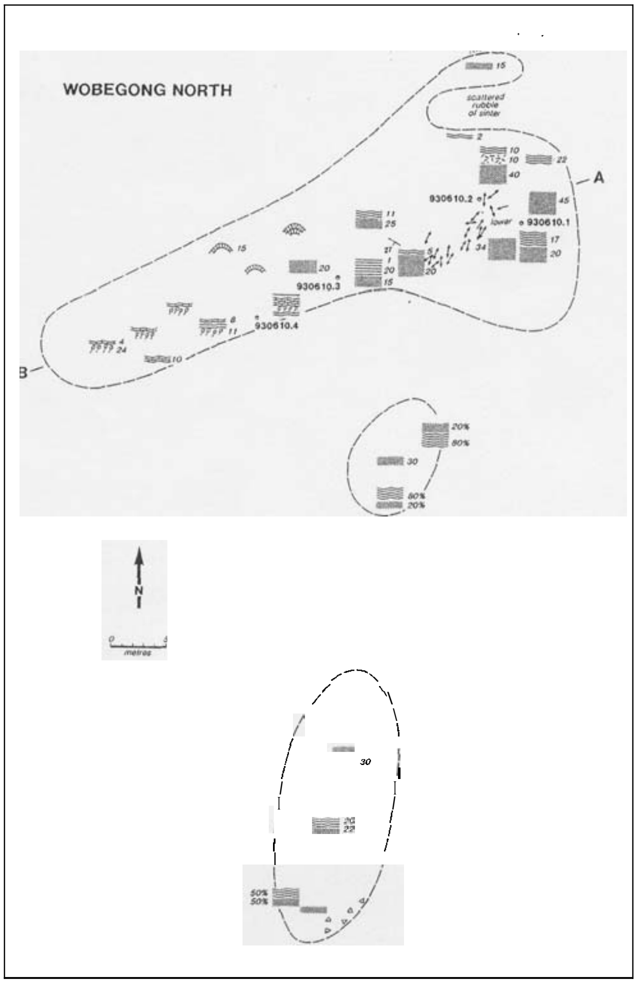


FIGURE 6—Microfacies distribution and thickness in "Wobegong North" sinter. For legend see Figure 8. Microfacies thicknesses are in centimeters or, where outcrop is rubbly, are given as percentage abundances. Numbered locations are of stratigraphic sections shown in Figure 9. **A–B** indicates the orientation of the palinspastic section in Figure 23.

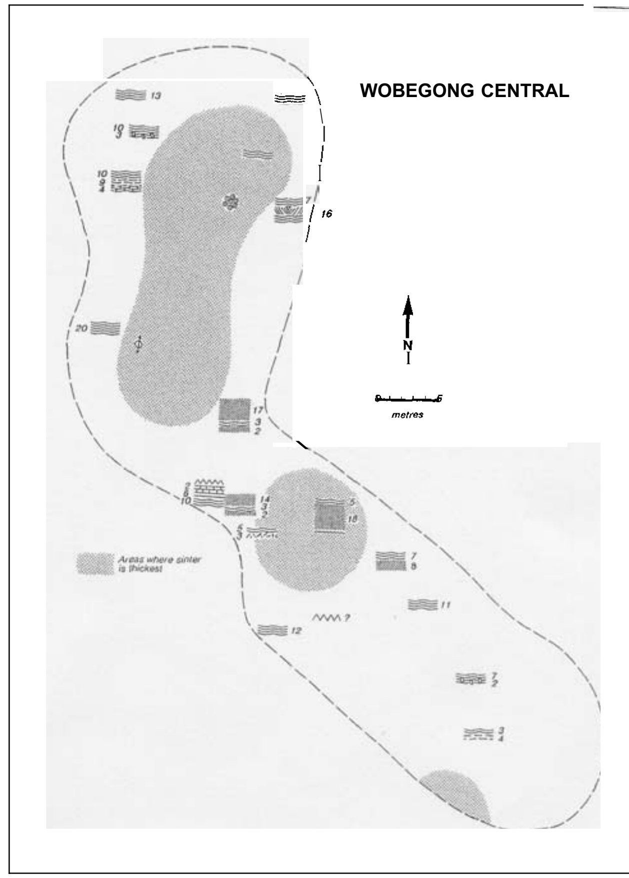


FIGURE 7—Microfacies distribution and thickness in "Wobegong Central" sinter. For legend see Figure 8. Microfacies thicknesses are in centimeters.

such bodies are hosted by the massive microfacies. They are associated with fractures, into which they grade laterally.

Spicular

At Verbena there are several areas up to 7–8 m wide of chert with a coarsely botryoidal bed-form within which there are fan-like aggregates of straight, cylindrical features each 1–5 mm wide by up to 25 cm long (Figs. 14a, 15). The botryoidal features are 10–20 cm wide. The outcrop is rubbly so large-scale bed-forms and microfacies relationships cannot be determined.

This rock type seems to have recrystallised extensively so that little of the original microscopic fabric is preserved; most thin sections show elongate patches of otherwise structureless coarse and fine-grained chert forming the spicular structures. Locally, however, the spicules consist of very finely laminated chert with steeply convex to parabolic lamina forms, and the interspaces between the spicules are filled fenestrae often with geopetal features (Fig. 15).

Comparable botryoidal structures occur in the splash zones around modern spring and geyser vents (Fig. 16a); the internal structure of these is columnar and spicular (Walter, 1976a, his figures 2, 4, 5, 8–13, 18). This sinter type currently forms at temperatures of more than about 73° C, where microbial mats are rare or absent (Walter, 1976b).

Oolitic/Pisolitic

At Wobegong Central chert ooids about 1mm in diameter were found in a chert bed a centimeter thick (Fig. 7); these could be more accurately described as coated grains, as most have only one concentric lamina. Pisoids 1–3cm wide were found in a float boulder at Verbena (Figs. 12,

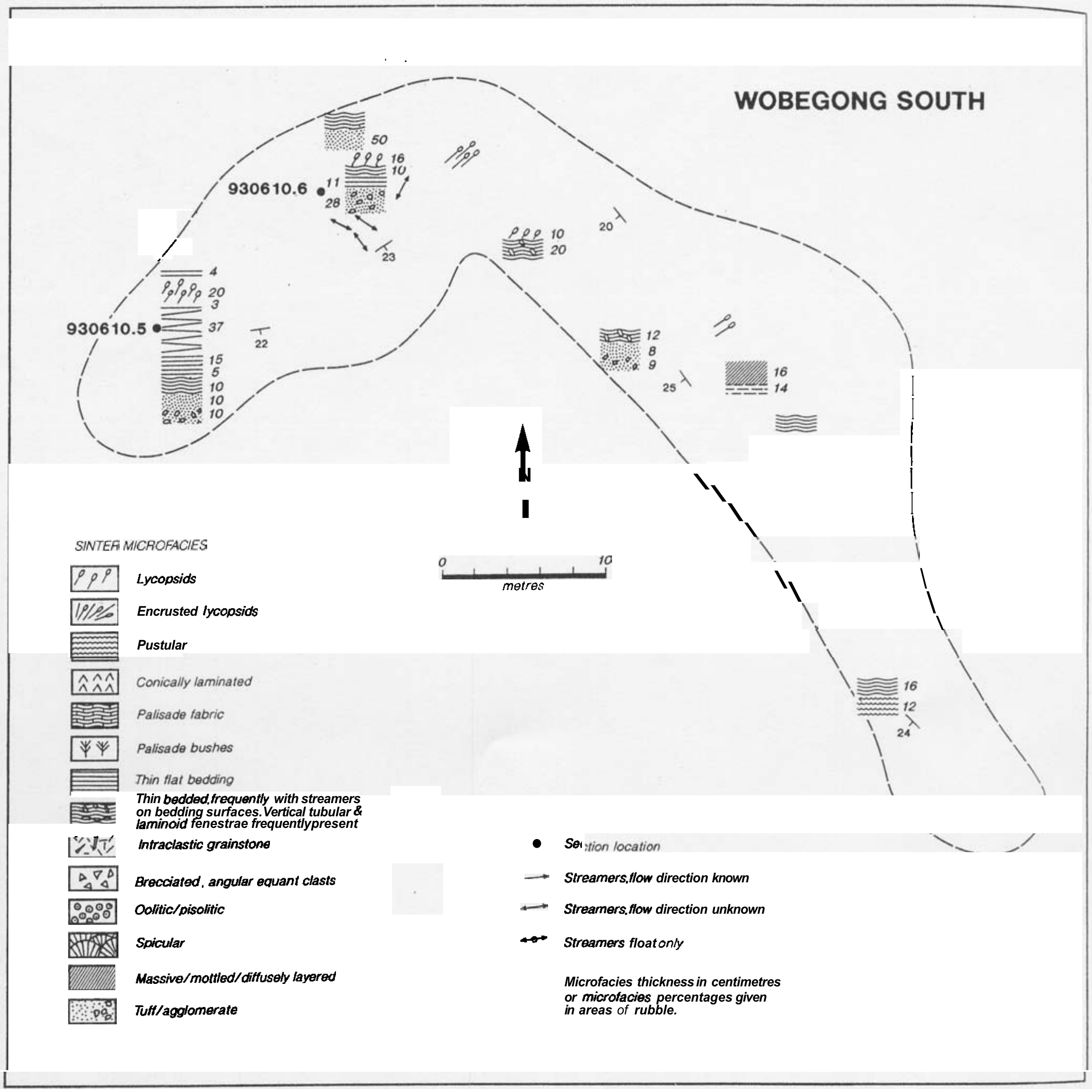


FIGURE 8—Microfacies distribution and thickness in "Wobegong South" sinter. Microfacies thicknesses are in centimeters. Numbered locations are of stratigraphic sections shown in Figure 9.

16c). Comparable pisoids form now in turbulent shallow pools near geyser and spring vents (Fig. 16a–b; Walter, 1976a, his figures 15–17, 25, 26).

Thin Flat-Bedded

This microfacies is rare, being recognised with confidence at only one locality at Verbena (Fig. 12). It is white chert with thick, flat, featureless laminae. It is similar to subaqueous high-temperature geyserite from Yellowstone National Park (Walter, 1976a, his fig. 19).

Thin-bedded with streamers and fenestrae

This ranges from finely laminated chert with laminae 2–3 mm thick with subparallel boundaries to wavy lami-

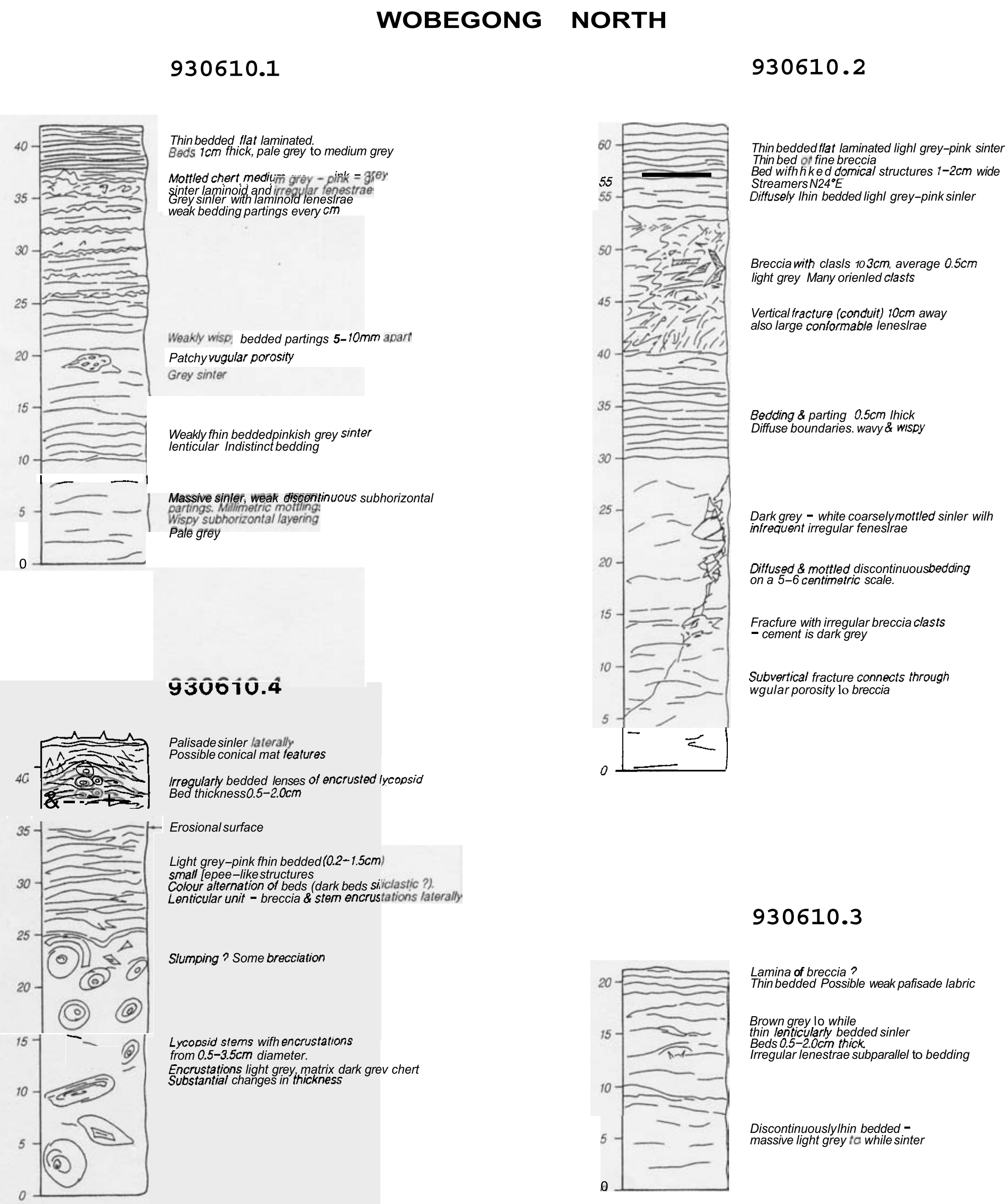


FIGURE 9—Stratigraphic sections of "Wobegong North", at locations shown on Figure 6.

nated in lenticular beds up to 2cm thick (Fig. 17c–e). At Verbena, laminae of iron-stained chert spaced 1–20 cm apart impart a cyclic appearance to this microfacies (Fig. 17c). Laminoid and vertical tubular fenestrae (cf. Logan, 1974) are generally abundant (Fig. 17c–e); the laminoid forms are 1–3 mm high by 1–20 mm long, and the tubular forms are 1–3 mm wide, 3–20 mm high and approximately perpendicular to bedding. "Streamers", elongate filamentous forms oriented parallel to lamination, are present on many bedding planes (Fig. 18a–b). At Wobegong

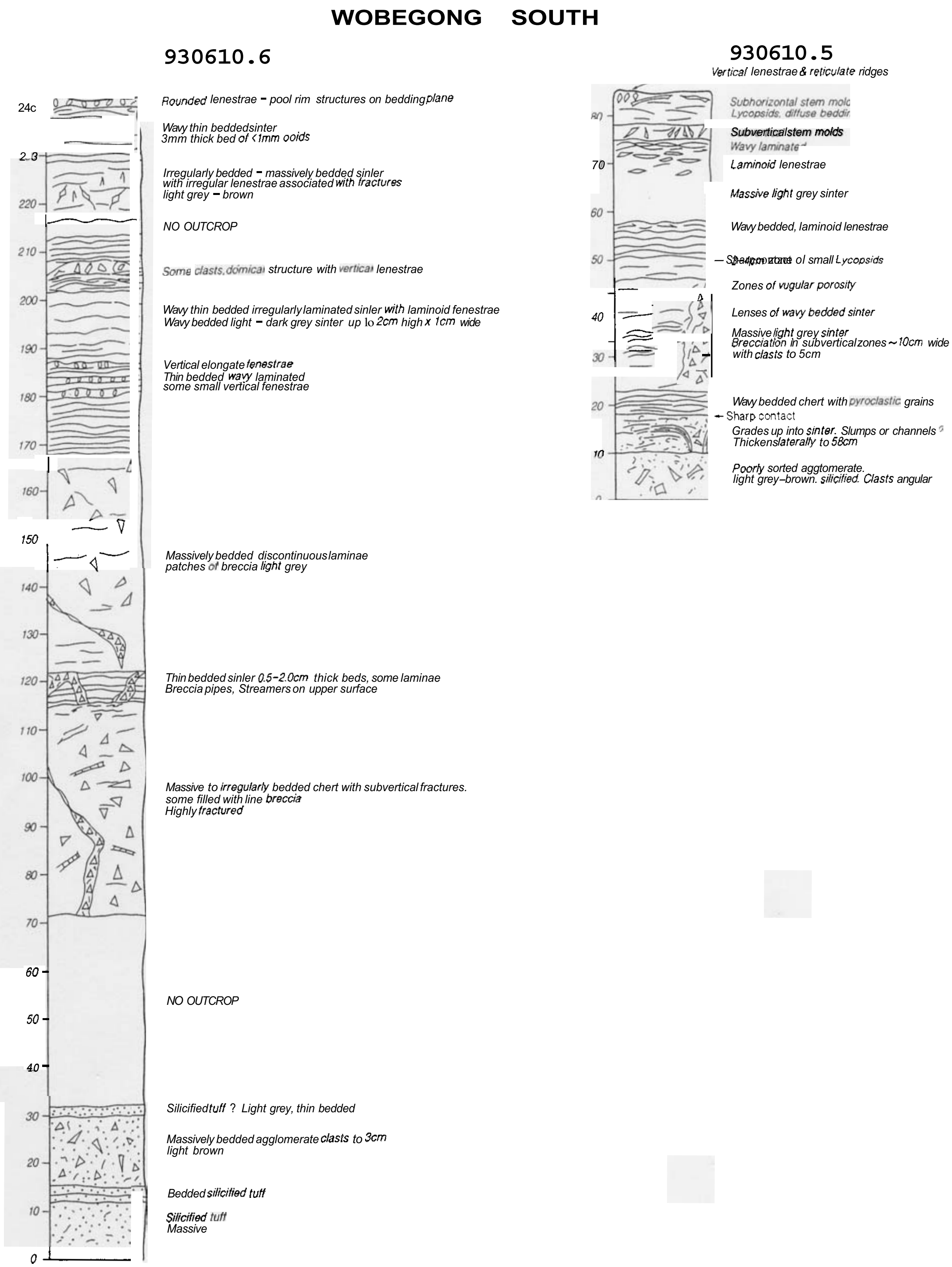


FIGURE 10—Stratigraphic sections of "Wobegong South," at locations shown on Figure 8.

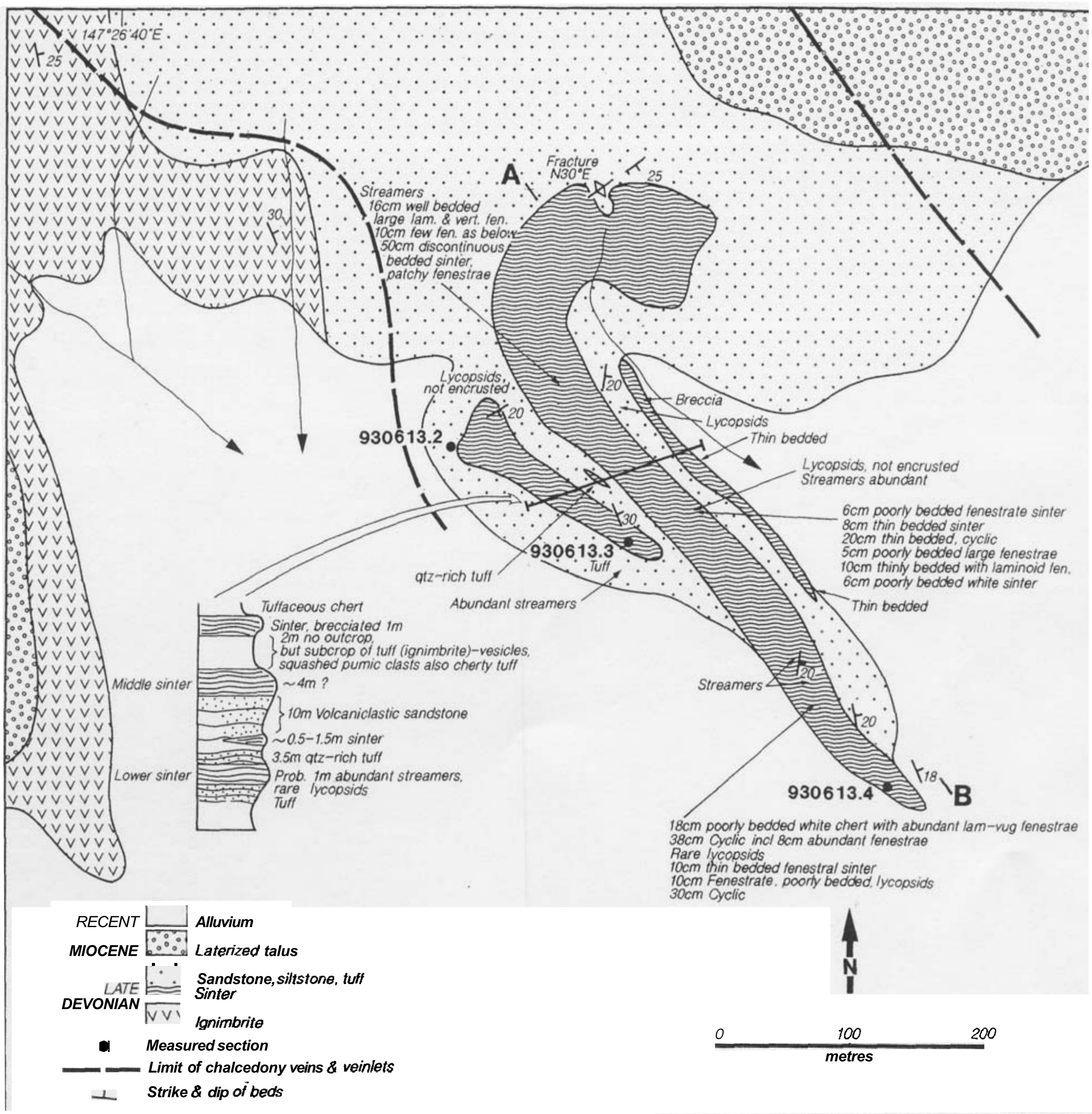


FIGURE 11—Geologic map of the sinters and enclosing volcanic rocks at Verbena. Numbered locations are of stratigraphic sections shown in Figure 13. A–B indicates the orientation of the palinspastic section in Figure 23. After Cuneen and Sillitoe (1989).

North a zone of streamers delineates a former channelway (Fig, 6). In modern springs, streamers (Fig. 18c) form by mineral encrustation of flow-oriented filamentous organisms. In travertine-depositing springs in Yellowstone streamers form over a broad range of temperatures from about 80" C down to –30" C, while in silica spring systems the temperature range is somewhat narrower, from about 60" C down to –30" C (oriented filaments are present at higher temperatures but are not encrusted; see Farmer and DesMarais, 1994b; authors' unpublished observations).

Where microfabrics are well preserved, laminae 10–50 μm thick may be observed in thin section (Fig. 19a). The laminae are alternately light and dark colored, generally

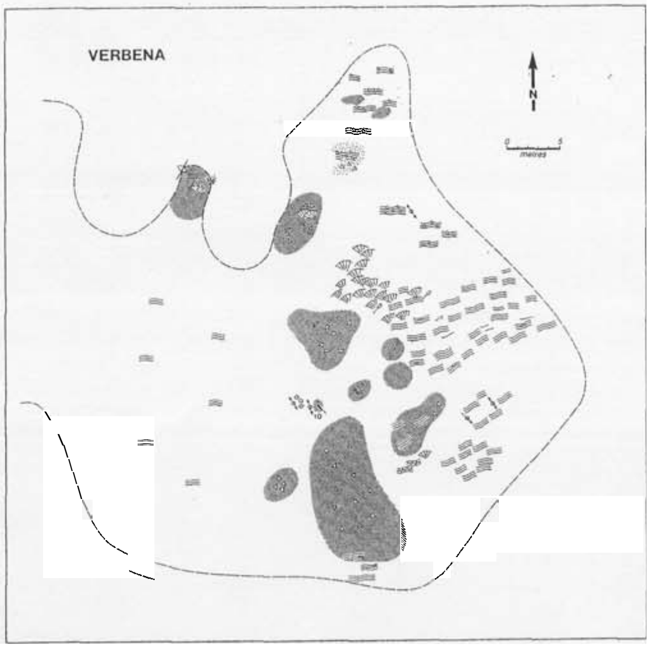


FIGURE 12—Microfacies distribution at the northwestern end of the main Verbena sinter ("middle sinter" of Figure 11). For legend see Figure 8.

with distinct boundaries. They are stacked to form small, linked columns (a pseudocolumnar fabric, in the terms used to describe stromatolites), and small conical features. Laminoid fenestrae are abundant. Such fabrics are very closely comparable with those built by finely filamentous cyanobacteria such as *Phormidium* in modern thermal springs at temperatures of 59–30"C (Walter et al., 1976, their figs. 1–35; Walter, 1976b).

Thin-Bedded With Palisade Fabric

This is the same as the microfacies described above, except that millimetric linear features perpendicular to the laminae are abundant (Fig. 17d). The term "palisade" is used here to refer to the fabric imparted by these linear features. In thin section these features can be seen to vary from straight to slightly sinuous (Fig. 19c–e). Where best preserved they are tubular and 10–15 μm wide (Fig. 19c–e). The tubes are outlined by dark mineral grains. They are interpreted as the former sheaths of microorganisms; their size and habit are consistent with their being the sheaths of cyanobacteria such as *Calothrix* that currently form stratiform mats in thermal springs at temperatures of less than 30"C (Walter, 1976b, his figures 6–8).

Closely comparable sinter forms from modern *Calothrix* mats in sheet flow situations, where water does not form pools more than a few millimeters deep (Figs. 17a–b, 20).

Locally there are millimetric lenses that have randomly oriented tubular features about 2–3 μm wide, outlined by dark mineral grains (Fig. 19f). Their size and habit suggests that they were the sheaths of filamentous fossil microorganisms similar to thermophilic species of the living cyanobacterium *Phormidium.*

The two thin-bedded microfacies described above dominate the spring sinters described here.

Thin-Bedded With Pustular Bedding Plane Features

Some thin-bedded sinters as above have an internal laminar fabric of millimetric to centimetric stacked, linked convex laminae forming "pseudocolumnar stromatolites" 1–2 cm high (cf., Preiss, 1976). Comparable structures are built in modern springs by the cyanobacterium *Calothrix* at temperatures of less than 30° C (Walter, 1976b, his figures 6–8), where centimeter-deep ponds form behind small "terracette" dams.

In modern settings where such pools reach depths of several centimeters or more, *Calothrix* mats may grow into centimeter-sized rounded shrubs. When silicified, this mat type produces what is referred to here as *large, bushy palisade fabrics.* These structures are rare in the Wobegong sinters, and are known from only one locality at Verbena (Fig. 12). In that example, cylindrical features 1–3 mm wide and up to several centimeters long branch profusely to form upright "shrubs" about 10 cm high by 1–3 cm wide. Identical features are found in modern thermal springs where they are constructed by coarsely filamentous cyanobacteria in shallow ponds.

Thin-Bedded With Conical Laminae

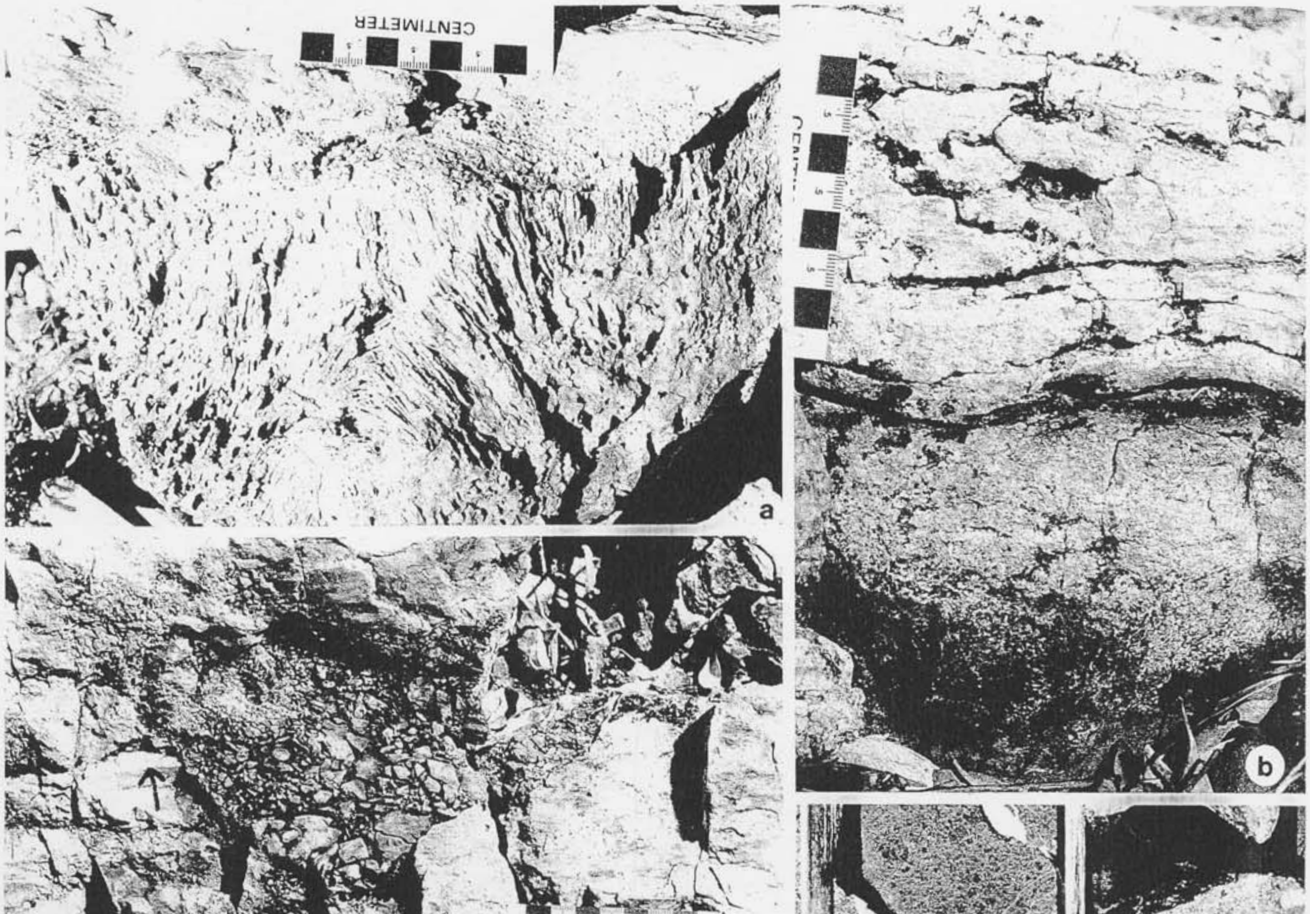
Some thin-bedded sinters have an internal laminar fabric of millimetric stacked, linked cones with upwardly directed apices forming "pseudocolumnar stromatolites", appearing in outcrop as minute cones on bedding planes (Fig. 6). These are very similar to conical features built by the cyanobacterium *Phormidium* in modern thermal springs (Walter et al., 1976, their figs. 6–35).

Thin-Bedded With Lycopsids

This microfacies consists of thin-bedded chert with silicified lycopsid stems or their molds lying in the bedding planes (Fig. 21b). There is little or no encrustation of the stems. In some examples the ornamentation of the stems, such as leaf scars, is well preserved. Comparable plant molds form in modern springs on the interfluves between channelways (authors' unpublished observations).

Intraclast Grainstone

Tabular intraclasts 1–5 mm thick by 1–30 mm long occur scattered through some thin-bedded sinter and as accumulations constituting lenticular bodies from millimeters to centimeters in thickness (Figs. 9, 10, 13). Intraclast grainstone is the dominant microfacies in the modern thermal springs we have studied in Yellowstone National Park (Walter, 1976b), and at Steamboat Springs and Beowawe in Nevada (Fig. 21). In striking contrast, this rock


CENTIMETER
a
b
CENTIMETER
INCH
c
CENTIMETER
d
CENTIMETER
e

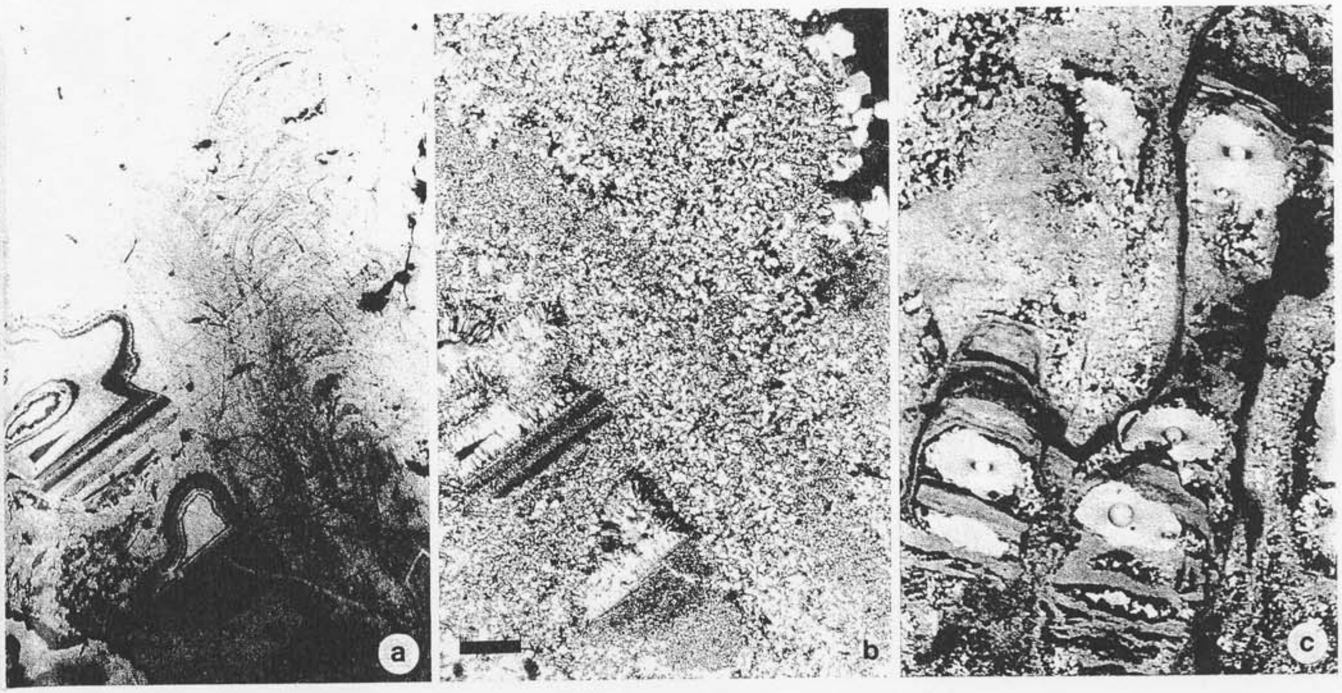


FIGURE 15—Thin sections of spicular sinter, uppermost sinter at Verbena; 'a' and 'c' plain light, 'b' crossed nicols. Scale bar in 'b' equivalent to 0.5 mm for 'a'–'c'. 'a' & 'b'—specimen 930612.2; 'c'—specimen 930614.1B1. Orientation uncertain as specimens are from rubbly outcrop.

type is rare in the Drummond Basin sinters. Though the origin of the clasts in the modern sinters has not been studied in any detail, they seem likely to result from desiccation, fracturing caused by freeze-thaw cycles and trampling by animals.

Encrusted Lycopsids

This microfacies consists of lenses and tabular beds of irregularly vugular chert with variously oriented plant stems encrusted by concentric laminae of chert (Fig. 21a).

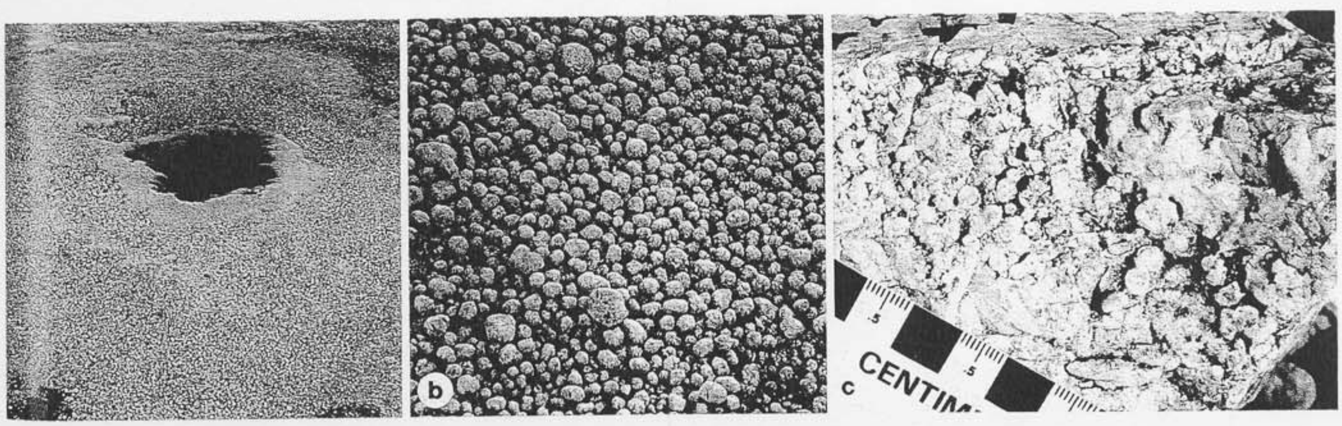


FIGURE 16—Modern and Paleozoic pisoids. 'a' & 'b', "Bead Geyser", Midway Geyser Basin, Yellowstone National Park (the vent in 'a' is surrounded by spicular sinter); 'c' uppermost sinter at Verbena.

e

←

FIGURE 14—Sinters and enclosing rocks from the Conway and Verbena hydrothermal systems. a—Spicular sinter, Verbena (orientation unknown); b—massive and crudely bedded sinter, Wobegong North; c—brecciated sinter grading up and down into fractures, Wobegong South; volcaniclastic sediments in core, Conway hydrothermal system; quartz-filled fractures in volcaniclastic sediments in core, Conway hydrothermal system.

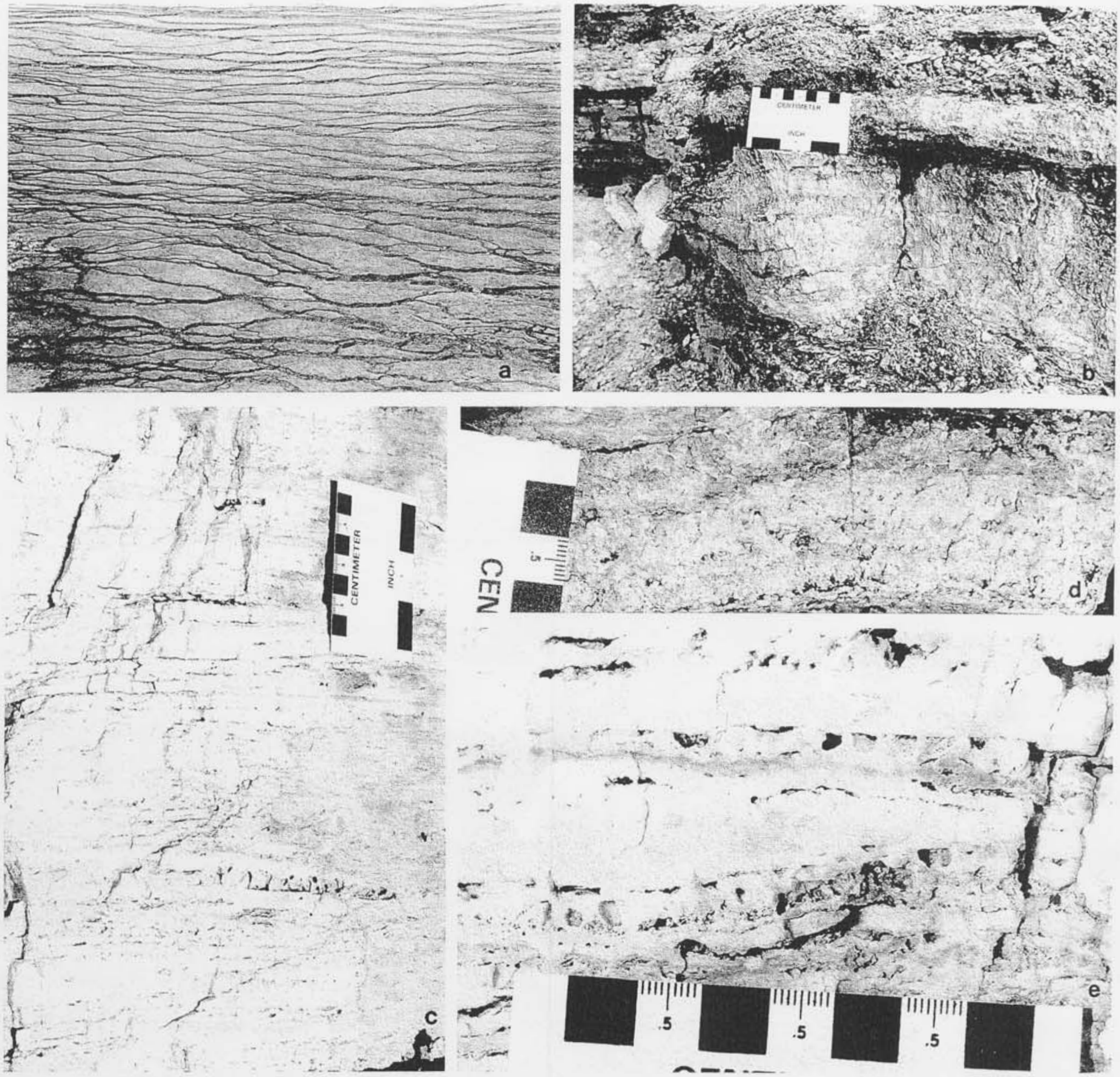


FIGURE 17—Modern and Paleozoic thin bedded sinters. 'a', sheet flood environment near the crest of Grand Prismatic Spring, Yellowstone National Park, where the cyanobacterium *Calothrix* is silicified *to* form "micro-terracettes" and thin bedded sinter such as that in 'b' from nearby in Excelsior Geyser Crater (where the vertical palisade fabric resulting from the silicification of *Calothrix* filaments is clearly evident); width of field of view about 3 m. 'c'—lowermost sinter at Verbena. 'd'—palisade fabric, Wobegong North. 'e'—close-up of 'c' showing fenestrae between between former tufted microbial mat features.

The orientation of the stems ranges from upright to apparently random. These fossils have previously been identified as the lycopsid *Oxroadia gracilis* (Olgers, 1972), but as noted above we have been unable to confirm this identification because our specimens are fragmentary. *Oxroadia* is a small, bushy lycopsid that grew up to 30 cm or so high, with horizontal and vertical branches. The range of orientations of the encrusted stems in our material could result from such a growth habit.

In some specimens silicification has preserved not only the macromorphology of the plant but also the cellular structure of the wood (Fig. 22).

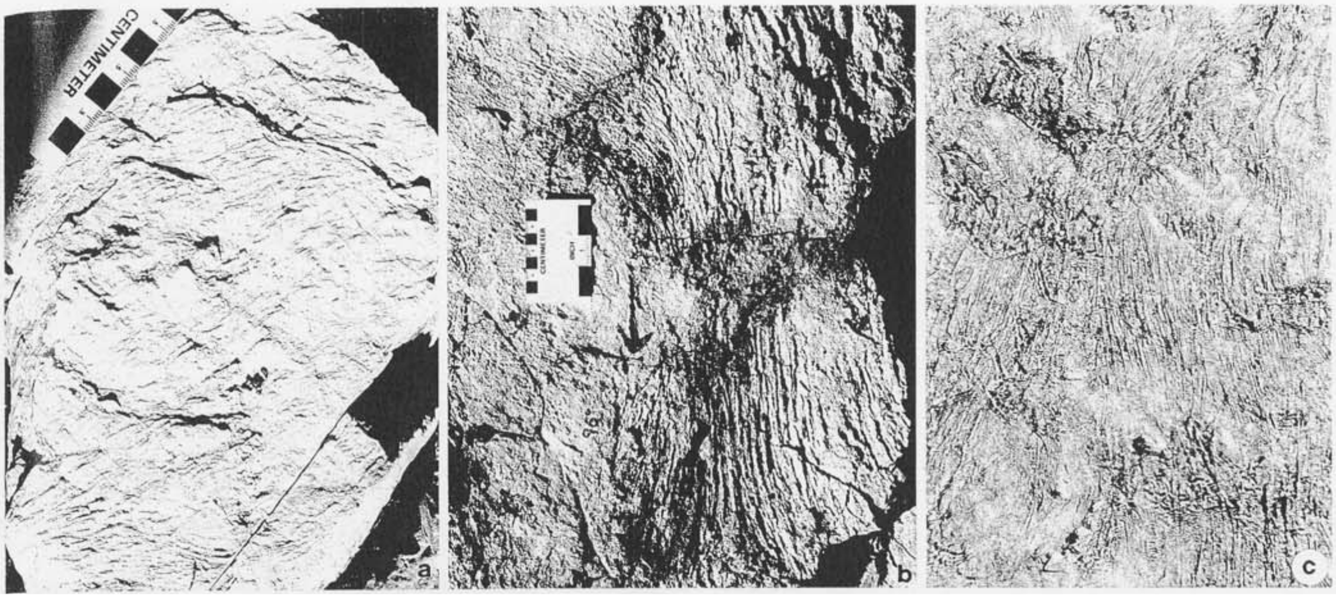


FIGURE 18—Streamers. 'a'—middle sinter at Verbena. 'b'—Wobegong North. 'c'—*Phormidium* streamer mat from Fountain Paint Pots, Lower Geyser Basin, Yellowstone National Park (scale is identical to 'a').

In modern springs, bushes and trees in growth position are frequently engulfed by newly formed ponds and become encrusted with opaline silica, forming structures identical to those described here (unpublished observations of the authors).

INTERPRETATION

The volcanic setting, siliceous composition, and presence of distinctive microfacies demonstrates that the cherts at Wobegong and Verbena are thermal spring sinters.

The thermal springs of Yellowstone National Park contain homologues for all of the recognised microfacies except the massive and brecciated examples (Weed, 1889a, b, *c;* Walter, 1972, 1976a, b; Walter et al., 1972, 1976; recent unpublished observations of the authors). These latter are considered here to have formed within and below vents and so have yet to be recognised in Yellowstone where most exposures are of surficial deposits. The subaqueous botryoidal masses of soft opal which occur in many springs (e.g., Octopus Spring, Midway Geyser Basin) may be a precursor of some of the massive sinter, or it may result from pervasive alteration of other sinter types within and adjacent to shifting fluid channelways below spring vents.

In the following discussion the terms in italics refer to the microfacies described above. The microfacies assemblage proximal to vents includes columnar and spicular geyserite *(spicular)* in splash zones of springs or geysers which erupt violently. Very high temperature (>73° C) pool floors have thickly laminated sinter with flat to wavy bedding *(thin flat bedded* and possibly some *diffusely layered).* Some very high temperature (>73° C) pools have sand and gravel of *ooids and pisolites.*

High temperature (59–73"C) stromatolitic sinter commonly is *thin-bedded* and has *streamers* (silicifiedflow-onented masses of bacterial filaments). *Conical lamination* marks the former presence of tufts of finely filamentous cyanobacteria in cooler water (59–30° C). Filamentous cyanobacteria form stratiform mats which are often *thin-bedded with streamers and fenestrae,* locally developing a *pustular* surface form (usually in very shallow pools). Where the filaments are coarse or bundled they impart a *palisade* internal fabric to the sinter. Where water stands in pools more than a few millimeters deep the mats develop surface growth features within which there is a *large, bushy palisade fabric.* Desiccation, temperature changes leading to the death and decomposition of mats, freeze-thaw cycles, and possibly also trampling by animals, break up the delicate silicified mats forming *intraclast grainstone.*

At ambient temperatures around springs and geysers, marshes develop and these have abundant diatoms, grasses and herbaceous angiosperms. The mid-Paleozoic analogues included herbaceous *lycopsids.* In pools these became *encrusted* by silica. In modern springs, grasses and herbaceous angiosperms also live on the interfluves between hot water channels on spring mounds; in these situations they commonly are incorporated in the sinter but do not get encrusted because there is no standing water; this environment is represented at Verbena by lycopsid stem and leaf molds in thin-bedded sinter.

While the origin of spring microfacies is moderately well understood, facies models that explain the large scale geometry of spring and geyser deposits are only now being

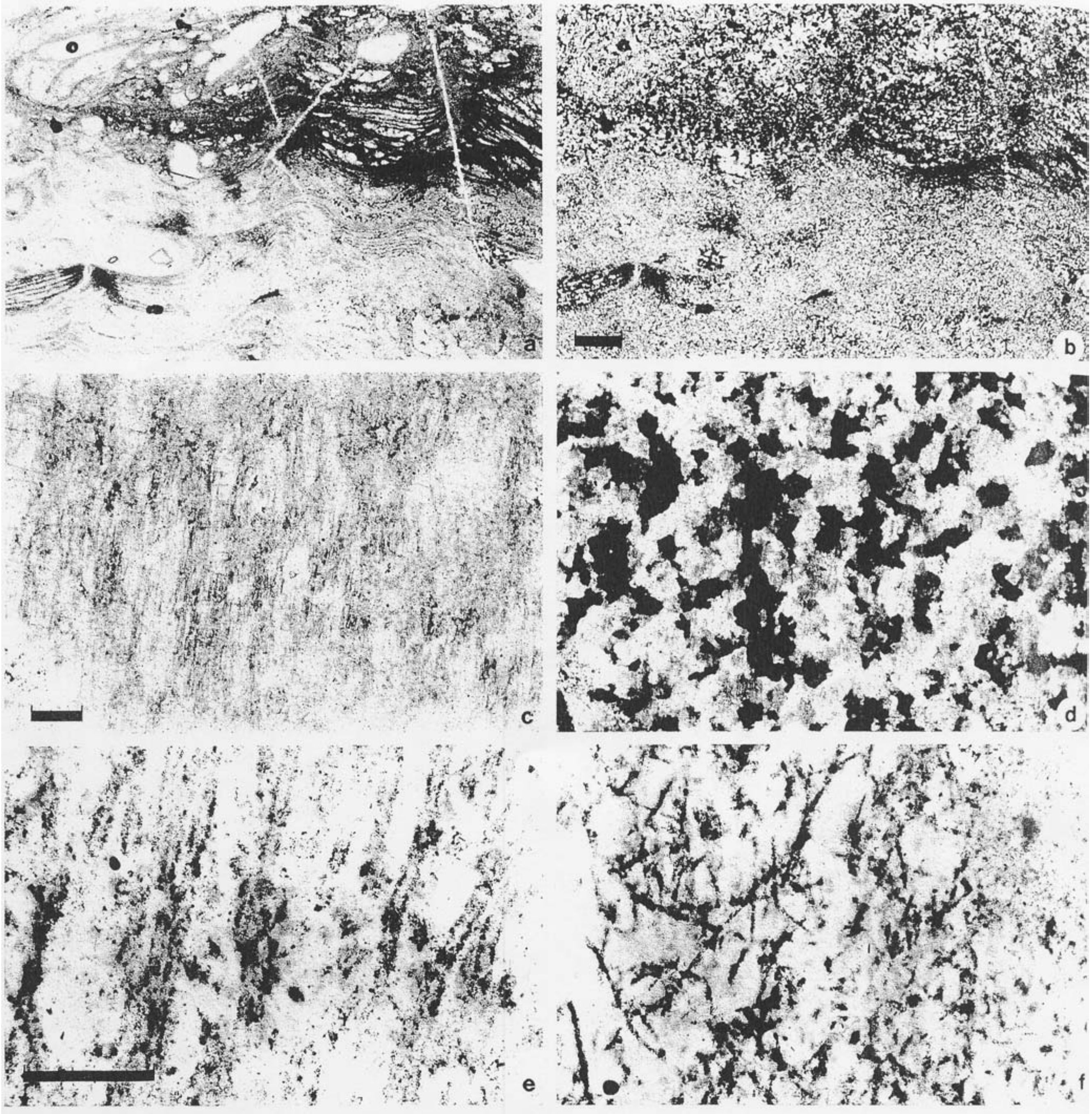


FIGURE 19—Thin sections of thin bedded sinter. 'a' & 'b'—specimen 930610.2D, Wobegong North, the latter with crossed nicols. Scale bar in 'b' equivalent to 0.5 mm for 'a' & 'b'. 'c'–'f'—lowermost sinter at Verbena; 'c' & 'd'—specimen 930614.2, same field of view, 'd' crossed nicols, scale bar equivalent to 100 μm. 'e'—Sinuous tubular molds of a coarsely filamentous microorganism, specimen 930613.2C, scale bar equivalent to 100 μm. 'f'—variously oriented tubular molds of a finely filamentous microorganism, specimen 930613.2C, scale as in 'e'.

developed. However, our observations in Yellowstone National Park allow some generalisations which bear on the interpretation of the Wobegong and Verbena deposits. Figure 23 summarises our interpretation of these deposits. To judge from the thickness of the sinters, both spring systems were short-lived, or were quickly buried by volcaniclastic sediment. For Wobegong, low flow rates can be inferred from the short distances between the high and low temperature microfacies. The Wobegong sinters show abundant evidence of ponding of water, characteristic of

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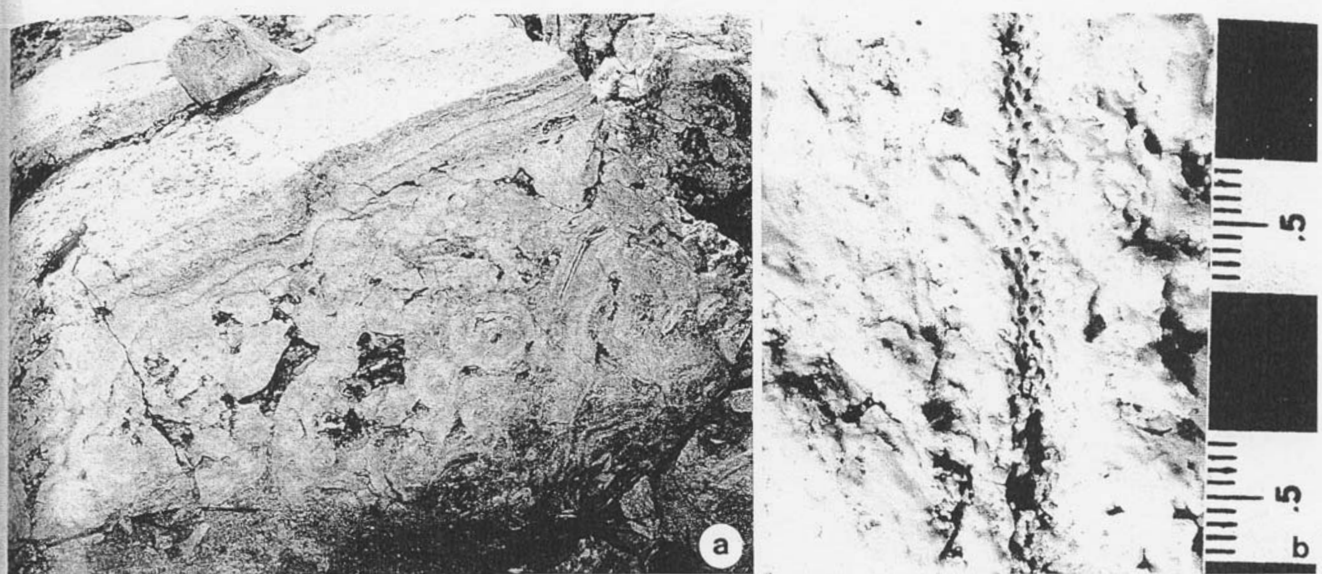

FIGURE 20—'a'—encrusted plant stems overlain by thin bedded sinter with a palisade fabric, Wobegong North; width of field of view about 30 cm. 'b'—mold of plant stem and leaves in lowermost sinter at Verbena.

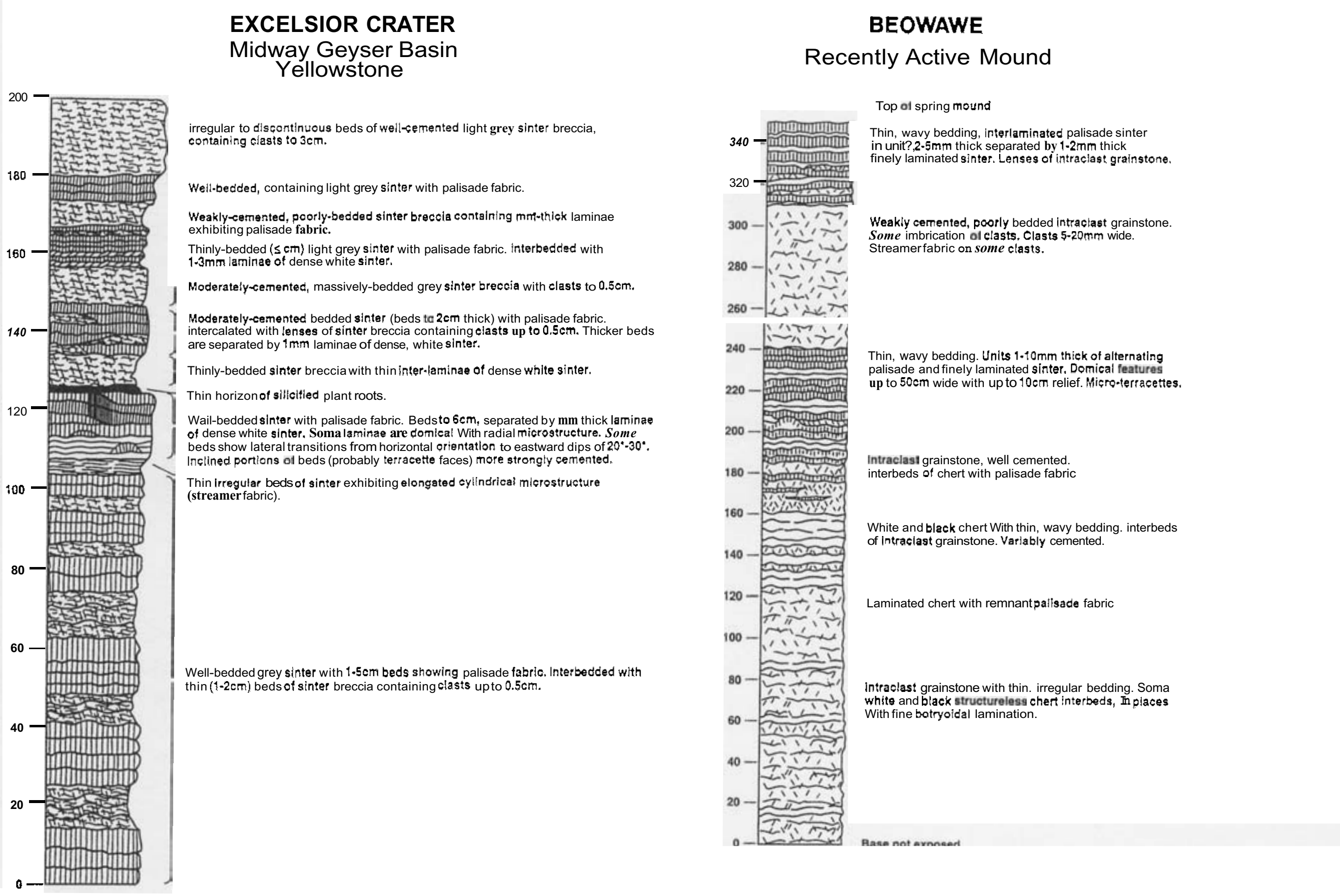

FIGURE 21—Stratigraphic sections of Quaternary sinters at Excelsior Geyser Crater, Yellowstone National Park, and Beowawe, Nevada. Scales in cm.

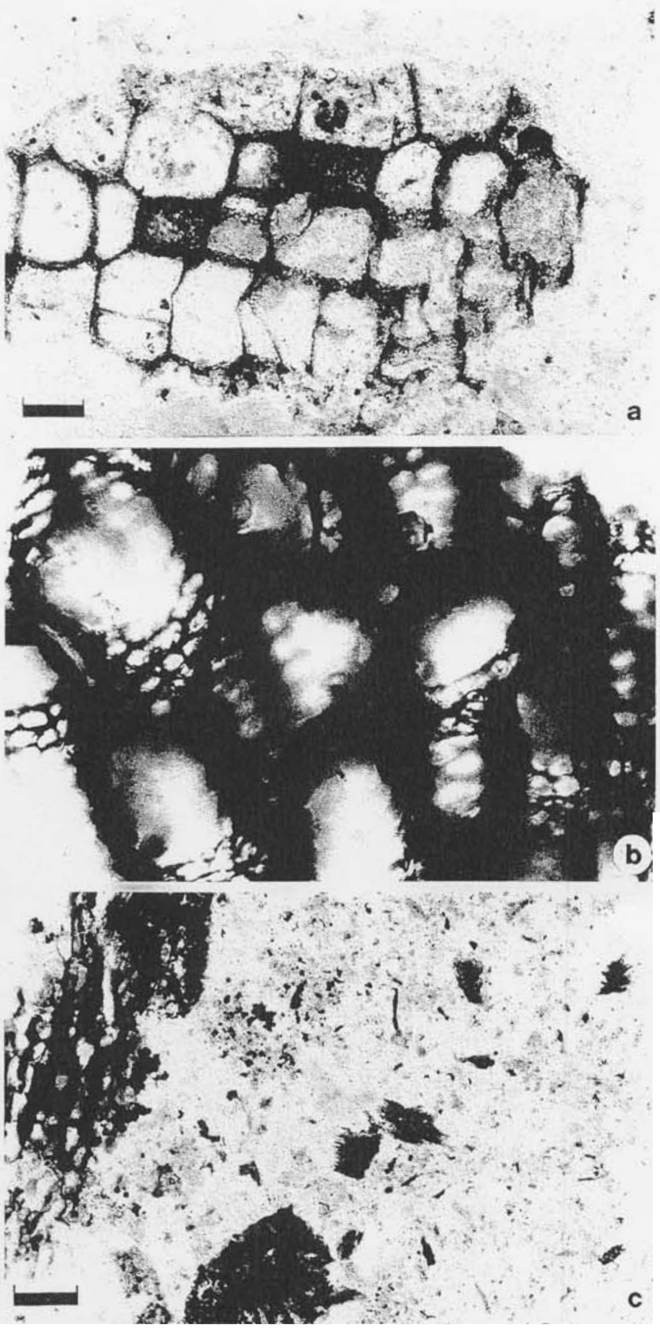

FIGURE 22—Plant fragments with cellular preservation, Wobegong North (specimen 930610.6E). Scale bar in 'a' also for 'b', 10 μm. Scale bar in 'c', 100 μm.

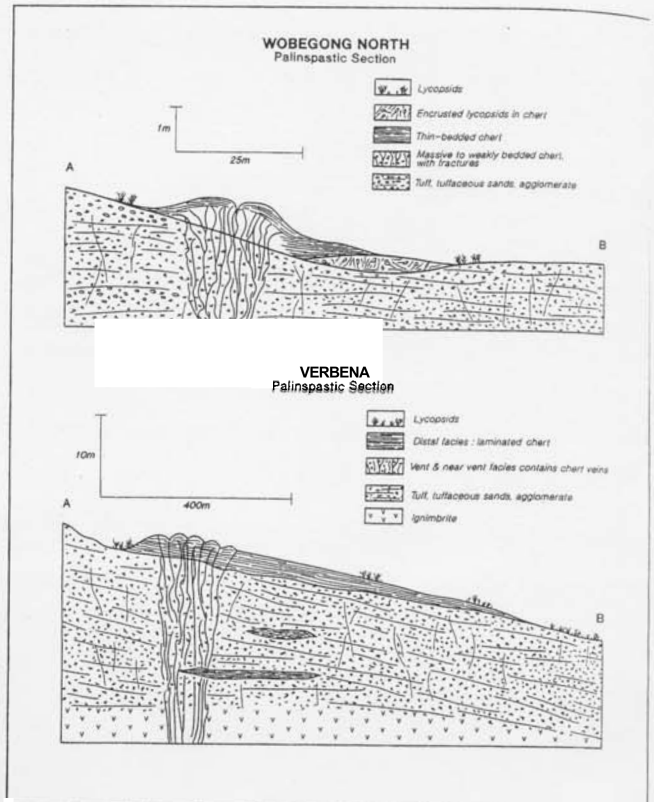

FIGURE 23—Palinspastic sections of the Wobegong North and middle Verbena sinters (see text for discussion).

springs with low flow rates and usually with minimal topographic relief (e.g., in Yellowstone, Octopus Spring, and some springs on the flanks of Fountain Paint Pots). The inference of low flow rates is also consistent with the small extent of the Wobegong sinters.

Evidence for ponding at Verbena is limited to the proximal vent area at the northwest end of the main sinter bed. There, bushy palisade fabrics characteristic of moderate temperature ponds occur with pisoids and pond floor microfacies such as now occur in high temperature ponds.

The spicular sinter which is abundant in this area is interpreted as geyserite characteristic of vents. Elsewhere at Verbena the sinters are thin-bedded with no features showing synoptic growth relief of more than a few millimeters. This is what is found in sheet-flow situations on the flanks of steeply sloping spring mounds (e.g., Beowawe and Steamboat Springs in Nevada), and in areas of sheet-flow in high discharge volume springs such as Grand Prismatic Spring in Yellowstone (Figs. 17a–b, 20). To judge from examples in Yellowstone and Nevada, lack of ponding is associated with slopes of more than 1:100. At Verbena, high discharge rates can be inferred from the great lateral extent of relatively high temperature microfacies (thin-bedded sinters frequently with streamers), and a slope of more than 1:100 is inferred from the lack of ponding. The slope must have been pre-existing because the spring deposit is not thick enough to have generated it. For these reasons the environment is interpreted as that of a complex of springs high on the flank of a hill. The size of the spring complex is much the same as those at Grand Prismatic and Fountain Paint Pots in Yellowstone.

ACKNOWLEDGEMENTS

This research was supported by a grant from NASA's Exobiology program to David DesMarais and Malcolm Walter, an NRC Senior Fellowship to Jack Farmer, and funding from NASA's JoVE program to Nancy Hinman. Newcrest Mining Ltd was generous in supplying maps and information on the Conway hydrothermal system, and access to core, and Dr Sabina Hopf allowed us access to her unpublished PhD thesis on that system. Present and former staff of James Cook University and Ross Mining company provided much useful information. Drs S. McLoughlin and A. Drinnan of Melbourne University provided information on the fossil plants. Profs R. A. Henderson of James Cook University and J. J. Veevers of Macquarie University made helpful comments on an early draft of the manuscript of this paper.

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ACCEPTED AUGUST 7, 1995