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SCIENTIFIC COMMUNICATIONS

PALEOZOIC HOT SPRING SINTER IN THE DRUMMOND BASIN, QUEENSLAND, AUSTRALIA

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Introduction

Sinter constructs terraced aprons around the hot spring discharge sites of many active, high-temperature (>150°C) geothermal systems, such as those at Steamboat Springs in Nevada, Yellowstone in Wyoming, and Wairakei in North Island, New Zealand. Recent progress in the understanding of epithermal systems has led to the recognition that identical hot spring sinter characterizes the paleosurfaces above several shallow epithermal (or hot spring) gold-silver deposits (e.g., White and Heropoulos, 1983). Well-preserved examples have been reported above epithermal gold-silver deposits of middle to late Cenozoic age at McLaughlin in California (Lehrman, 1986), Hasbrouck Mountain (Graney, 1987) and Buckskin Mountain (Vikre, 1985) in Nevada, and elsewhere.

In this paper we report the discovery of identical pristine sinter from an epithermal system of Late Devonian age—to our knowledge the only pre-Mesozoic example of unambiguous sinter documented to date. The sinter and associated hydrothermal products are located in the Drummond basin of east-central Queensland, Australia. The site, centered on latitude 21°29′29″ S, longitude 147°26′43″ E, is near the Verbena (syn. Glen Eva and Glenifer) homestead, some 15 km southeast of Mount Coolon village and the nearby gold deposit (Fig. 1).

Regional Setting

The Drummond basin is a structural remnant of a large intracratonic basin that developed after the mid-Devonian Tabberabberan orogeny in the northern part of the Tasman orogenic zone (Fig. 1) of eastern Australia (Olgers, 1972). The Drummond is a foreland basin and probably occupied a back-arc position with respect to a subaerial, Andean-type volcanoplutonic arc farther east (Powell, 1984; Murray, 1986). The Drummond basin sequence, of Late Devonian to early Carboniferous age, was deposited on a basement of early and mid-Paleozoic metamorphic and granitic rocks and crops out over some 25,000 km^2 (Fig. 1; Olgers, 1972). The sequence comprises at least 12,000 m of mainly fluviatile sedimentary rocks, the lower, Late Devonian parts of which accumulated in extensional grabens (Hutton, 1988) and are interbedded with volcanic rocks (Olgers, 1972).

In the eastern part of the Drummond basin, east of the Anakie inlier (Fig. 1), the lower, volcanic-dominated part of the sequence is represented by the Silver Hills Volcanics (Olgers, 1972), which in the Mount Coolon area consist of rhyolitic ignimbrite and tuff interbedded with lithic and feldspathic sandstone, siltstone, and shale (Grimes et al., 1986).

Sedimentation and volcanism in the Drummond basin ceased with the onset of widespread mid-Carboniferous orogeny, during which the Late Devonian-early Carboniferous sequence underwent open folding (Olgers, 1972). The late Carboniferous Bulgonunna Volcanics were deposited unconformably across the northeastern part of the Drummond basin sequence (Fig. 1) and were broadly contemporaneous with a number of felsic intrusions.

Local Geology

The Verbena epithermal system was developed in volcanic and sedimentary rocks assigned by Olgers (1972) to the Silver Hills Volcanics. As depicted in Figure 2, we have distinguished three volcanic and three sedimentary units in and around the mineralized area. The volcanic rocks are rhyolitic ignimbrites, which carry variable proportions of pumice and lithic clasts, and underwent little or no welding. The sedimentary rocks are epiclastic and dominated by lithofeldspathic sandstone, which is interbedded with subordinate siltstone, and locally, with conglomerate. The sedimentary units display high-angle crossbedding and ripple marks, and locally carry poorly preserved fossils of plant stems. Two of the three sedimentary units contain sinter horizons, as described below.

The Late Devonian rocks which acted as hosts for the Verbena epithermal system underwent gentle folding during the mid-Carboniferous to produce two synclines and an intervening anticline (Fig. 2). The folds are characterized by limbs that dip mostly from 20° to 30°; the folds plunge southeast to east-southeast at 20°. No other rock deformation nor any fabric development was recognized.

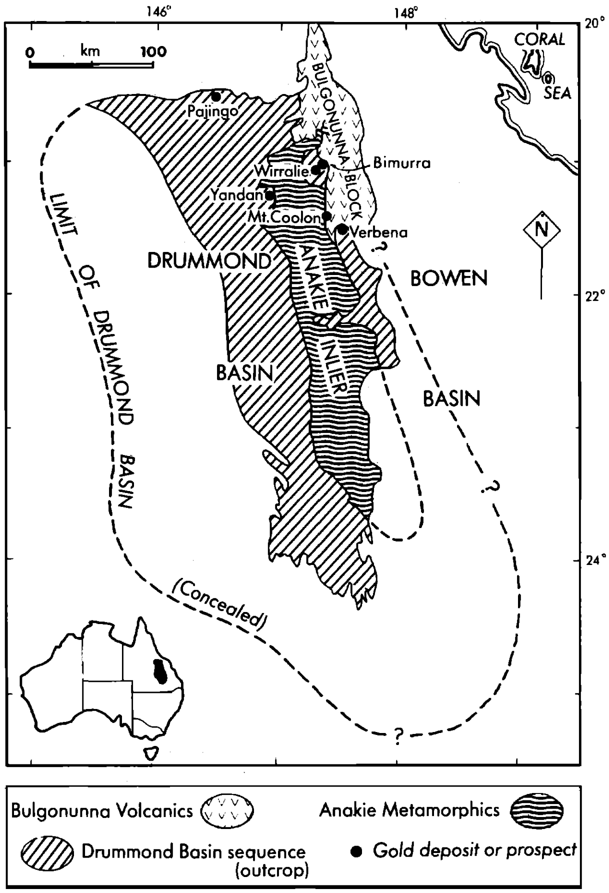

FIG. 1. Locations of the Verbena hydrothermal system and selected gold deposits in the Drummond basin of east-central Queensland. Geology taken with slight modification from Olgers (1972).

The sinter-bearing Late Devonian rocks underlie a low hill which is surrounded by lateritized mesas of sedimentary accumulations, mainly paleotalus of local provenance, and Recent alluvium (Fig. 2). The lateritized paleotalus is considered as part of the Suttor Formation, a regionally extensive detrital sequence of mid-Tertiary age (e.g., Grimes et al., 1986).

Hydrothermal Products

Chalcedonic veins, stockworks, and sinter at Verbena are present in a northwest-trending zone ranging from 400 to 600 m wide and exposed over a strike extent of 1,500 m (Fig. 2). Sinter horizons occur in the lower and middle sandstone units whereas veins and stockworks are most widespread in the middle and upper sandstones and the intervening (upper) ignimbrite (Fig. 2).

Stockworks and veins

Stockworks comprise irregular, multidirectional veinlets of dense, massive, porcelaneous chalcedony, up to about 5 cm wide, which are associated with various degrees of pervasive silicification, especially of host sandstone. Locally, stockworks are transitional to hydrothermal breccia in which similar chalcedony is present as a cement to clasts. The middle sandstone unit (Fig. 2) is extensively silicified even where stockworking is poorly developed. Accompanying hydrothermal effects, tentatively considered to be marked by the introduction of illite and smectite, are largely masked by supergene alteration, which generated kaolinite and subordinate chalky alunite.

The stockworks appear to have been overprinted by a west-northwest-striking set of steep chalcedony veins. They crop out poorly, and those mapped (Fig. 2) are traceable only as aligned float trains. Individual veins do not attain widths greater than 0.5 m and may be followed at surface for distances of 5 to 50 m. The veins exhibit abundant crustification and carbonate-replacement textures (Fig. 3), the latter produced by hydrothermal dissolution of lamellar calcite. More locally, the veins contain open spaces, some resulting from calcite dissolution, that are lined with tiny quartz crystals.

The sulfide content of veins and stockworks is judged to be low (say, 3 vol %) on the basis of the paucity of supergene limonite. However, limonite tends to be more abundant in the adjoining host rocks.

Sinter

The principal exposures of sinter (Fig. 4A) are in the middle sandstone unit (Fig. 2). Two discrete sinter horizons dip at about 20° southeastward, and the uppermost is traceable along strike for some 600 m. Although depositional dips of this order have been recorded from modern sinter terraces (e.g., Beowawe, Nevada; Rimstidt and Cole, 1983), the present attitude of the Verbena sinter is attributed to the effects of folding. The most extensive sinter horizon at surface exceeds 10 m in thickness whereas the more restricted, lower sinter is 5 m thick. The two are separated by about 1.5 m of sandstone and siltstone. A thinner horizon of sinter, probably 1 to 2 m thick, is present in the lower sandstone unit and crops out on the axis of the anticline (Fig. 2).

All three beds of sinter are identical texturally to their Cenozoic chalcedonic analogues. They are well bedded, composed of dense, laminated, vitreous chalcedony, and display abundant interlayer cavities up to 4 cm long which, although irregular in shape, are elongate parallel to the layering (Fig. 4B). Individual layers range in color from white through gray to tan and orange-brown and are partly translucent. Brown colors are due to pigmentation by limonite, which also lines many of the cavities. No sulfides were observed. Thin, irregular intercalations of silicified sand were observed very locally in the sinter, and sinter fragments were noted in sandstone abutting the thickest sinter. The sinter is devoid of fragmental textures and crosscutting features.

Bedding planes in the sinter exhibit external moulds of lycopod stems (Fig. 4C and D), random arrays of circular to polygonal cavities (up to 0.5 cm across and 0.25 cm deep) of uncertain origin (Fig. 4E), geyserite "pearls," and silicified filamentous bacterial mats (Fig. 4F). Several external molds of lycopod stems with exceptionally well-preserved ovate leaf scars, and in one example, leaf molds, too (Fig. 4D), were examined by J. F. Rigby of the Queensland Geological Survey. He concluded (written commun., 1988) that they resemble known Devonian-early Carboniferous forms but probably represent a new species. The bacterial mats are not dissimilar to those described from modern sinters (e.g., Yellowstone; Walter et al., 1972).

Sinter was more extensive previously as evidenced by the presence of abundant angular fragments of sinter, up to 0.5 m in length, in Suttor paleotalus, especially 400 m west of the principal sinter outcrops (Figs. 2 and 5). Paleotalus 200 m north of the principal sinter (Fig. 2) contains clasts of distinctive gray- and white-banded sinter unlike any of that observed in situ.

Lithogeochemistry

Representative samples of sinter from the lower and middle sandstone units and of 12 typical chalcedony veins at Verbena were analyzed for Au, Ag, Hg, As, Sb, and Ba by Tetchem Labs in Cairns, Australia. Analyses for Au and Ag were by fire-assay fusion with an atomic absorption finish, the analytical technique also used for Hg. Arsenic, Sb, and Ba were analyzed by X-ray fluorescence. The results are presented in Table 1, which also summarizes analytical data for epithermal gold-bearing chalcedony veins from Wirralie in the Drummond basin (Fig. 1; see below) and for several hot spring sinters unrelated to known precious metal deposits in the western United States. These American hot spring sinters overlie geothermal systems promoted by both felsic magmatism (Steamboat Springs, Long Valley, Coso, Roosevelt) and high heat flow in a nonmagmatic basin-and-range setting (Beowawe, Pinto, Brady).

Table 1 shows that the epithermal suite of elements is not strongly anomalous in either sinter or vein chalcedony from Verbena. In fact, the average Au, Hg, Ba, and probably also Ag values are lower than the corresponding crustal averages (Krauskopf, 1967, appendix III). The only lithogeochemical difference between sinter and vein chalcedony is the higher barium values in some of the vein samples (Table 1).

Precious metal values at Verbena are appreciably lower than those determined for sinters at Steamboat Springs, Long Valley, Roosevelt, and McGinness Hills but comparable to those at Beowawe, Pinto, Brady, Coso (Table 1), and several other sinter localities in the western United States (White and Heropoulos, 1983). The Sb and Hg values at Verbena are lower than for all the United States sinters listed in Table 1, and the As values are lower than all except those in the Beowawe, Brady, Coso, and McGinness Hills sinters, with which they are comparable.

The contents of Au, Ag, As, and Hg in oxidized vein ore from the Wirralie gold deposit are an order of magnitude or more greater than those recorded for sinter and vein chalcedony from Verbena (Table 1). However, Sb values from the two localities are comparable (Table 1).

Environment of Formation

Sinter precipitation during the Late Devonian at Verbena took place in a fluviatile environment in which lycopods flourished at times. Sinter was a local facies of the fluviatile sediments and is believed to have accumulated in drainage channels. Fluviatile sedimentation was interrupted periodically by deposition of small-volume pyroclastic flows. The volcano-sedimentary package lacks features indicative of proximity to a volcanic center. However, recognition of a flow-banded rhyolite plug and associated lava flows only 2 km southeast of the Verbena system, albeit at a higher stratigraphic level, suggests that ignimbrite eruption and hydrothermal activity may have been related to an unlocated and probably concealed rhyolite flow-dome complex.

The Verbena sinters constitute a stacked system, with hydrothermal activity clearly having been active, at least intermittently, during the accumulation of some 600 m of volcanic and epiclastic rocks (Fig. 2). Much of the chalcedony veining is present in sandstone and ignimbrite which are younger than the outcropping sinters, and it may have been capped by one or more higher sinter horizons which are now concealed or have been eroded away. Sinter clasts in the Suttor paleotalus may have been derived in part from stratigraphically higher sinter horizons.

Fluviatile sediments and ignimbrites were accumulating while the Verbena epithermal system was active. In fact, construction of the individual sinter aprons was probably curtailed by influxes of riverborne sediments. The relatively fine grain size of the fluviatile sediments suggests that the Late Devonian paleosurfaces in existence during the lifespan of the Verbena hydrothermal system were subdued topographically. This factor, along with progressive burial by sediments and pyroclastic flows, and during the late Carboniferous, beneath the Bulgonunna Volcanics, were conducive to preservation of near-surface hydrothermal products at Verbena. The Verbena system is located on the southern edge of the Bulgonunna Volcanics (Fig. 1) and therefore may have been exhumed as recently as the early Tertiary.

The stacked configuration of sinter at Verbena is reminiscent of that in the upper part of the Steamboat Springs geothermal system, where three principal sinter horizons are interbedded with basaltic and

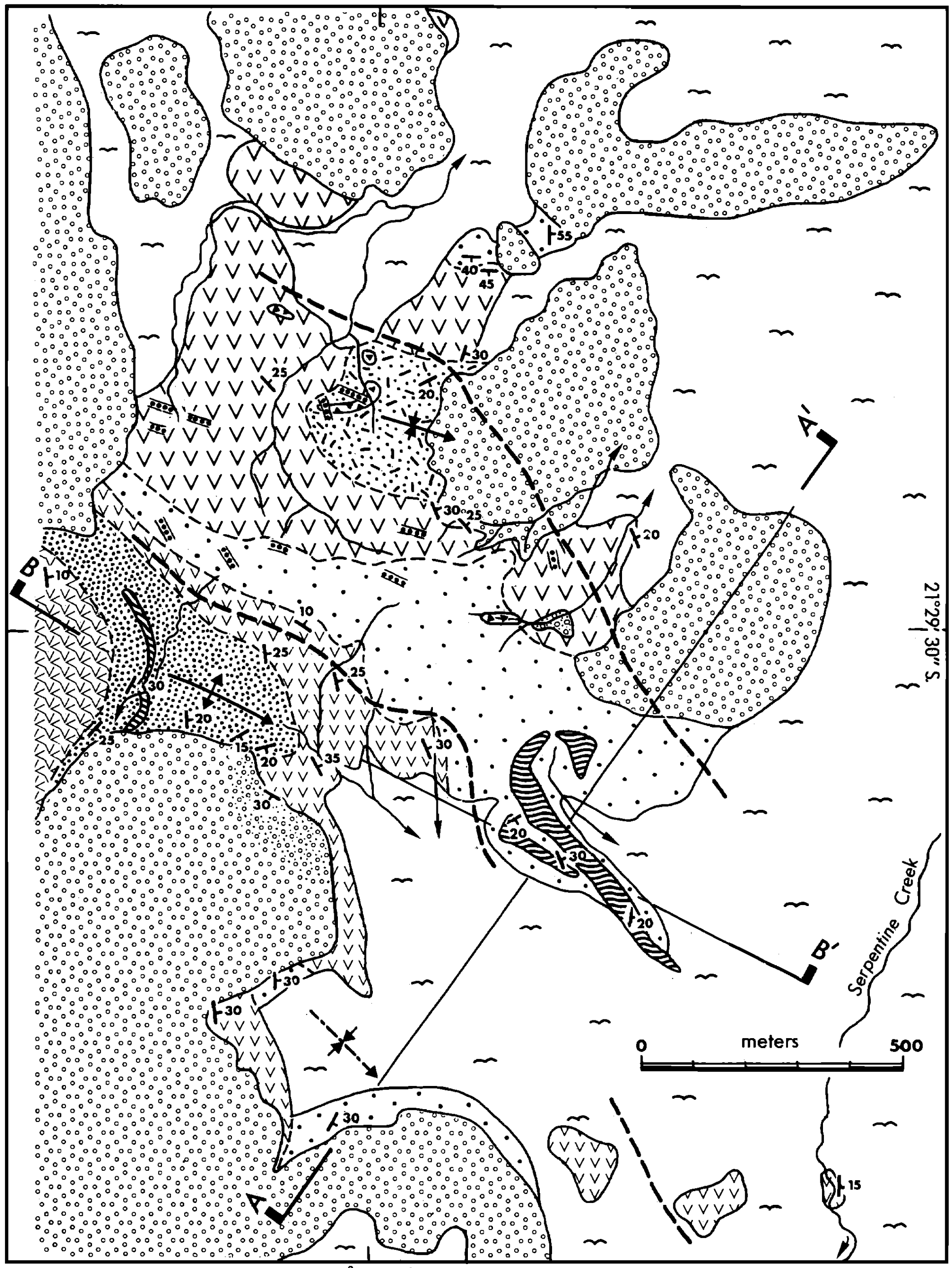

FIG. 2. Surface geology and interpretative cross sections of the Verbena hydrothermal system, Queensland. Veins are schematized on cross section A-A'.

rhyolitic volcanic products and alluvial deposits (White et al., 1964). Using radiometric and stratigraphic dating, Silberman et al. (1979) showed that hydrothermal activity at Steamboat Springs has been active, possibly intermittently, for >2.5 m.y. However, such longevity is not required at Verbena, although it cannot be excluded on present evidence. The sinter, with a preserved aggregate thickness of <20 m, could have accumulated in 6,000 yrs if the long-term rates of sinter accumulation summarized by Vikre (1987) are employed. Deposition of the interbedded ignimbrites could have taken as little as a few days, and fluviatile sediments are unlikely to represent protracted time intervals.

Regional Comparisons

Volcano-sedimentary sequences of Late Devonian-Carboniferous age in the Drummond basin are the

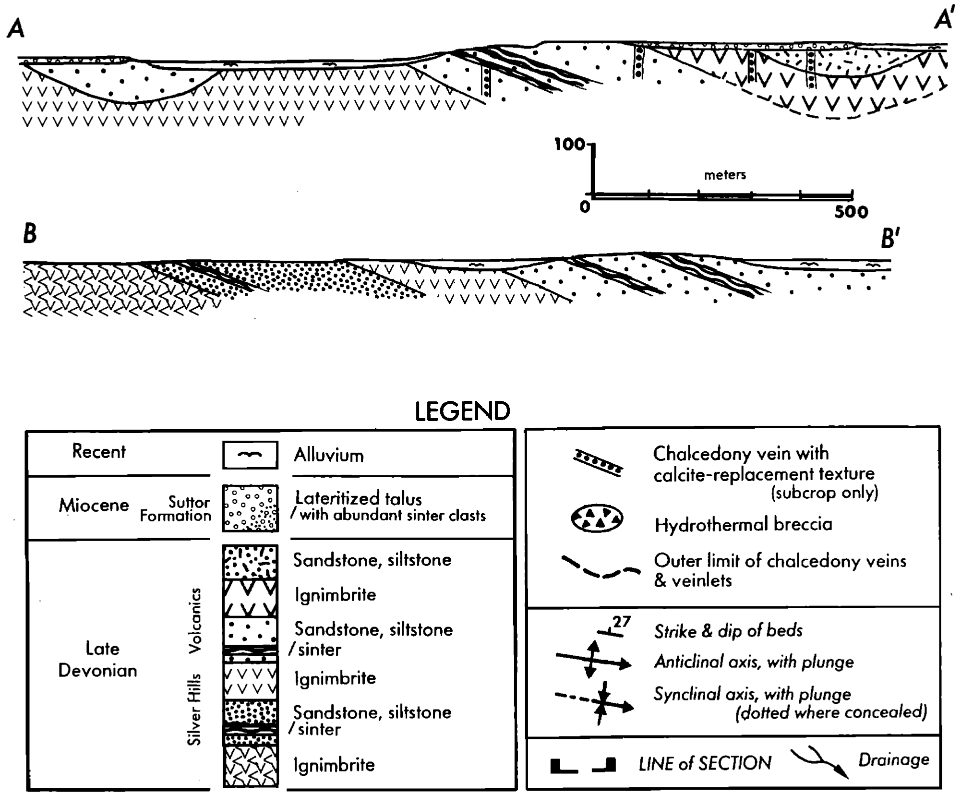

FIG. 2. (*Cont.*)

hosts for one previously exploited (Mount Coolon; Morton, 1935) and several recently discovered epithermal systems of low-sulfidation, adularia-sericite type (Fig. 1). Two of them, Pajingo (Porter, 1986; Etminan et al., 1988) and Wirralie (Fellows and Hammond, 1988), contain economic gold deposits. In fact, Wirralie was developed in broadly similar volcanic and sedimentary lithologies to those exposed at Verbena. Gold mineralization at Mount Coolon, Pajingo, and Wirralie is present in wide, multiphase chalcedony-quartz veins, which are characterized by crustification and carbonate-replacement textures closely similar to those at Verbena. Furthermore, poorly exposed sinters have been recognized tentatively at both Pajingo (R. G. Porter, pers. commun., 1987) and Wirralie (Fellows and Hammond, 1988).

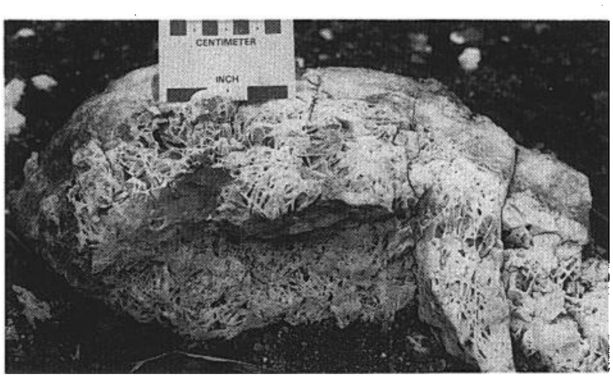

FIG. 3. Carbonate-replacement textures in chalcedony vein, Verbena, Queensland.

The limited widths and lengths of the chalcedony veins at Verbena are attributed to repeated burial of the hydrothermal system during its lifespan and the absence from the system of a single master structure. As a result, hydrothermal fluid flow kept changing its position within the system, especially after each major burial event, and was not focused through a single conduit for a prolonged period. Therefore, the small individual veins at Verbena did not undergo rebrecciation and failed to experience as many stages of opening and filling as the wide veins at Pajingo and Wirralie (Etminan et al., 1988; Fellows and Hammond, 1988). However, given the close similarity of vein textures and mineralogy at Verbena, Pajingo, and Wirralie, we believe that the totally barren character of the Verbena system ultimately reflects the passage of hydrothermal fluids deficient in precious metals and other elements of the epithermal suite.

Finally, it should be mentioned that the nearest gold deposit to Verbena, at Mount Coolon (Fig. 1), differs mineralogically from the other principal epi-

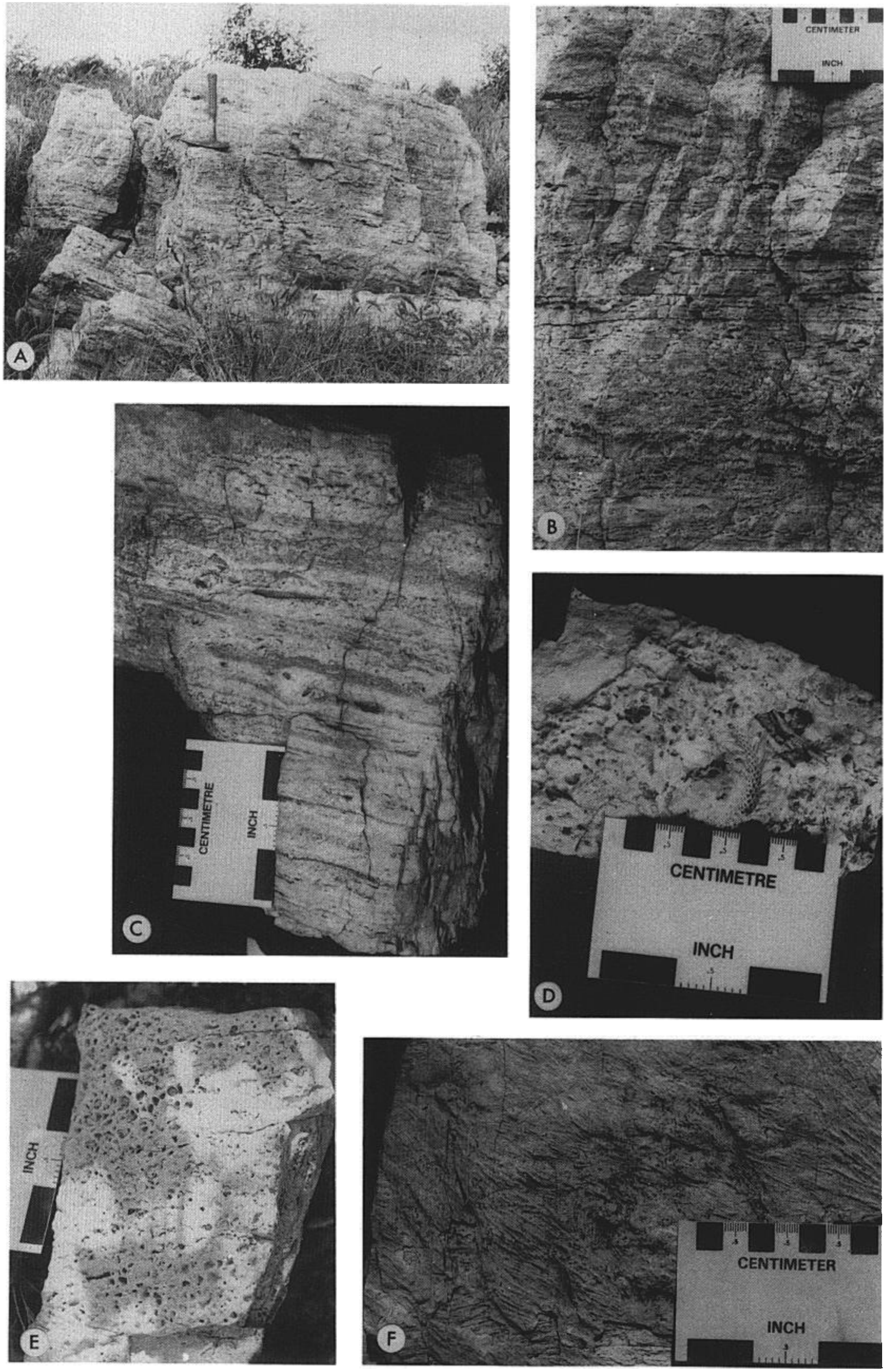

FIG. 4. Features of the lower sinter in the middle sandstone unit at Verbena, Queensland. A. Outcrop viewed from the west, pick for scale. B. Layering and interlayer cavities. C. External mold of lycopod stem (middle) parallel to layering. D. External mold of lycopod stem and attached leaves on bedding surface. E. Array of circular to polygonal cavities of uncertain origin on bedding plane. F. Filamentous bacterial mat on bedding surface.

TABLE 1. Geochemical Comparison between Sinters and Veins at Verbena and Elsewhere (mean values and ranges in ppm)

Locality	n	Au	Ag	As	Sb	Hg	Ba	Data source
Upper sinter, Verbena, Queensland	8	n = 7: <0.008, n = 1: 0.01	<1	n = 7: 9(3–29), n = 1: <2	10(6–13)	n = 7: <0.005, n = 1: 0.01	58(30–90)	This study
Lower sinter, Verbena, Queensland	2	<0.008	<1	33(16–50)	5(4–6)	<0.005	52(51–53)	This study
Veins, Verbena, Queensland	12	<0.008	<1	n = 8: 16(3–44), n = 4: <2	n = 8: 8(4–18), n = 4: <3	n = 9: <0.005, n = 3: 0.02	162(11–814)	This study
Veins, Wirralie, Queensland	?	avg: 2.8	avg: 7	avg: 270	avg: 11	avg: 0.31	nd	Fellows and Hammond (1988)
Steamboat Springs, Nevada	10	n = 4: 0.2–1.5, n = 6: <0.1	n = 1: 15, n = 1: 5, n = 6: 0.1–1, n = 2: <0.1	n = 4: 100–700, n = 6: 2–70	n = 7: 700–<2,000, n = 3: 70–300	n = 3: 1,000–<2,000, n = 6: 1–30 n = <1: 1	nd	White and Heropoulos (1983)
Beowawe, Nevada	4	n = 1: 0.2, n = 3: <0.1	n = 3: 0.5–1, n = 1: <0.1	5–10	n = 3: 20, n = 1: 5		nd	White and Heropoulos (1983)
Pinto, Nevada	3	<0.1	n = 1: 0.3 n = 2: <0.1	47(10–100)	27(20–30)	440(20–1,000)	nd	White and Heropoulos (1983)
Brady, Nevada	2	<0.1	0.5	25(20–30)	40(30–50)	20	nd	White and Heropoulos (1983)
McGinness Hills, Nevada	9	0.067	0.3	19	41	0.084	nd	Casaceli et al. (1986)
Long Valley, California	4	n = 1: 1, n = 3: <0.1	n = 1: 10, n = 1: 0.3, n = 2: <0.1	n = 3: 50	n = 3: 200–300, n = 1: 100	3(2–5)	nd	White and Heropoulos (1983)
Coso, Caifornia	2	<0.1	<0.1	13(7–20)	150(100–200)	35(20–50)	nd	White and Heropoulos (1983)
Roosevelt, Utah	7	n = 1: 0.5, n = 6: <0.1	<0.1	n = 1: 300, n = 1: 100, n = 5: 5–20	n = 1: 2,000, n = 3: 200, n = 3: 30–100	n = 3: 2–20, n = 4: 1	nd	White and Heropoulos (1983)

nd = not determined, avg = average value

FIG. 5. Blocks of sinter in paleotalus of the mid-Tertiary Suttor Formation, 400 m west of the lower (middle sandstone) sinter outcrops at Verbena, Queensland.

thermal gold deposits in the Drummond basin. The entire Mount Coolon structure underwent introduction of both delicately banded chalcedony-adularia of typical epithermal character and an irregularly distributed, coarse-grained actinolite-biotite-epidote-magnetite-pyrite assemblage (R. H. Sillitoe and R. Cunneen, unpub. data; Morton, 1935). These two vein fillings, the relative timing of which remains to be clarified, were overprinted by sericitic alteration and minor late tourmaline. The actinolite-bearing assemblage is compatible mineralogically with hornfels and hydrothermal alteration developed in the wall-rock ignimbrite, effects which may be attributed with confidence to a nearby tonalite pluton of late Carboniferous age (280–290 m.y.; Malone, 1969).

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