Geologic record of partial ocean evaporation triggered by giant asteroid impacts, 3.29–3.23 billion years ago

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ABSTRACT

Although lunar studies suggest that large asteroid impact rates in the inner solar system declined to their present low levels at 3.8–3.7 Ga, recent studies in greenstone belts indicate that asteroids 20 km to 70+ km in diameter were still striking the Earth as late as 3.2 Ga at rates significantly greater than the values estimated from lunar studies. We here present geologic evidence that two of these terrestrial impacts, at 3.29 Ga and 3.23 Ga, caused heating of Earth's atmosphere, ocean-surface boiling, and evaporation of tens of meters to perhaps 100 m of seawater. Rapid ocean evaporation resulted in abrupt sea-level drops, erosion of the exposed sea floor, and precipitation of distinctive layers of laminated silica representing marine siliceous sinter. Such events would have severely affected microbial communities, especially among shallow-water and photosynthetic organisms. These large impacts profoundly affected Archean crustal development, surface environment, and biological evolution until 3.2 Ga, or even later.

INTRODUCTION

Sleep et al. (1989) argued that the oceans would have evaporated completely and Earth's surface would have been sterilized if struck by an asteroid greater than ~440 km in diameter, and that a depth of water corresponding to the photic zone would have been evaporated by a 190-km-diameter object. Such large impacts would have superheated the world's atmosphere and generated near-surface ocean temperatures at or above boiling for hundreds to thousands of years (Sleep et al., 1989). More recent calculations (Segura et al., 2013) have shown that thinner layers of ocean water would have been evaporated by smaller impacts, and that even bolides 50–100 km across could have evaporated tens of meters of ocean water.

The Barberton greenstone belt, South Africa, includes eight known layers of ejecta, termed S1 through S8, produced by large asteroid impacts between 3.470 Ga and 3.225 Ga (Lowe et al., 1989, 2014; Lowe and Byerly, 2010). Estimates of bolide sizes are imprecise, but vary from 20 to >100 km (Byerly and Lowe, 1994; Johnson and Melosh, 2012). All of the layers represent distal ejecta deposited far from the impact sites, and all but one are marked by sand-sized spherules formed by the condensation of impact-generated rock vapor clouds (Lowe et al., 1989, 2003). Several of these layers show pronounced iridium anomalies, and all spherule beds were widely reworked and commonly removed completely by tsunamis that accompanied or shortly followed spherule deposition. We here present evidence that deposition of two of these layers, S5 and S8 (Lowe et al., 2014), was accompanied by ocean boiling, partial evaporation, and drops in sea level, and explore the implications of these catastrophes for life and early surface evolution.

SPHERULE BED S8

Spherule bed S8 (Lowe et al., 2014) occurs in member M2c of the Mendon Formation (Lowe and Byerly, 1999), a thin sedimentary unit deposited at ca. 3.29 Ga and bracketed by volcanic episodes represented by komatiitic members M2v (below) and M3v (above). Near the type locality of S8 (Fig. 1A; 25°54′8.82″S, 31°02′52.6″E, revised from Lowe et al., 2014), M2c ranges up to ~5 m thick (Fig. 1B) and consists mainly of black and banded chert overlain by <1 m of laminated silica

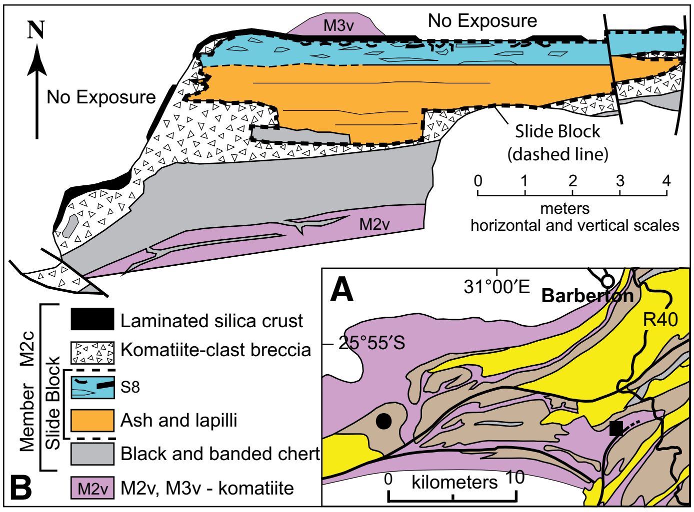

Figure 1. A: Regional map showing locations of spherule beds S5 (solid circle) and S8 (solid square) in South Africa. Symbols: purple—Mendon Formation and older volcanic units; brown—Fig Tree Group; yellow—youngest greenstone belt rocks; R40—main road across the greenstone belt. B: Section through member M2c of Mendon Formation at S8 type locality. Spherule bed caps and is part of a slide block (dark dashed line). S8 was disturbed during sliding and partially mixed with black carbonaceous sediments and fragmented silica crust.

(Fig. 2). The black chert represents fine carbonaceous debris, ash, and siliceous chemical sediments. The fine grain sizes, finely laminated character, and absence of current features suggest deposition in quiet, possibly deep water. At the type locality, the black chert is separated from the laminated silica by a slide block embedded in breccia composed of small angular clasts of komatiite (Fig. 1). The breccia has a black chert matrix that contains sparse spherules. The slide block includes up to 150 cm of current-deposited volcanic ash overlain by S8, a 50–70-cm-thick bed of black carbonaceous sediment, ash, masses of spherules, and fragments of laminated silica rock, all disrupted and mixed during sliding. The top 30–40 cm of the block are cut by thin silica dikes representing fractures developed during sliding.

The slide block and surrounding carbonaceous sediments on the sea floor were exposed and eroded, and the erosion surface subsequently mantled by 10–30 cm of laminated silica crust (Fig. 2A). Laminated silica also extends down into and coats the sides of the fractures that cut the top of the slide block. The silica crust is a regionally deposited layer at this stratigraphic position, ranges up to ~1 m thick, and shows a complex internal architecture of small domes and undulating laminations interpreted to be stromatolites (Byerly et al., 1986) and minor erosion surfaces (Fig. 2A).

Approximately 0.4 km to the south-southeast (at 25°54′21.53″S, 31°02′56.24″E), M2c consists of several meters of black and banded chert, 50–150 cm of current-deposited platy fragments of laminated silica and admixed sparse spherules, and a 50–100 cm cap of intact laminated silica. The layer of laminated silica chips (Fig. 2B) shows alternating zones of horizontal and vertical clasts similar to those found in shallow-water storm-generated edgewise breccias in younger deposits (Mount and

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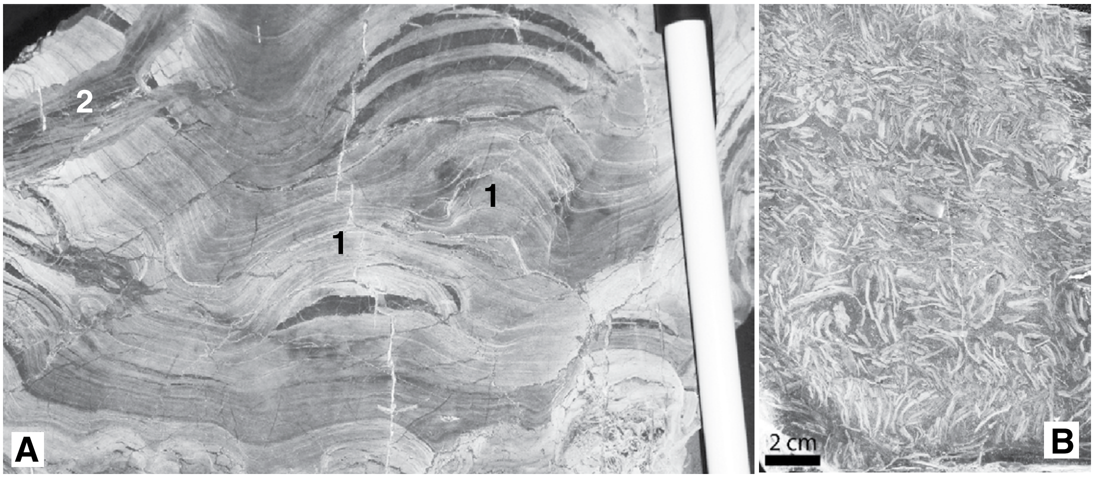

Figure 2. Laminated silica crust. A: Fine laminations and domal structures (1) have been interpreted as stromatolites (Byerly et al., 1986). Also present is a cross-cutting fracture (2), also filled with laminated silica. Pen on right for scale. B: Edgewise conglomerate composed of current-deposited platy chips of laminated silica crust.

Kidder, 1993; Sepkoski, 1982). Approximately 0.8 km west of the type locality (25°54′12.5″S, 31°02′22.8″E), the black chert layer and spherule bed have been removed by erosion. Here, laminated silica coats an eroded surface on, and fills fractures extending downward into, underlying M2v volcanic rocks. Twelve kilometers west of the S8 type locality (25°54′25″S, 30°55′33″E), spherule deposition was followed by exposure and erosion that locally stripped off all older M2c sediments, S8, and at least 5 m of underlying volcanic rocks. A small 5-m-high erosional pinnacle of M2v komatiite is capped by laminated silica crust that contains reworked spherules. Clastic sediments and eroded chunks of silica crust fill the low areas flanking the pinnacle. Following deposition of the laminated silica crust, the area again became a site of deposition of fine carbonaceous sediments and ash.

These deposits suggest the following history:

(1) Following M2v volcanism, biogenic and ashy sediments represented by the black chert accumulated under regionally quiet- and possibly deep-water conditions.

(2) Volcaniclastic sediments, now preserved only in the slide block, were deposited elsewhere under more wave- and/or current-active conditions.

(3) The S8 impact produced a global rock vapor cloud that condensed, solidified, and accumulated to form the S8 spherule layer.

(4) The fall of the S8 spherules and waning of any wave or current activity associated with the impact was followed by the settling of fine ash, carbonaceous matter, and other sediment out of the water column forming 30–50 cm of fine, organic-rich debris on top of the spherules.

(5) At the type section, sliding emplaced the block of volcaniclastic sediments capped by the S8 spherule bed into deeper water. Jostling during sliding disrupted and partially mixed the upper, unlithified carbonaceous sediments and S8. The earliest laminated silica deposited on the sliding block during sliding was brecciated and mixed with the upper carbonaceous sediment and spherules during movement.

(6) Sliding was accompanied and/or followed by a drop in sea level and widespread erosion of the volcaniclastic sediments, S8 spherule bed, and, locally, underlying black chert and top of M2v.

(7) The presently intact, capping, laminated silica was precipitated across this erosional surface during the lowstand and subsequent sea-level rise.

(8) This cycle was terminated by a return to quiet-water conditions and/or eruption of M3v komatiitic lavas.

Events 3 through 7 closely followed, and we infer were related to, the S8 impact. We suggest that the abrupt drop of sea level, widespread exposure of the sea floor, and erosion of the spherule bed and underlying layers following S8 deposition were driven by atmospheric heating and ocean evaporation due to the S8 impact. The exposure and erosion of sea floor previously characterized by long-term quiet-water sedimentation suggest evaporation of at least tens of meters of water. Ocean evaporation would have resulted in supersaturation of ocean surface water in silica and other salts and regional deposition of laminated silica crust. Formation of the crust would have been enhanced along the shoreline where boiling water was splashed onto exposed rocks and sediments, superheated by exposure to the very hot atmosphere, and evaporated, leaving behind a precipitative crust. Tidal cycles would have enhanced the wide development of these crusts. Other dissolved materials may also have been precipitated, but most, such as carbonates, were much more soluble than silica and were later redissolved and/or replaced. During sea-level fall, deposition, exposure, and erosion of the precipitative crusts produced abundant detrital fragments of laminated silica (Fig. 2B). Silica crust deposited during the lowstand and early sea-level rise was progressively submerged and not eroded and remains as the capping, post-unconformity, intact laminated silica crust. Silica crust deposition was followed in some areas by deposition of M3v komatiites and in others by renewed deposition of fine-grained carbonaceous and ashy sediments under quiet-water conditions.

Byerly and Palmer (1991, p. 387) describe tourmaline from the silica crust in M2c: "the $\delta^{11}B$ values of tourmaline-rich stromatolitic sediments (−9.8 and −10.5‰) are consistent with two-stage boron enrichment, in which earlier marine evaporitic boron was hydrothermally remobilized and vented in shallow-marine or subaerial sites, mineralizing algal stromatolites." This interpretation is consistent with the scenario presented here where the boiling "hydrothermal" fluid was seawater heated by the S8 impact.

SPHERULE BED S5

Spherule bed S5, 3.23 Ga (Lowe et al., 2014), is known from only two closely spaced localities in the northern Barberton belt (Fig. 1A), where it lies in the transition zone from the Sheba Formation of the Fig Tree Group, >200 m of turbiditic lithic sandstone, to the overlying Belvue Road Formation of the Fig Tree Group, a turbiditic unit of felsic tuff, tuffaceous sandstone, and mudstone. At the type locality (25°53′14.54″S, 30°52′31.99″E), S5 is a current-deposited and/or wave-deposited unit 40 cm thick, composed of spherules, volcaniclastic debris, and detrital grains. It is underlain by 1.7 m of silicified fine-grained mafic tuff (Fig. 3A).

The mafic tuff below S5 shows in situ fracturing and brecciation. A breccia zone 1 m below S5 shows in situ shattering of the mafic tuff with little or no displacement of the angular fragments (Fig. 3B). The tuff immediately below S5 was also fractured before S5 deposition and the fractures filled by the downward flowage of soft surface sediments, as occurred widely below spherule bed S2 (Lowe, 2013). The upper 30 cm of tuff below S5 also contains dispersed silica-replaced pseudomorphs

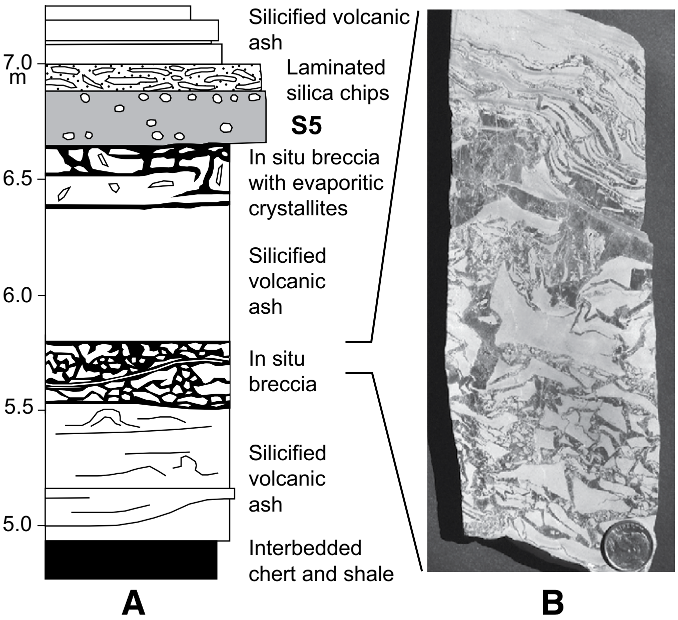

Figure 3. S5 spherule bed. A: Stratigraphic section of rocks at type locality of spherule bed S5. B: Breccia 1 m below spherule bed formed by in situ fragmentation of very fine mafic tuff.

of sand-sized idiomorphic crystallites. Their pseudohexagonal shapes suggest that they may represent nahcolite, which has been reported from evaporitic layers in other parts of the Barberton belt (Lowe and Fisher-Worrell, 1999). S5 is capped by a 15-cm-thick layer of micaceous laminated silica chips.

We interpret this assemblage of features as reflecting atmosphere superheating by the S5 impact, ocean heating, and partial ocean-water evaporation:

(1) The fine mafic ash was deposited. This unit and the underlying chert and shale separate thick turbidite sections but their actual environment(s) of deposition are poorly constrained.

(2) The distant S5 impact produced a cloud of rock vapor that condensed to form the S5 spherules. The initial fall-deposited spherule layer was probably composed entirely of spherules, but these were worked by waves and currents, probably resulting from impact-related tsunamis, and mixed with debris eroded from the sea floor.

(3) Atmospheric heating resulting from the impact initiated ocean surface boiling and evaporation.

(4) A sea-level drop associated with ocean evaporation locally exposed sea-floor sediments represented by the present outcrops to the superheated atmosphere, triggering boiling of shallow interstitial waters and in situ hydrofracturing of the near-surface sediments, including boiling of pore water and fragmentation of the uppermost partially cemented mafic tuff, and precipitation of evaporitic crystals within near-surface sediments.

(5) In shallow water, evaporation-driven precipitative silica crusts incorporated fine sea-floor ash and mud. Their erosion formed the silica-chip breccia capping S5;

(6) Atmospheric cooling resulted in condensation of ocean water, sea-level rise, and return to regional subaqueous conditions and deposition of felsic volcaniclastic turbidites.

DISCUSSION

Deposits associated with 3.23–3.29 Ga impact layers S5 and S8 in the Barberton belt, South Africa, suggest that these impacts triggered periods of atmospheric heating, ocean-surface boiling, and partial ocean evaporation. Evidence includes: (1) sea-level drops immediately following the impacts, which exposed sediments deposited in quiet, subaqueous settings to subaerial erosion and the superheated atmosphere, followed by rapid sea-level rise; (2) deposition of distinctive layers of laminated silica crust, here interpreted to a represent silica precipitation from the oceans due to surface evaporation; (3) erosion of the silica crusts deposited during falling sea level to form small flat to curved siliceous plates that were widely distributed in surrounding environments; (4) local evidence for brecciation of sediments below spherule beds due to boiling of the interstitial fluids; and (5) local precipitation of interstitial evaporite grains within sediments immediately below the impact beds.

How much ocean water was evaporated during these episodes can only be broadly estimated. For both S8 and S5, sediments deposited before the impacts and later, following condensation of the evaporated water and rise in sea level, were deposited under quiet, low-energy conditions. S5 is bracketed by hundreds of meters of deep-water turbiditic sediments. While the sea-level fall associated with S5 was not, in the few localities where S5 is well exposed, accompanied by visible erosion, immediately underlying sediments show evidence of fragmentation due to interstitial fluid boiling and evaporite deposition. For both S8 and S5, evaporation of tens of meters to perhaps 100 m of seawater seems likely. Based on the modeling results of Segura et al. (2013), this level of ocean evaporation would suggest atmospheric temperatures above the boiling point of water for over a year, and higher than 500 °C for up to a few weeks. While these would not have been sterilizing impacts in the sense of Sleep et al. (1989), they would have profoundly affected life in shallow water and possibly resulted in mass extinction of low-temperature microbes in surface waters, including many or most obligate photosynthetic organisms, which are restricted to temperatures below ~73 °C (Brock, 1994). This amount of ocean evaporation is consistent with that expected for bolides 50–100 km across (Segura et al., 2013).

The structuring and carbonaceous matter in the laminated silica crusts suggest that they are, at least in part, stromatolites (Byerly et al., 1986) and during deposition hosted microbial communities, presumably composed of thermophilic and/or hyperthermophilic microbes. The crusts closely resemble siliceous sinter deposited around modern hot springs, which is coated by microbial mats and biofilms (Jones et al., 1997; Jones and Renaut, 2003). The structuring of modern hot-spring sinter is complex and variable depending on hydrodynamic conditions, microbial biota, temperature, and evaporation rates (Braunstein and Lowe, 2001; Lowe and Braunstein, 2003). The bottoms and sides of many current-active thermal pools show small ripple- or dome-like bedforms (Fig. 4A), comparable in size and internal structuring to those in the Archean laminated silica crusts. Lamination in both is commonly continuous across the domes and intervening troughs (Figs. 2A and 4B), internal truncation surfaces are well developed, and curved sinter fragments eroded from the sinter crusts are widespread around both (Figs. 2B and 4A). In both, silica chips commonly occur in the troughs between domes. The current-active conditions under which these bedforms develop in modern thermal springs closely resemble the wave- and current-active conditions that would have characterized shallow-marine environments in a boiling Archean ocean. We suggest that the silica crust was deposited as a rim of siliceous sinter fringing the ocean at and slightly below the shoreline when ocean surface layers were essentially a global hot spring.

CONCLUSIONS

We here present a speculative scenario of events suggesting that catastrophic, impact-induced thermal spikes and resulting ocean-surface boiling and evaporation occurred on Earth at least as late as 3.23 Ga. Evolution of photosynthetic life forms would have been severely affected by events of this magnitude. More systematic studies should serve to characterize the events associated with these and the other Barberton spherule beds more fully and to evaluate their role in the early Archean evolution of life and surface environments.

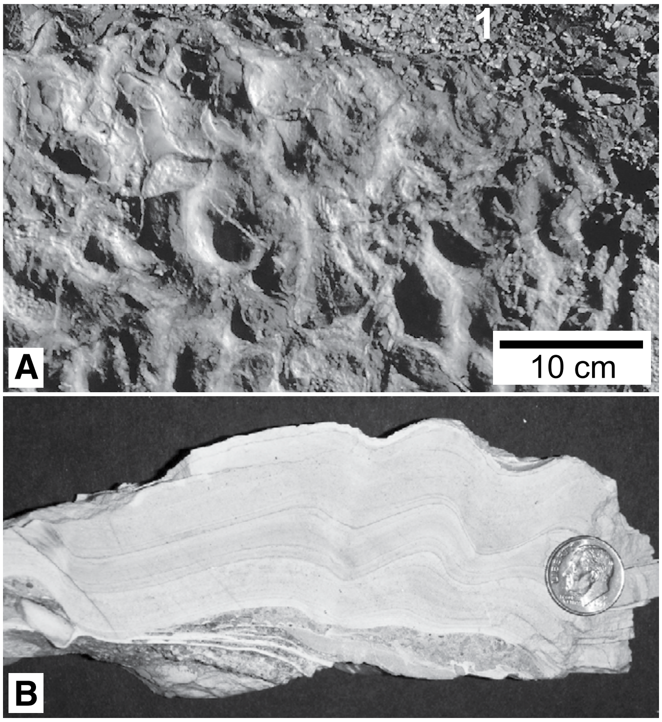

Figure 4. Siliceous sinter deposited around Inferno Crater, Waimangu geothermal area, North Island, New Zealand. A: Surface view of small waveforms, domes, and intervening depressions on steeply sloping surface of siliceous sinter deposited during episodes of activity in Inferno Crater. An area covered by small sinter chips eroded from the sinter, like those associated with Archean laminated silica crust, is shown at top of photo (1). B: Slab showing continuous internal laminations across small sinter domes shown in A.

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