Reports

Early Proterozoic Microfossils and Penecontemporaneous Quartz Cementation in the Sokoman Iron Formation, Canada

Abstract. *Early Proterozoic microfossils from the Sokoman Iron Formation, northeastern Canada, are indistinguishable from those of the Gunflint Formation in both morphology and inferred community structure. The contemporaneity of the Sokoman assemblage with the Bitter Springs–like cyanobacteria of the Belcher Supergroup indicates that differences between the two major types of early Proterozoic microbiotas are primarily ecological and not temporal (evolutionary) in nature. In arenaceous iron formations, microfossils are restricted to peloids and are absent from pore-filling silica interpreted as cement. Cemented arenaceous intraclasts indicate that some of the silica was penecontemporaneous, and the abundance of minus-cement porosity in arenaceous iron formations demonstrates that early (precompaction) cementation was common.*

In the 15 years since Barghoorn and Tyler (*1*) published their seminal monograph on Precambrian microorganisms from the Gunflint Iron Formation, Ontario, paleontologists have learned a great deal about early life on the earth. Dozens of biotas document the benthonic and planktonic microbial inhabitants of environments of the late Precambrian (< 1400 million years ago) (*2*). The record of earlier Precambrian life is far less extensive. Many questions remain, not the least of which concern the nature of the Gunflint biota itself. During the late 1960's, the Gunflint microflora seemed a logical evolutionary and temporal intermediate between the simple spheroids of the Archean Fig Tree Group and the morphologically modern microbes of the late Precambrian Bitter Springs Formation (*3*); however, Hofmann's (*4*) description of microfossils from the Belcher Islands, Northwest Territories, that are similar in age to the Gunflint but taxonomically much more closely related to the Bitter Springs biota, forced reconsideration of this interpretation. The handful of other known early Proterozoic microbiotas include both Gunflint-like and morphologically modern cyanobacterial assemblages (*5*). How, then, should one interpret the Gunflint? The discovery of abundant, well-preserved microfossils in cherts of the Sokoman Iron Formation, northeastern Quebec, removes any doubt that Gunflint- and Belcher-type biotas existed contemporaneously and that differences between them must be explained primarily in environmental rather than evolutionary terms (*6, 7*). In addition, petrographic analysis of fossiliferous Sokoman rocks constrains sedimentological theories of iron formation deposition.

The Sokoman Formation is a thick, laterally extensive iron formation found in the Aphebian (approximately 1900 million years old) Labrador Trough sequence (*7, 8*). A variety of sedimentary structures and textures can be seen in the Sokoman. Some members are predominantly cross-bedded, arenaceous iron formations (that is, chemical sands) and contain rare chert stromatolites; these were clearly deposited in shallow-water, high-energy environments (*9*). Other members consist of thinly laminated chemical muds, which must have been deposited in still-water, low-energy environments (*9*).

I. S. Zajac (Iron Ore Company of Canada) lent us two Sokoman thin sections that contain microfossils. One (ZA-270), a black chert from the Upper Lean Cherty Member (Zajac's member X) 5.5 km west of Schefferville, Quebec (66°55′18″W, 54°44′8″N), consists largely of medium to coarse sand-size chert peloids (equivalent to the granules of many previous workers) with slightly coarser-grained interstitial chert and quartz (Fig. 1a). Most of the chert peloids are dark with included organic matter, whereas the interstitial quartz is transparent. For the following reasons, we interpret the peloids as detrital sand grains and the interstitial quartz as a chemical cement:

1) The texture of the rock is comparable to that of a carbonate pelsparite (*10*); that is, the peloids are predominantly well-rounded, internally fine-grained bodies that meet at point and long contacts to form a grain-supported framework (Fig. 1a).

2) The crystal size of the quartz in the interstices consistently increases inward from the margins to the central parts of the pores, and crystals immediately adjacent to peloid margins are elongated perpendicular to the margins (Fig. 1a). These textural features are characteristic of a void-filling chemical cement (*11*).

The second sample furnished by Zajac (ZA-A1) is of stromatolitic chert and was collected about 270 km northwest of Schefferville (~68°51′W, 56°31′N). The sample almost certainly comes from the Upper Iron Formation (Zajac's members VII to X). The stromatolites consist largely of a fine mosaic of equant quartz crystals. Individual columns are about 5 mm wide, and concave-up laminae connect adjacent pillars. Small pockets of coarse to very coarse sand-size chert grains with thin, oolitic chert rims occur in the concave-up laminae. The stromatolites are similar in macrostructure and, especially, microstructure to Gunflint forms described as "unnamed stromatolites" by Awramik and Semikhatov (*12*). In the Sokoman stromatolites, as in their Gunflint counterparts, the dark material that gives definition to the laminae consists of densely concentrated, thin filaments oriented parallel to lamination, along with subordinate numbers of coccoidal unicells. Fossils are preserved as extremely fine-grained hematitic outlines, rather than as organic matter. The filaments, predominantly aseptate sheaths, average 1.5 μm in diameter (range, 0.5 to 5.0 μm; $N = 200$) and range up to several hundred micrometers in length (Fig. 1, e, f, g, and i). Their size frequency distribution is statistically indistinguishable from that of the Gunflint taxon *Gunflintia minuta* Barghoorn (*1*), leaving little doubt that the dominant Gunflint and Sokoman stromatolitic microbes are conspecific.

The Sokoman coccoid unicells (Fig. 1d) are similarly indistinguishable from those characteristic of Gunflint stromatolites. From statistical analyses, Schopf (*13*) concluded that Gunflint *Huroniospora* populations contained at least three distinct taxa falling into size classes of approximately 1 to 3, 4 to 9, and 10 to 15 μm in diameter, a division independently corroborated by Awramik (*14*). Measurements on a sample population of 350 individuals from the Sokoman stromatolites show a trimodal size frequency distribution with modes at 3, 5, and 10 μm. These modes closely correspond to the expected distributions of three negatively skewed populations having overlapping ranges which approximate the suggested ranges for the Gunflint unicells. Rare dyads are found in the Sokoman *Huroniospora* population, but otherwise there is little evidence of a reproductive mode.

In the Sokoman stromatolites, *G. minuta* constitutes 70 to 80 percent of all microfossils, while *Huroniospora* species contribute most of the remaining percentage. Specimens of *Gunflintia grandis*, *Animikiea septata* (Fig. 1c), and *Eoastrion simplex*, all originally described from the Gunflint (*1*), comprise less than 1 percent of the assemblage. In the Sokoman material, we can find no evidence that would allow us to determine whether *Gunflintia* and *Huroniospora* were cyanobacteria or *Sphaerotilus/Leptothrix*-like filamentous and spheroidal iron-loving bacteria. It is also not clear from our material whether these organisms actually built the Sokoman stromatolites or accumulated passively in abiogenic sinter-like structures such as those forming today in Yellowstone Park (*15*).

The taxa (organically preserved) found in Sokoman peloids (Fig. 1b) are the same as those from the stromatolites, but proportions are sufficiently different to preclude the digitate stromatolites as sources for the peloidal chert. *Huroniospora* unicells dominate the clasts, forming 65 to virtually 100 percent of the assemblages in various individual peloids. Large unicells (10 to 20 μm) are significantly more common in these assemblages, as are specimens of the *Metallogenium*-like bacterium *Eoastrion* Barghoorn, which may constitute up to 5 percent of the peloidal populations. *Gunflintia* filaments are often short and may well be allochthonous, at least in part. This assemblage approximates one found in distinctive Gunflint cherts discovered by Barghoorn (*1*) in which microbes are arrayed in diffuse (and apparently nonstromatolitic) bands.

In short, the Sokoman biota is indistinguishable from that of the Gunflint on several levels. Individual taxa are identical in shape, size, and distribution. Assemblages of taxa, representing partially preserved paleocommunities, are quite similar in both species composition and relative species abundance. This corroborates and extends observations from other formations suggesting that, while Gunflint-type microbiotas may not be representative of the early Proterozoic Earth in general, they were probably the characteristic microfloras in the shallow portions of iron formation basins that were widespread during this period of Earth history (*16*).

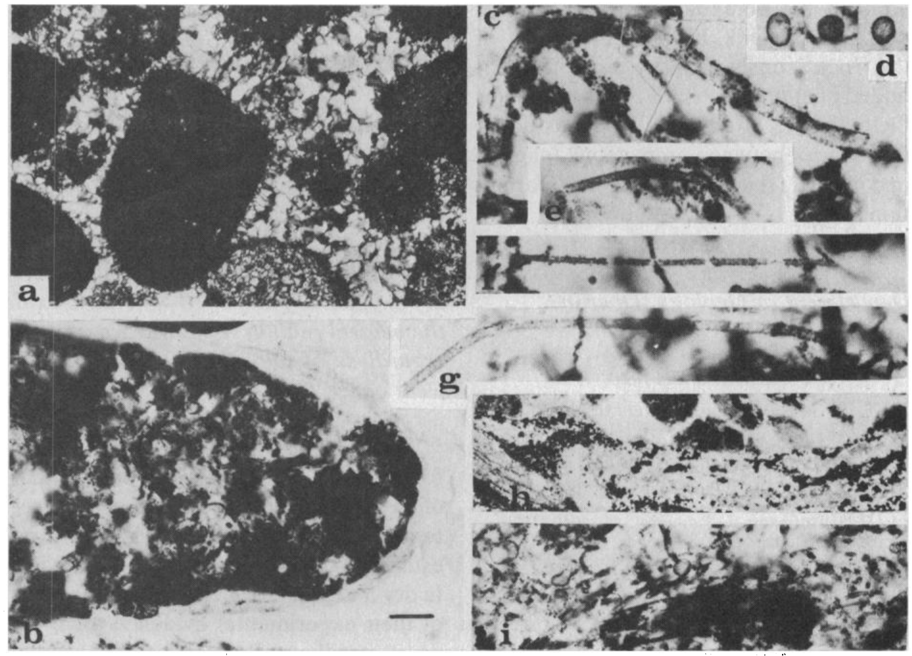

Fig. 1. Scale bar in (b) equals 165 μm for (a), 50 μm for (b), 10 μm for (c) to (g), 100 μm for (h), and 20 μm for (i). (a) Photomicrograph of microfossil-bearing peloids with finely crystalline quartz cement filling interstices; crossed Nicols, field of view approximately 1.7 by 0.7 mm. (b) More highly magnified view of single microfossil-rich peloid with faint, discontinuous oolitic chert rim; plane polarized light; field of view approximately 0.5 by 0.4 mm. (c) *Animikiea septata* (×500). (d) Three *Huroniospora* unicells (×500). (e to g) *Gunflintia minuta* (×500). (h) Photomicrograph of jasper peloids and quartz cement inside intraclast (above) smoothly truncated against matrix (below) on margin of pebble; plane polarized light, field of view approximately 1.0 by 0.3 mm. (i) Photomicrograph of microfossils in jasper stromatolite (×250).

Chertz peloids in iron formations have generally been interpreted as sand grains (*9, 10, 17*), whereas the interstitial chert and quartz have been interpreted as either detrital matrix (*17, 18*) or chemical cement (*10*). The restriction of the microfossils to peloids in sample ZA-270 strengthens the interpretation of the peloids as detrital grains and of the interstitial silica as cement. The observed truncation of filaments at peloid margins demonstrates that the peloids are intraclasts, that is, that they formed by erosion of previously deposited chemical muds followed by abrasional rounding and winnowing of the eroded particles.

Intraclastic pebbles with internal peloidal textures from the Sokoman in the Astray Lake area (21 km southeast of Schefferville) indicate that some of the silica cementation was penecontemporaneous. The peloids in the intraclasts consist of jasper, chert, and/or iron silicates, and the interstices are filled with quartz cements like those of sample ZA-270. These arenaceous intraclasts have smoothly rounded boundaries that cut indiscriminately across peloids and cement (Fig. 1h), demonstrating conclusively that the cements were present at the time the intraclasts originally formed. Such intraclasts are not abundant, but abundant minus-cement porosity characterizes many arenaceous beds of the Sokoman (as well the Gunflint, Biwabik, and Ironwood Iron Formations), indicating that early cementation was widespread. Modal percentages of quartz cement in iron formation sands range as high as 40, which is about the same as the initial porosity of well-rounded modern sands of comparable coarseness (*19*). Hence, much of the cementation must have preceded any compaction of the sands.

The penecontemporaneous cements in the arenaceous iron formations of the Sokoman have several important implications: (i) Inasmuch as quartz cements precipitated close enough to the sediment-water interface to be eroded, the basin waters of the Labrador Trough must have been rich in silica during Sokoman time. This supports the hypothesis that the silica in this iron formation is original rather than a later diagenetic replacement. (ii) Some iron formation silica was clearly a direct precipitate; thus we see no need to invoke biogenic processes to explain the siliceous composition of iron formations. (iii) Bulk chemical compositions of arenaceous iron formations with abundant minus-cement porosity *cannot be equat-*

ed with the compositions of their precursor sediments, because up to half of the rock consists of siliceous cement added postdepositionally. This is a major factor in the often noted compositional differences between arenaceous (cherty) and lutitic (slaty) rocks in iron formations.

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References and Notes

1. E. S. Barghoorn and S. Tyler, *Science* **147**, 563 (1965).
2. J. W. Schopf, *Annu. Rev. Earth Planet. Sci.* **3**, 213 (1975); G. Vidal, *Fossils Strata 9* (1976).
3. J. W. Schopf, *Biol. Rev. Cambridge Philos. Soc.* **45**, 319 (1970).
4. H. J. Hofmann, *J. Paleontol.* **50**, 1040 (1976).
5. M. R. Walter, A. D. T. Goode, W. D. M. Hall, *Nature (London)* **261**, 221 (1976); A. H. Knoll and E. S. Barghoorn, *Origins Life* **7**, 417 (1976); P. Cloud and K. Morrison, *Geol. Soc. Am. Abstr. Programs* **11**, 227 (1979); L. A. Nagy, *J. Paleontol.* **52**, 141 (1978).
6. The exact temporal relationship between the Gunflint and Belcher biotas is not known; however, the Sokoman biota lies within the same geosynclinal sequence as the Belcher and, if anything, may be slightly younger than the Belcher microflora (7). New dates for the Frere Formation, Western Australia, also suggest that its Gunflint-like microbiota may be up to several hundred million years younger than the Belcher biota (K. Grey, paper presented at the 26th International Geological Congress, Paris, 13 July 1980). Hofmann (4) first suggested that environment might be critical to the understanding of early Proterozoic microfossils.
7. B. J. Fryer, *Can. J. Earth Sci.* **9**, 652 (1972).
8. E. Dimroth, *Geol. Soc. Am. Bull.* **81**, 2717 (1970); G. A. Gross, *Geol Surv. Can. Econ. Geol. Rep. 22* (1968).
9. I. S. Zajac, *Geol. Surv. Can. Bull. 220* (1974).
10. E. Dimroth, *Que. (Prov.) Minist. Richesses Nat. Rapp. Geol.* **193**, 225 (1978); R. J. Floran and J. J. Papike, *Geol. Soc. Am. Bull.* **86**, 1171 (1975).
11. F. J. Pettijohn, P. E. Potter, R. Siever, *Sand and Sandstone* (Springer-Verlag, New York, 1972), p. 400.
12. S. M. Awramik and M. A. Semikhatov, *Can. J. Earth Sci.* **16**, 484 (1979).
13. J. W. Schopf, *Origins Life* **7**, 19 (1976).
14. S. M. Awramik, in *Stromatolites*, M. R. Walter, Ed. (Elsevier, New York, 1976), pp. 311-320.
15. M. R. Walter, *Econ. Geol.* **67**, 965 (1972); in *Stromatolites*, M. R. Walter, Ed. (Elsevier, New York, 1976), pp. 87-112.
16. This does not imply that these microbes were responsible for iron formation deposition. We simply state that they were abundant in such iron-rich basins.
17. J. T. Mengel, in *Ores in Sediments*, G. C. Amstutz and A. J. Bernard, Eds. (Springer-Verlag, New York, 1973), pp. 179-193.
18. J. Eichler, in *Handbook of Strata-bound and Stratiform Ore Deposits*, K. H. Wolf, Ed. (Elsevier, New York, 1976), p. 179.
19. Well-sorted medium sands of epiclastic quartz average 40 to 45 percent initial porosity [D. C. Beard and P. K. Weyl, *Bull. Am. Assoc. Pet. Geol.* **57**, 351 (1973)]; well-sorted, medium sand-size calcareous ooids from the Bahamas average 43 percent initial porosity [R. B. Halley and P. M. Harris, *J. Sediment Petrol.* **49**, 980 (1973)]. Iron formation sands of comparable grain size described by G. A. Gross [*Sediment Geol.* **7**, 244 (1972)] show 40 percent intergranular material, interpreted here as cement.
20. We thank I. S. Zajac for the loan of fossiliferous material and H. J. Hofmann for helpful criticism. Fieldwork by B.S. was supported by grants in aid of research from Sigma Xi, the Geological Society of America, and Johns Hopkins University, as well as NSF grant EAR 77-08137 (L. A. Hardie, principal investigator). Financial support was also provided by NSF grant DEB 80-04290 (A.H.K.) Illustrated specimens will be deposited in the Canadian National Type Collection at the Geological Survey of Canada, Ottawa.

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Effects of Trace Gases and Water Vapor on the Diffusion Coefficient of Polonium-218

Abstract. *The two-filter method described by Thomas and LeClare was used to investigate the effects of trace concentrations of nitric oxide and nitrogen dioxide in dry nitrogen on the diffusion coefficient of radium A (polonium-218). Charged radium A was neutralized in 10 parts per million (ppm) nitrogen dioxide in dry nitrogen, in 8.3 ppm nitric oxide in dry 92 percent nitrogen and 8 percent oxygen, and in nitrogen with 20 and 80 percent relative humidity. No neutralization was seen in dry nitrogen, dry oxygen, dry air, or 10 ppm nitric oxide in dry nitrogen. The diffusion coefficient of the neutral radium A species was found to be 0.079 square centimeters per second, regardless of the relative humidity of the nitrogen gas atmosphere. Lower values were observed for charged species.*

There are conflicting reports of values for the molecular diffusion coefficient (D) of several of the radon daughter isotopes. Chamberlain and Dyson (*1*) first estimated the D value of radium A (^{218}Po) in dry air to be 0.054 cm^2/sec on the basis of their experimental evidence for ^{220}Rn decay products. Porstendorfer (*2*) found a 33 percent reduction in the D value of charged ^{212}Pb (thorium B), a decay product in the series of radionuclides formed from ^{220}Rn, relative to that of the neutral species. Porstendorfer and Mercer (*3*) later determined that the charged thoron daughters appear 88 percent of the time, and the neutral species appear the remaining 12 percent of the time. Raabe (*4*) reported a reduction in the value of D for radium A as a function of increasing humidity. At 16 percent relative humidity (RH), D was 0.047 cm^2/sec; at 35 percent RH, D was reduced to 0.034 cm^2/sec.

Porstendorfer and Mercer (*3*) have clearly distinguished the properties of neutral and charged ^{212}Pb. For the neutral species, D was found to be 0.068 cm^2/sec independent of RH. The D value of the charged species could not be determined unequivocally but was estimated as 0.024 cm^2/sec, and was found to be affected by increasing humidity. In air with RH between 30 and 90 percent D for the positively charged species was found to be 0.068 cm^2/sec, the same as for the neutral species. Thomas and LeClare (*5*) also observed a change in the D value of radium A at RH up to 20 percent but a constant value with increasing RH above 20 percent. Kotrappa *et al.* (*6*) observed no change in the D value of thoron decay products between 5 and 90 percent RH but did see a decrease in D with increasing residence time in their diffusion carboy. More recently, Kotrappa and Raghunath (*7*) compared the D values of radon and thoron daughters in air to the values in pure argon. Although small decreases in D were seen with increasing RH in the argon atmosphere, substantial decreases were observed in air.

Table 1. Diffusion coefficients (D) of radium A in different experimental gases.

Experimental gas in N_2	D (cm^2/sec)
N_2 (dry)	0.044 ± 0.003
97 percent O_2 (dry)	0.031 ± 0.003
10 ppm NO (dry)	0.031 ± 0.003
10 ppm NO_2 (dry)	0.072 ± 0.004
8.3 ppm NO (dry) with 8 percent O_2	0.079 ± 0.004
Dry pump air	0.027 ± 0.003
20 percent RH N_2	0.052 ± 0.003
80 percent RH N_2	0.079 ± 0.004

Busigin *et al.* (*8*) have examined D in a manner similar to that used by Raabe. They observed complex transmission curves for the passage of ^{218}Po through a diffusion tube. They suggested that complex reactions are occurring that lead to the presence of several different diffusing species.

The variation and conflicting nature of these earlier results indicate that complex mechanisms govern the behavior of D. More than one mechanism may be in operation. Possibly Kotrappa and Raghunath saw the formation of heavier, more slowly diffusing molecules in air. Porstendorfer and Mercer, as well as Thomas and LeClare, observed the neutralization of charged species of these radioelements. Busigin *et al.* suggested the importance of trace gases with low ionization potentials in the neutralization process. We have reexamined the D value of ^{218}Po in an effort to resolve these questions.

The two-filter method described by Thomas and LeClare (*5*) was used to measure the D values of radium A in N_2 with 0, 20 and 80 percent RH; in 97 percent dry O_2; in 10 parts per million (ppm) NO_2 and 8 percent O_2; and in dry pump air. Three stainless steel tubes (50, 75, and 100 cm in length and 3.17 cm in diameter) were used with a glass-fiber filter placed at the inlet to remove radon daughters from the gas stream. The radon daughters formed in the tube as a result of decay and not diffusing to the tube

