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# Microorganisms from the Gunflint Chert

## These structurally preserved Precambrian fossils from Ontario are the most ancient organisms known.

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Although an element of skepticism has traditionally prevailed, on the part of both geologists and biologists, with regard to the existence and nature of Precambrian life, evidence is now rapidly accumulating which supports the view that widespread and abundant biological activity occurred as far back in the geologic record as half the presently accepted age of the earth. Geochemical evidence and evidence from the mineralogical and petrographic characteristics of Precambrian rocks is equivocal regarding the time of origin of life and the physical setting of biogenesis. However, structurally preserved fossils showing well-defined morphology are now known from sediments of an age approaching 2000 million years (*1*, *2*). It is the purpose of this article to discuss the geologic occurrence of these oldest known Precambrian fossils, their morphology, and certain chemical analyses of the extractable organic residues. Detailed study of hundreds of thin sections has demonstrated a complex of biologically variable morphological entities. From the range of structures examined, eight distinct generic categories have been selected for detailed description. Twelve new species are described; these range from single-celled isolated spheroidal bodies to filamentous branched and unbranched forms. Among these forms are rather complex, highly distinctive organisms of unusual morphology and uncertain phylogenetic affinity. Within well-preserved units of the chert the organisms occur in profusion.

No attempt is made here to review the voluminous literature on Precambrian fossils. This has been recently and excellently done by Glaessner (*3*) and Rutten (*4*).

## General Geology

The term *algal cherts* has long been applied to certain facies of the Gunflint iron formation of the northern Lake Superior region of Canada and adjacent Minnesota. The Gunflint iron formation is one of two structurally conformable units, of which the Rove shale is the overlying member. Together the Gunflint and the Rove comprise the recognizable Animikie series in the Thunder Bay District of Ontario. The term *Animikie* rather than *Huronian* is used here because of the lack of direct stratigraphic correlation with the classical tripartite Huronian sequence in the Lake Huron–Georgean Bay area to the east. The absolute age of the Gunflint formation is approximately 2000 million ($2.0 \times 10^9$) years (*5*), and this age places the formation in the lower third of the Middle Precambrian.

The Gunflint sediments extend eastward some 175 kilometers from the vicinity of Gunflint Lake, on the U.S.–Canada boundary, to Loon Lake, Ontario (Fig. 1). Isolated remnants of the formation occur on the mainland and upon islands in Lake Superior in the Rossport–Schreiber area some 98 kilometers east of Loon Lake. In the Gunflint sequence of Minnesota four major members may be distinguished: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty (*6*). In many exposures of the formation, however, one or more of the upper members has been removed by erosion. However, Gill (*7*) extended Broderick's work on the subdivisions of the Gunflint formation by recognizing and tracing the four members from Gunflint Lake to Mink Mountain, a distance of about 80 kilometers. Goodwin (*8*) presented additional information regarding the lithofacies of the Gunflint and emphasized the cyclical nature of sedimentation during Gunflint time. Moorhouse (*9*) and Goodwin (*10*) present an excellent summary of the Gunflint and related general geology of the Animikie series in the Port Arthur and Whitefish Lake regions.

The structurally preserved organisms originally described by Tyler and Barghoorn (*1*) were discovered in dense black cherts collected from the lower algal chert member at several other localities in exposures of the formation in the Thunder Bay area and west to Nolalu, Ontario. The organisms preserved in the black cherts are known to occur at the same stratigraphic horizon over a distance of approximately 190 kilometers along the strike of the formation. Preservation is best in the Schreiber locality, and discussion of the detailed geologic occurrence of the chert is limited here to this area, although the organisms have been secured from several other localities as well.

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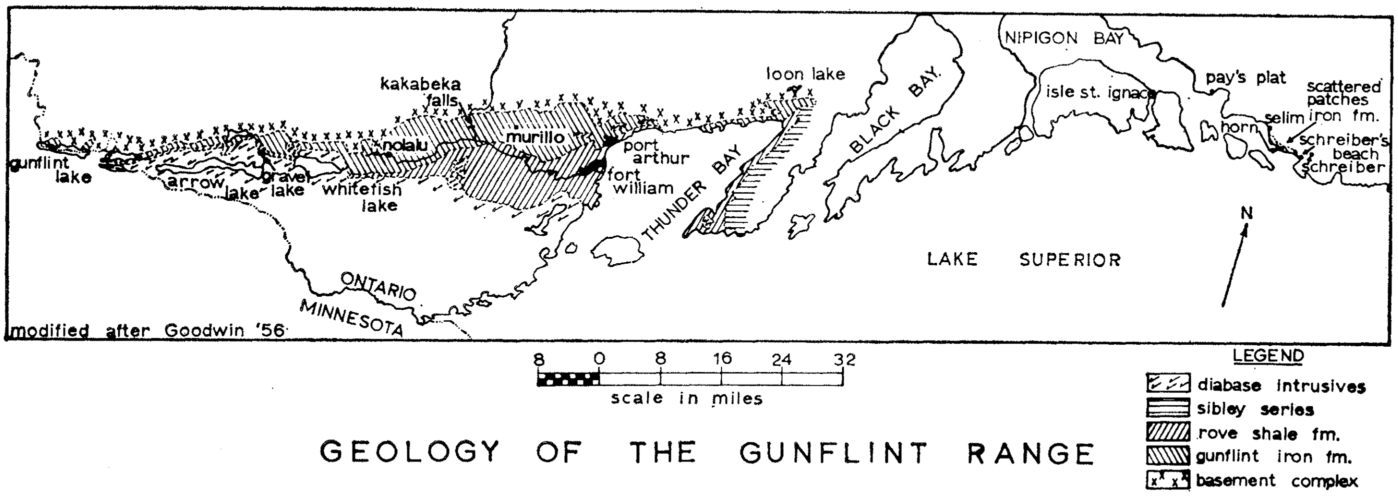


Fig. 1. Map showing general areal geology of the Gunflint range north of Lake Superior. Note above *N* on directional arrow the isolated eastern outlier of the Gunflint formation. Most of the structurally preserved organisms shown in Figs. 2 to 8 are from this easternmost outcrop.

*Schreiber locality*. Small erosion remnants of Animikie sediments occur on the shore of the mainland between Schreiber Beach and Winston Point, and also on a small island south of Horn, locally known as Flint Island; on Powder Island in Pays Plat Bay; and on small islands near Rossport. These occurrences have been described by Tanton (*11*), Hopkins (*12*), and Harcourt (*13*).

The Animikie sequence in this area consists of a basal clastic member ranging in thickness from 0.3 to 1.8 meters, overlain by 1.2 to 3 meters of iron formation, which in turn is overlain by 4.5 to 10.5 meters of thin-bedded fissile black shale. In places where the Gunflint rests upon red porphyritic granite the basal member consists of a dark colored, poorly sorted clastic consisting of rounded-to-angular quartz grains set in a dark gray shaly matrix. South of Horn, Ontario, where the Animikie sediments rest upon ellipsoidal greenstones, the basal clastics consist of a half meter or so of poorly sorted and poorly lithified massive shaly material consisting of angular-to-subangular greenstone fragments which are partially altered to 1M muscovite associated with well-rounded-to-angular grains of quartz, jasper, chert, and greenstone with occasional grains of fresh pink feldspar. The clastics are cemented by a minor amount of carbonate and chert.

The basal 15 to 45 centimeters of the iron formation contains an abundance of structurally preserved organisms. There are numerous algal domes, ranging from a few centimeters up to 1½ meters in diameter and from 15 to 45 centimeters in height. The domes are often developed upon greenstone boulders of the underlying basal conglomerate. The gross internal structure of the domes consists of somewhat irregular layers of white, coarsely crystalline, structureless quartz alternating with layers of fine-grained black chert or flint. The individual layers are usually 2 to 10 centimeters thick.

The black chert is characterized by discontinuous anastomosing pillars oriented roughly perpendicular to the gross structure of the algal dome. The individual pillars range in diameter from a fraction of a millimeter up to a centimeter; in length, up to 4 centimeters or more; and in height, up to 10 centimeters or more. The pillars often bifurcate upward. The internal structure of the pillars consists of a series of laminae produced by variations in grain size of the chert or by concentrations of pyrite and organic matter. The laminae are oriented convexly upward, the individual layers steepening and tending to become tangential to the borders of the pillars (Fig. 2, parts 3 and 4). The general appearance is that of a nest of thimbles, strikingly similar in morphology to structures associated with certain modern algal growths (Fig. 2, parts 1 and 2). The interpillar zone ranges in width from 1 to 10 millimeters and is usually filled with white, light gray, greenish, or black granular and oolitic chert embedded in a fine-grained cherty matrix. The granules and oolites appear to be clastic particles which became entrapped between the pillars during the growth of the algal colonies. Occasionally the area between the pillars is occupied by an iron-bearing carbonate or by white, coarsely crystalline quartz with drusy cavities or more rarely by anthraxolite.

The upper ½ to 1½ meters of the iron formation is composed of lenses of white-to-gray chert 1 or 2 to 5 or 10 centimeters thick, alternating with iron-bearing carbonate layers. Structurally preserved organisms are rare in these lenses, although the algal pillar structure is often conspicuous.

The algal cherts are overlain conformably by a fissile black pyritic shale interbedded with limey argillites. The total thickness of the black shale unit and the character of the overlying rocks are unknown, since the shales dip southeastward and disappear beneath the waters of Lake Superior. The general stratigraphic position of the black-shale unit of the Gunflint is uncertain, and the black shale may represent the equivalent of what is known in the western portion of the Gunflint iron range as the Rove shale, which is usually recognized as a separate formation overlying the Gunflint formation.

## Petrography of the Chert

The rocks of the lower algal horizon of the Gunflint formation are composed dominantly of dense black chert associated with subordinate amounts of gray, green, red, and white cherts. The red and green colors are due to the presence of fine-grained hematite and siderite, respectively. The black cherts owe their color to an abundance of fine-grained pyrite and, more particularly, to the presence of yellow, brown, and black organic matter. These constituents, particularly the organic matter, have exerted a strong influence upon the texture of the rock, for there is a close correlation between the grain size of the chalcedony and quartz and the abundance of finely disseminated organic matter. The organic matter has had a pronounced effect in inhibiting grain growth.

The chert consists of chalcedony grains which average ±100 to 400 microns in diameter but attain a maximum size of 500 $\mu$ or more in local areas. The chalcedony grains form a mosaic pattern, the grain boundaries ranging from roughly linear to highly sutured. When they are observed with polarized light, a dark, rather narrowly defined line marking the extinction position sweeps across the grains, indicating a sheaf-like structure. Chalcedony grains 200 $\mu$ or more in diameter exhibit a pronounced radial structure. Quartz exhibiting undulating extinction occurs in subordinate amounts in localized areas. The quartz grains range from 200 to 400 $\mu$ or more in diameter. The chalcedony and quartz which occurs as a matrix to chert granules and oolites in the areas between the algal pillars is often coarse-grained. The abundance of chalcedony and the pronounced local variation in grain size of both chalcedony and quartz indicate that the Gunflint cherts of the lower algal horizon have suffered little if any thermal or regional metamorphism. This conclusion is substantiated by the abundance of I M muscovite at several horizons in the Gunflint formation.

Carbonate is usually present in the black cherts of the lower algal horizon as a minor constituent occurring as scattered rhombs in the chert matrix, as fracture fillings or as irregular borders along narrow fractures. The rhombs range in diameter up to 300 $\mu$ and generally have well-developed outlines. The carbonate is evidently younger than the chert, for the borders of chert granules and the successive zones of chert oolites are often partially enclosed within carbonate rhombs.

Apatite occurs in the lower algal cherts as doubly terminated crystals which range from less than 1 $\mu$ up to about 15 $\mu$ in diameter. The apatite is present in the chert groundmass as isolated crystals, irregular clusters of crystals, partial borders to chert granules, and ovoid bodies or granules with a subordinate chert matrix.

The interface between the red algal jasper and the black chert reveals an interesting transition zone. Bedding in the algal pillars is marked by discontinuous wispy lenses, 100 to 1000 $\mu$ thick, of black chert containing pyrite and organic matter alternating with gray chert. As the jasper interface is approached the gray chert becomes light red and alternates with lenses of black chert. The black chert lenses gradually give way to red jasper. Bedding in the red jasper is evidenced by slight differences in the hematite content of adjacent laminae. The grain size of the hematite shows a marked increase from the light red transition zone, where the individual hematite particles are 1 $\mu$ or less in diameter, into the red jasper, where aggregates

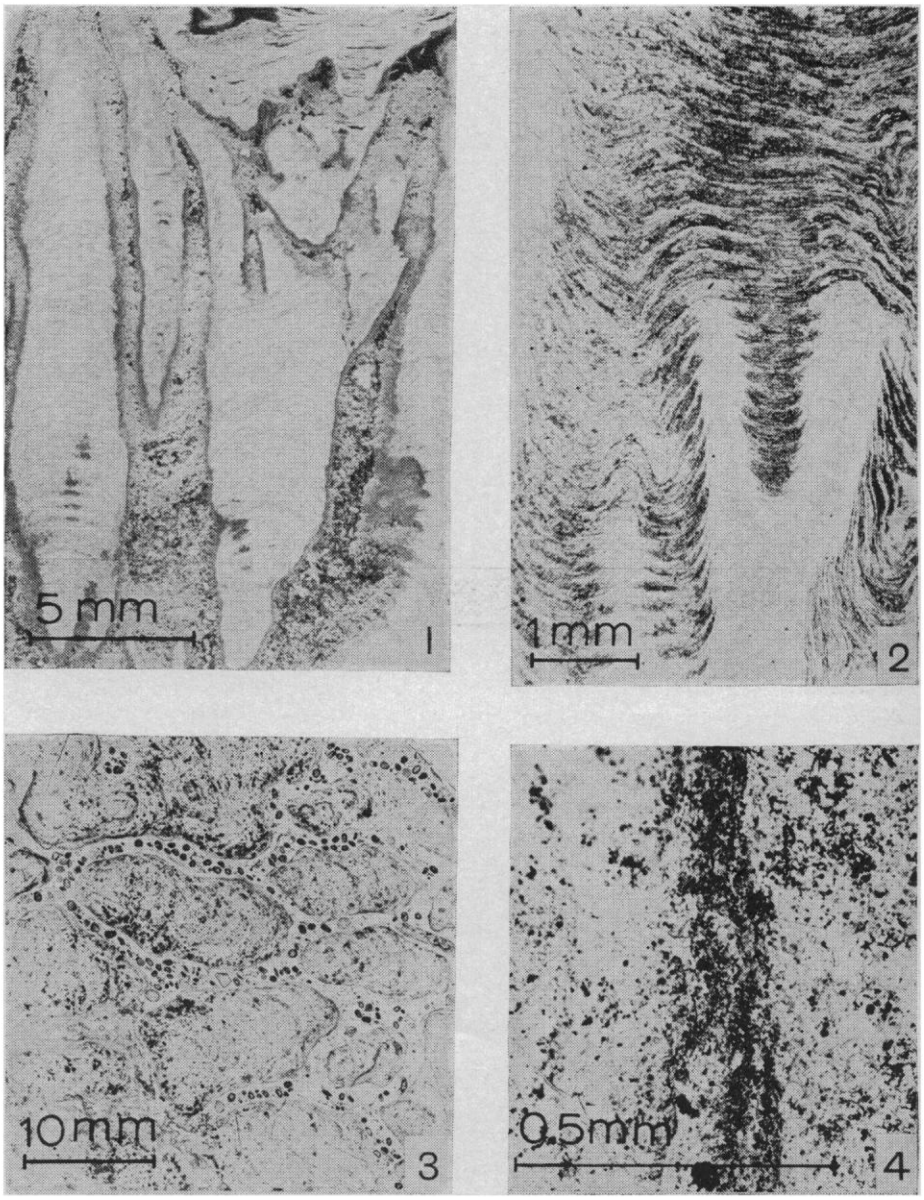


Fig. 2. Thin sections of rock, photographed in transmitted light. Part 1, Surface of specimen of siliceous sinter (about × 4) from currently forming geyserite deposits, Yellowstone National Park, Wyoming. Note the pillar and thimble structure and the concentric banding of algal remains. In the figure, direction of growth is upward. Part 2, Different specimen (about × 13) of the material shown in part 1. The zones of concentration of the algal remains are more conspicuous and more heavily matted than in part 1. In the figure, direction of growth of algal colony is downward. Part 3, Thin section of Gunflint chert (about × 1.6) showing pillar and thimble structure comparable to that shown in parts 1 and 2. The section is cut nearly parallel to the long axis of the pillars. Algal filaments form concentric mats which comprise the bedding of the stromatolitic chert mass. Spherical structures in the tubes are clastic oolites which often contain organic matter (slide Sch-E; Paleobotanical Collection, Harvard, No. 58250). Part 4, Thin section of Gunflint chert (about × 82) showing a single algal mat zone extending vertically across center of figure. The dark organic-rich lamellae consist of fragments of filaments and sporelike bodies (slide Sch-W-57-CF-10; Paleobotanical Collection, Harvard, No. 58251).

of hematite range in diameter up to about 50 μ.

The transition from the black to the red algal cherts probably reflects a change from reducing to oxidizing conditions at the time of deposition. This change appears to have been gradual, as indicated by the alternating light red and black laminae in the pillars. The occurrence, in the interpillar zones, of oolites with jasper centers and black outer zones indicates (i) that the hematite is primary in origin and (ii) that reducing conditions persisted in the interpillar depressions at a time when the upper portion of the individual algal pillars extended into a more strongly oxidizing environment. Jasper oolites that were formed in the oxidizing environment occasionally were trapped in the narrow depressions between the algal pillars and continued to grow in a reducing environment.

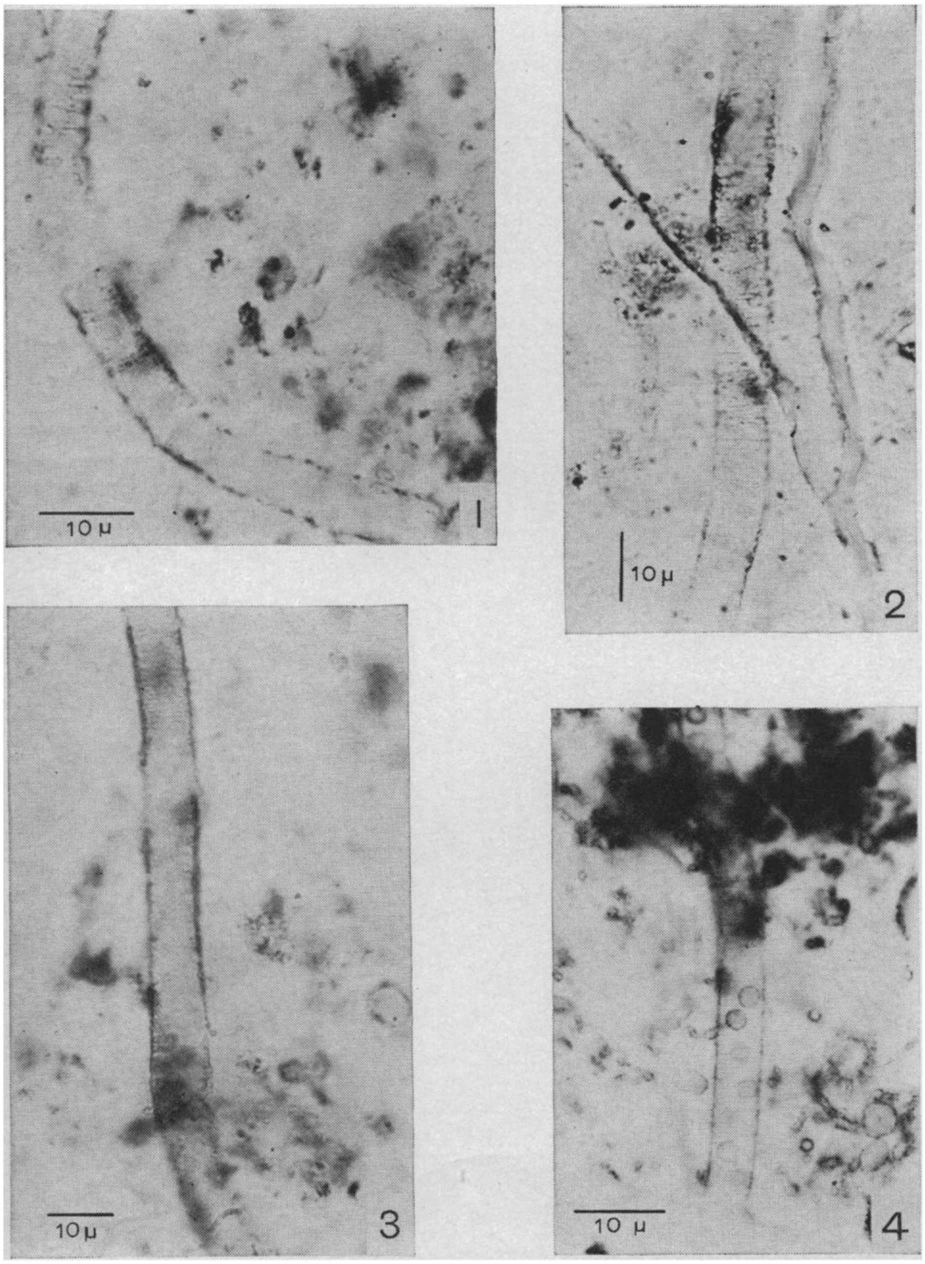


Fig. 3. Organisms from the Gunflint formation in thin sections of rock, photographed in transmitted light. Part 1, *Animikiea septata* Barghoorn, filament (about × 1235), probably algal in affinity, showing closely spaced fine transverse septae or cross walls. In general appearance, size, and form the fossil resembles species of the extant genera *Oscillatoria* and *Lyngbya*. Diameter of filament, 7.0 μ (slide Sch-E-30; Paleobotanical Collection, Harvard, No. 58252). Part 2, *A. septata* Barghoorn, type specimen (see appendix). Probable algal filament (about × 945), showing structure similar to that in part 1. Note the well-delineated transverse septae. The filament is 9.0 μ in diameter. The irregularly undulating structures parallel to and passing through the filament are fractures in the chert matrix. Part 3, *A. septata* Barghoorn, filament (about × 830) of the *Oscillatoria* type but showing thicker filament walls. The thicker walls may represent the contracted organic residue of a gelatinous sheath. Diameter of filament, 9.5 μ (slide Sch-H; Paleobotanical Collection, Harvard, No. 58254). Part 4, *Entosphaeroides amplus* Barghoorn, type specimen (about × 1235). Filamentous organism showing presence of sporelike bodies interpreted as endogonidia or endospores within the filament lumen. Internal sporulation morphologically comparable to this is known from several of the blue-green algae (*Chamaesiphon*) and the iron bacteria (*Crenothrix*). Diameter of filament, 5 to 6 μ.

## Age of the Gunflint Formation

The Gunflint iron formation has been correlated by Leith, Lund, and Leith (*14*) and others with the Biwabik iron formations of Minnesota and the Ironwood, Negaunee, and Vulcan iron formations of Michigan. This correlation is based upon similarity in lithology and general position in the Precambrian stratigraphic sequence. Whether or not these formations are equivalent with respect to time of deposition remains to be determined.

Recent studies by Hurley and his co-workers (*5*) on the Ar$^{40}$/K$^{40}$ and Rb$^{87}$/Sr$^{87}$ ratios in several suites of unmetamorphosed minerals from diverse localities in the Gunflint sequence have yielded remarkably consistent absolute ages. Granules of a potassium-rich mica extracted from a tuff-argillite band in the Upper Gunflint formation exposed in the Port Arthur district showed a potassium constant of 4.69 percent with an Ar$^{40}$/K$^{40}$ ratio of 0.146, indicating an age of 1600 ± 50 million years.

Regarding the true age of the Gunflint, Hurley and his co-workers state (*5*): "It is therefore expected that, owing to the ideal conditions for preservation of the clay minerals in this area, the measured age values should represent at least 80% of the true age of the Gunflint sedimentation." If this correction be applied, the true age of the Gunflint sediments, as estimated from the authigenic minerals, should be 1900 ± 200 million years.

It is of interest to note, in connection with the age of the Gunflint sediments, that the unconformably underlying granite in the Kakabeka Falls locality yields an Ar$^{40}$/K$^{40}$ ratio of 0.332 in the biotite concentrate, with age 2570 ± 75 million years. The Rb$^{87}$/Sr$^{87}$ ratios for this same granite indicate an age of 2365 ± 70 million years (*5*).

## Preservation of Organisms

The organic remains present in the Gunflint cherts have been preserved in several different ways: by association with (i) organic residues and films, (ii) fine-grained pyrite, (iii) solid pyrite, (iv) carbonate, and (v) hematite.

*Organic residues and films.* In preservation of this type, a tenuous film, varying in thickness and of a light-to-dark-brownish material, outlines the organic structures. When the chert is dissolved in hydrofluoric acid the brown material floats on the surface of the liquid and aggregates into black opaque masses. This material is readily volatilized upon ignition. Local recrystallization of the chert to a coarser grain size leads to the elimination of the brownish material and the accumulation of a black opaque substance along the grain boundaries of the quartz. This opaque material resembles anthraxolite. The organic forms are also preserved in the chert by a diffuse, light yellow substance. This type of preservation resembles a stain. The yellow substance is clearly an organic compound or group of compounds, since it grades into the brownish films and accumulates as anthraxolite on grain boundaries in areas where chalcedony has recrystallized to quartz. The yellow material is also observed to preserve, or represent morphologically, the substance of organic remains such as filaments and sporelike bodies within disseminated carbonate rhombs within the chert.

Where the morphology of the contained organisms is best preserved (Fig. 3, parts 1–4; Fig. 4, parts 1, 4, and 8; Fig. 5, parts 1 and 8; Fig. 6, part 1; Fig. 7, parts 6, 8, 11, and 12; Fig. 8, parts 3, 10, and 11), thin sections (50 $\mu$ thick or less) of the chert, when viewed in transmitted light, appear light amber to dark brown. It is evident that the remains of the organisms where structure is best retained are represented by the altered remnants of the original organic matter and that the structures are not pseudomorphs produced by condensation or polymerization of material which entered the chert prior to crystallization of the chalcedonic matrix. This is further attested to by the remarkable three-dimensional preservation of both filaments and spherical structures (Fig. 3, parts 2 and 4; Fig. 4, parts 1 and 4; Fig. 5, parts 1, 3, and 4).

*Pyrite.* The color of the black cherts

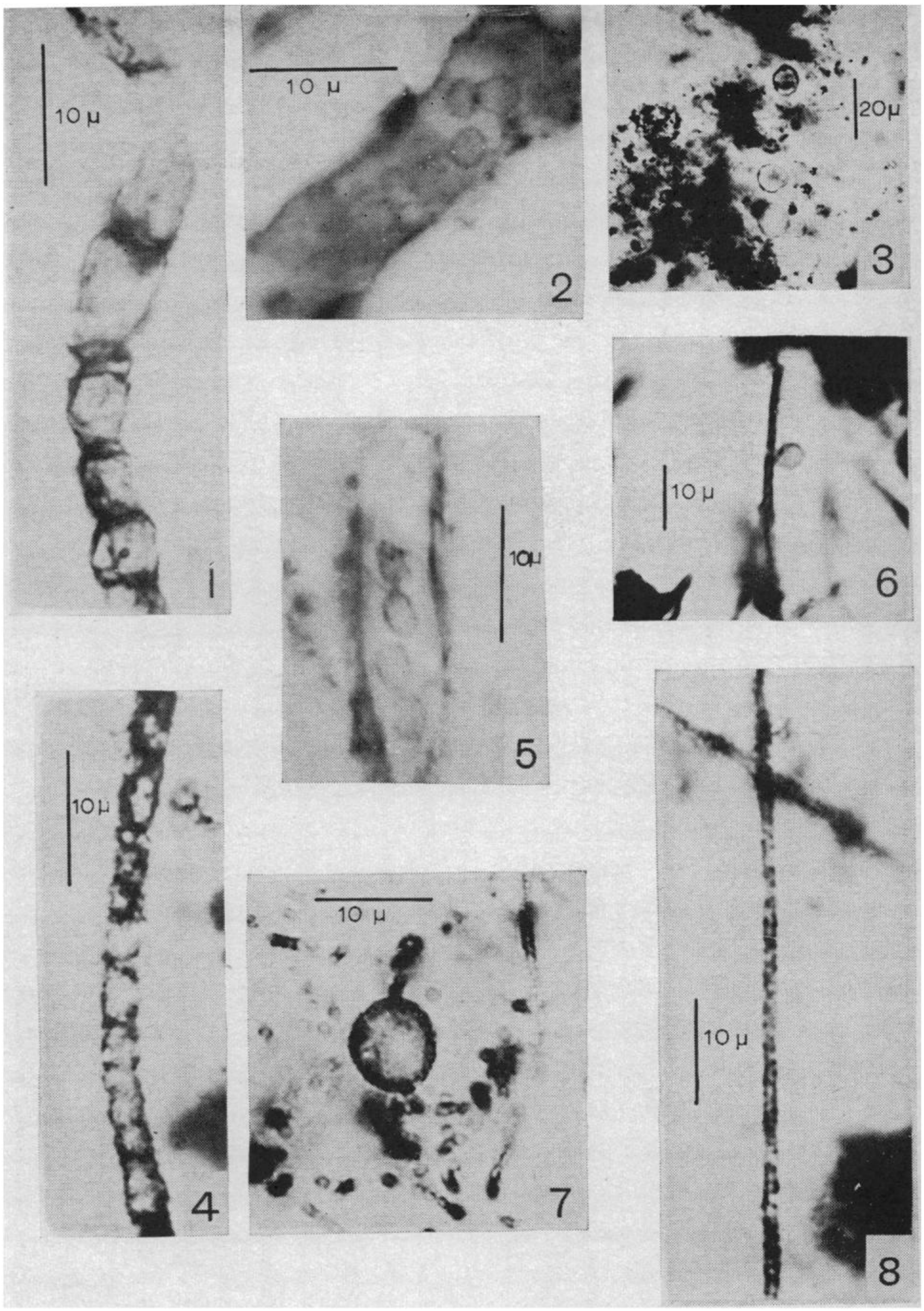


Fig. 4. Organisms from the Gunflint formation in thin rock sections, photographed in transmitted light. Part 1, *Gunflintia grandis* Barghoorn, type specimen (about × 2135). Filament shows thick cross walls separating cells of irregular dimensions. This degree of cellular irregularity is unusual among the blue-green algae and is more suggestive of the green algae of the family Ulotrichaceae. Part 2, *Entosphaeroides amplus* Barghoorn (about × 2135). Portion of a nonseptate filament showing endogonidia somewhat comparable to those shown in Fig. 3, part 4. In general morphological organization the structure compares closely with the endogonidial formation in the iron bacterium *Crenothrix* (slide Sch-W-CF-11; Paleobotanical Collection, Harvard, No. 58257). Part 3, *E. amplus* Barghoorn (about × 432). Section of chert showing organic detritus in which spherical bodies are intermixed. The spheres are in varying degrees of degradation and incorporation with the organic detritus (slide Sch-72; Paleobotanical Collection, Harvard, No. 58258). Part 4, *G. grandis* Barghoorn (about × 2135). Filament comparable in morphology to the filament shown in part 1, but of somewhat smaller diameter and cell size (slide 55-23-10; Paleobotanical Collection, Harvard, No. 58259). Part 5, *E. amplus* Barghoorn (about × 2135). Nonseptate filament showing endogonidia (see part 2 and Fig. 3, part 4). Part 6, *G. minuta* Barghoorn (about × 922). Filament showing typical gross morphology but altered to opaque anthraxolitic texture, with adjacent translucent sporelike body. It is not possible to determine with certainty whether the sporelike body is attached or merely appressed (slide Sch-3; Paleobotanical Collection, Harvard, No. 58261). Part 7, *Huroniospora macroreticulata* Barghoorn (about × 1620). Spheroidal sporelike body showing thick wall intensified by hematite staining (slide Sch-72; Paleobotanical Collection, Harvard, No. 58262). Part 8, *G. minuta* Barghoorn, type specimen (about × 1440). Unbranched filament showing remnants of regularly spaced transverse septae or cross walls. When viewed slightly out of focus the filament appears to possess a spiral structure reminiscent of the blue-green alga *Spirulina* or the iron bacterium *Gallionella*.

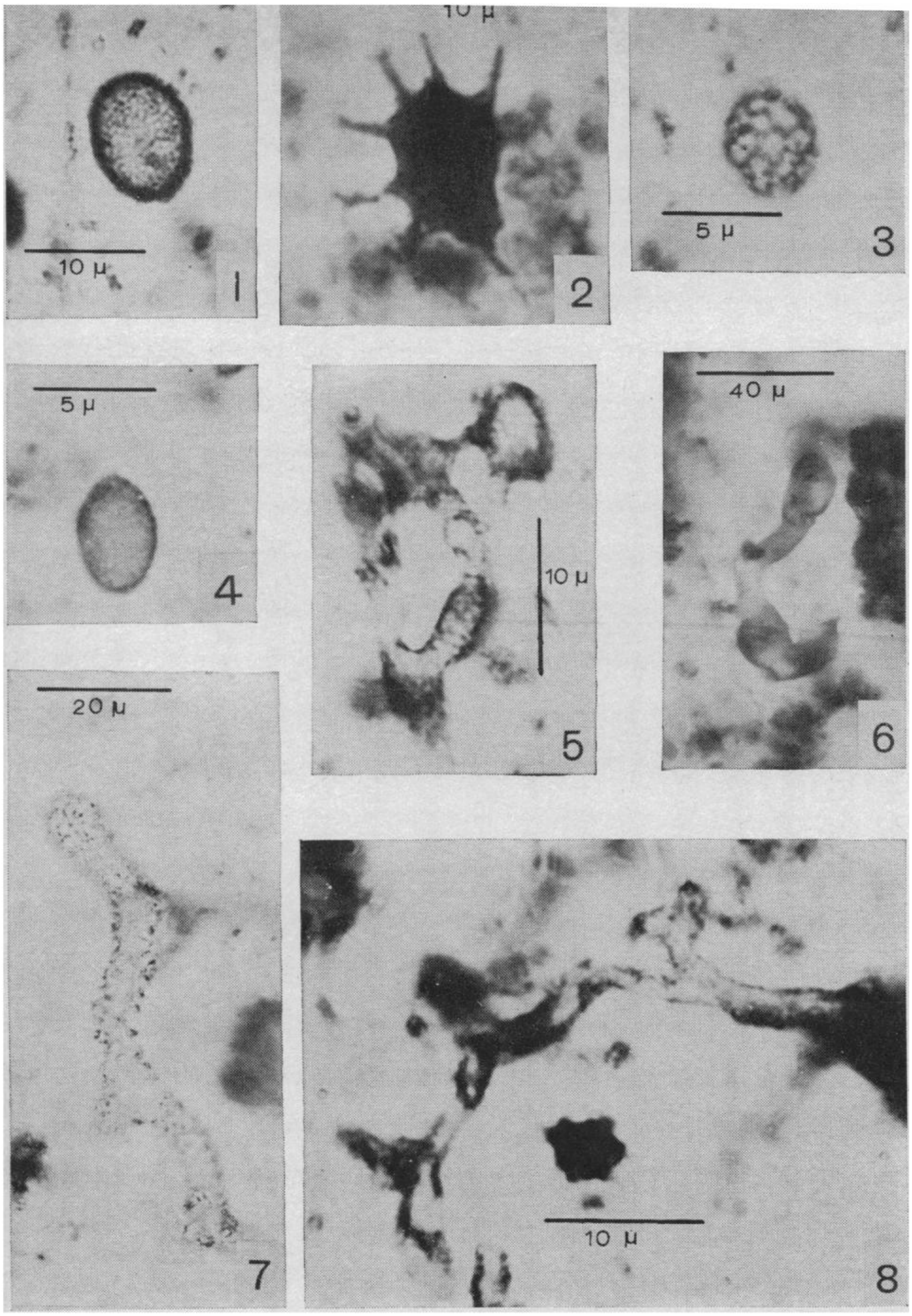


Fig. 5. Organisms from the Gunflint formation in thin sections of rock, photographed in transmitted light. Part 1, *Huroniospora microreticulata* Barghoorn (about × 1566). Ellipsoidal sporelike body exhibiting a thick wall with sculpture pattern regularly reticulate. Part 2, *Eoastrion bifurcatum* Barghoorn (about × 1079). Actinomorphic body with segmented, bifurcated filamentous processes radiating from an opaque, irregular anthraxolitic center. Although this specimen is somewhat atypical (see Fig. 6, parts 7 and 8), it is not possible to determine to what extent postmortem changes have affected the external form of the structure (slide Sch-W-25; Paleobotanical Collection, Harvard, No. 58265). Part 3, *Huroniospora macroreticulata* Barghoorn, type specimen (about × 3132). Spheroidal sporelike body exhibiting a thick wall with sculpture pattern regularly murate. Part 4, *H. psilata* Barghoorn, type specimen (about × 3132). Ellipsoidal sporelike body with a minute aperture at the more constricted (upper) end. The wall is relatively thin and unornamented. Part 5, *Archaeorestis schreiberensis* Barghoorn (about × 2088). A nonseptate, convoluted, and branched tubular filament. The phylogenetic affinity of this structure is difficult to surmise, although it is somewhat comparable to certain of the coenocytic green algae of the Vaucheriaceae. No reproductive organs are determinable (slide K-4-Z; Paleobotanical Collection, Harvard, No. 58268). Part 6, Organism (about × 435) of irregular tubelike structure, probably a member of species *A. schreiberensis* Barghoorn. Note the absence of septae and the presence of bulblike swellings (slide K-18; Paleobotanical Collection, Harvard, No. 58269). Part 7, *A. schreiberensis* Barghoorn (about × 870). Nonseptate tubular organic structure preserved as a replicate by large numbers of minute pyrite granules. The pyrite granules outline the original form; the organic matter has been lost (see parts 5 and 8) (slide 57-3-8; Paleobotanical Collection, Harvard, No. 58270). Part 8, *A. schreiberensis* Barghoorn, type specimen (about × 2088). Branched nonseptate filament comparable to structures shown in parts 5 to 7, but more extensively branched. In general, the morphology of this organism does not conform to that of structures present among the blue-green algae or of structures present in the iron bacteria. It is possible that parts 5, 6, 7, and 8 all represent stages of the same taxon of problematical affinity.

of the Gunflint results from the presence of both pyrite and organic matter. The pyrite occurs as individual crystals and aggregates. The pyrite particles range in diameter from a maximum of 3 to 4 millimeters down to less than 0.1 μ. The grains are usually closely associated spatially with organic matter. Crystals in the size range of 5 to 10 μ are observed in some instances to occur closely spaced along organic filaments, resembling a string of beads. The pyrite grains less than 1 μ in diameter tend to outline the organic structures, producing an effect similar to stippling (Fig. 5, part 7). When the pyrite grains are larger—about 1 μ in diameter—the individual grains are more distinct, and the organic forms take on a grainy aspect. In a few instances the organic filaments and sporelike bodies are composed of solid pyrite. Individual filaments of solid pyrite have been observed to pass laterally and continuously into carbonaceous films containing scattered pyrite grains less than 1 μ in diameter. The association of fine-grained pyrite with organic matter is the most common type of preservation of organic structures in the algal cherts.

*Carbonate.* Filaments, sporelike bodies, and other organic structures are preserved in some instances by carbonate imbedded in a chert matrix. The carbonate may form a continuous body which outlines the filament, or the carbonate occurs as a series of lenses along the axis of the filament. The small size of the carbonate filaments—1 μ or less in diameter—and the fact that they are enclosed in chert make it impossible to determine the type of carbonate present. The carbonate preservation of organic entities in the Gunflint chert is not to be confused with the phenomenon described by Tyler and Barghoorn (*15*), in which carbonate trails are appendaged to ambient pyrite crystals which have moved through the solid chert matrix, forming tubular pseudofossils.

*Hematite.* The black algal cherts pass locally into red algal jaspers. Thin sections of black chert-jasper interfaces show filaments, outlined by carbonaceous films and pyrite grains, passing as continuous bodies into the jasper, where hematite outlines the filament. Sporelike bodies and other organic structures are also preserved by hematite. The hematite often occurs as disseminated particles, less than 1 μ in diameter, set in a red-stained groundmass. The occurrence is similar to that of pyrite, suggesting that the hematite may represent oxidation of pyrite. However, the common occurrence of filaments and sporelike bodies composed of solid hematite, as compared to the rareness of solid pyrite filaments in the black cherts, suggests that the hematite may be replacing original organic matter in many cases. One aspect of the structural preservation of the organisms in the Gunflint chert which should be emphasized is the fact that their gross physical alteration has been extraordinarily small in view of their antiquity and geologic history. It is probable that the microorganisms were entrapped in amorphous silica (gel?) which, upon dehydrating to solid opal, provided an incompressible matrix with minimal deformation. The resistance of opal and of the subsequently crystallized chalcedony (chert) to pressure and crushing provided the physical environment which permitted three-dimensional preservation of the organisms and kept to a minimum the effects of pressure over long periods, by which organic matter is degassed and coalified. Moreover, crystallization of the chert to the chalcedonic structure commonly had little effect on the morphology of the organisms. The vast majority of the countless organic structures (filaments, sporelike bodies, and so on) show no primary deformation in relation to the chalcedony grains, as may be seen by comparing the organic structure as viewed in normal transmitted light and in polarized transmitted light. In the latter case the organic structures are seen to pass without alteration across the crystal boundaries of the chert grains.

## Structurally Preserved Organisms

Paleontologic study of the Gunflint chert has been carried out through examination of more than 800 thin sections, in conjunction with acid maceration and other chemical techniques. The tenuous and friable nature of the organic residues of the organisms, even of those that are best preserved, necessitates the use of thin sections for optimum results with white light microscopy. Maceration, even when carried out very slowly by means of dilute hydrofluoric acid, results in nearly complete fragmentation of the more delicate structures and partial fragmentation of the more thick-walled organic remains. Thick-walled filaments initially several hundred microns long in the chert tend to break up into small segments when freed through maceration. Of the sporelike bodies only the more massive-walled forms can be freed intact. The photomicrographs of Figs. 2 to 8 are from thin ground sections of rock, averaging 30 to 60 $\mu$ in thickness.

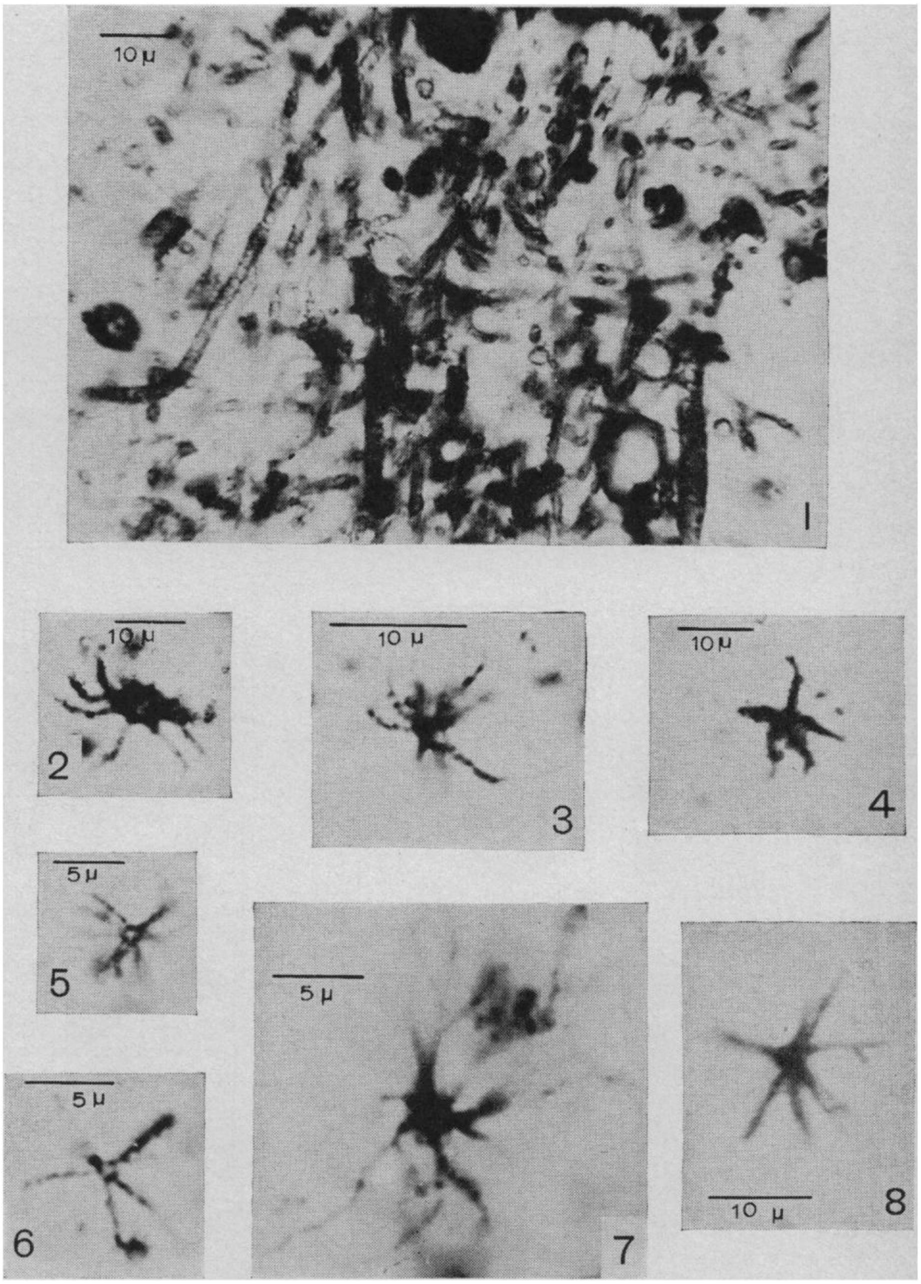


Fig. 6. Organisms from the Gunflint formation, in thin sections of rock, photographed in transmitted light. Part 1, Typical assemblage of tangled filaments (about × 935), predominantly *Gunflintia minuta*, and enmeshed sporelike bodies, *Huroniospora* spp., characteristic of the better phases of organic preservation of the Gunflint chert from the Schreiber locality. Note the variation in diameter of the filaments and the wide variation in both size and shape of the spheroidal bodies (slide 55-97; Palebotanical Collection, Harvard, No. 58272). Parts 2–6, *Eoastrion simplex* Barghoorn. Several specimens of an organism of uncertain affinity characterized by radially oriented, sinuous filaments centrally attached. Filaments are segmented and unbranched. Length of central body, ⅕ to ⅓ that of filaments. Structure 2, about × 935; slide 56; Paleobotanical Collection, Harvard, No. 58273. Structure 3, about × 1763; slide 52; No. 58274. Structure 4, about × 935; slide 56–1; No. 58275. Structure 5, about × 1763; slide K-4-Z; No. 58276. Structure 6, *E. simplex* Barghoorn, type specimen, about × 2403. Parts 7 and 8, *E. bifurcatum* Barghoorn. Specimens of an organism of uncertain affinity characterized by radially oriented, sinuous filaments centrally attached. The filaments are segmented and bifurcate. The filaments of the central body vary greatly in length. Structure 7, type specimen, about × 2403. Structure 8, about × 1312; slide 55-23-2; Paleobotanical Collection, Harvard, No. 58279.

We do not, here, describe in detail the whole range of microstructures thus far observed in the Gunflint chert. Rather, we discuss the major categories and microorganisms representative of those in which the chert abounds, and present a formal taxonomic treatment of the most distinctive of these microfossils. Of the more abundant structures, such as filaments and sporelike bodies, several square centimeters of thin sections of the chert may show the presence of thousands of discrete entities. The more complex forms, such as the forms shown in Figs. 7 and 8, are far less abundant. The absolute frequency of occurrence of the better-preserved entities is a rather meaningless value, owing to extremely wide variation within relatively short distances in the rock matrix.

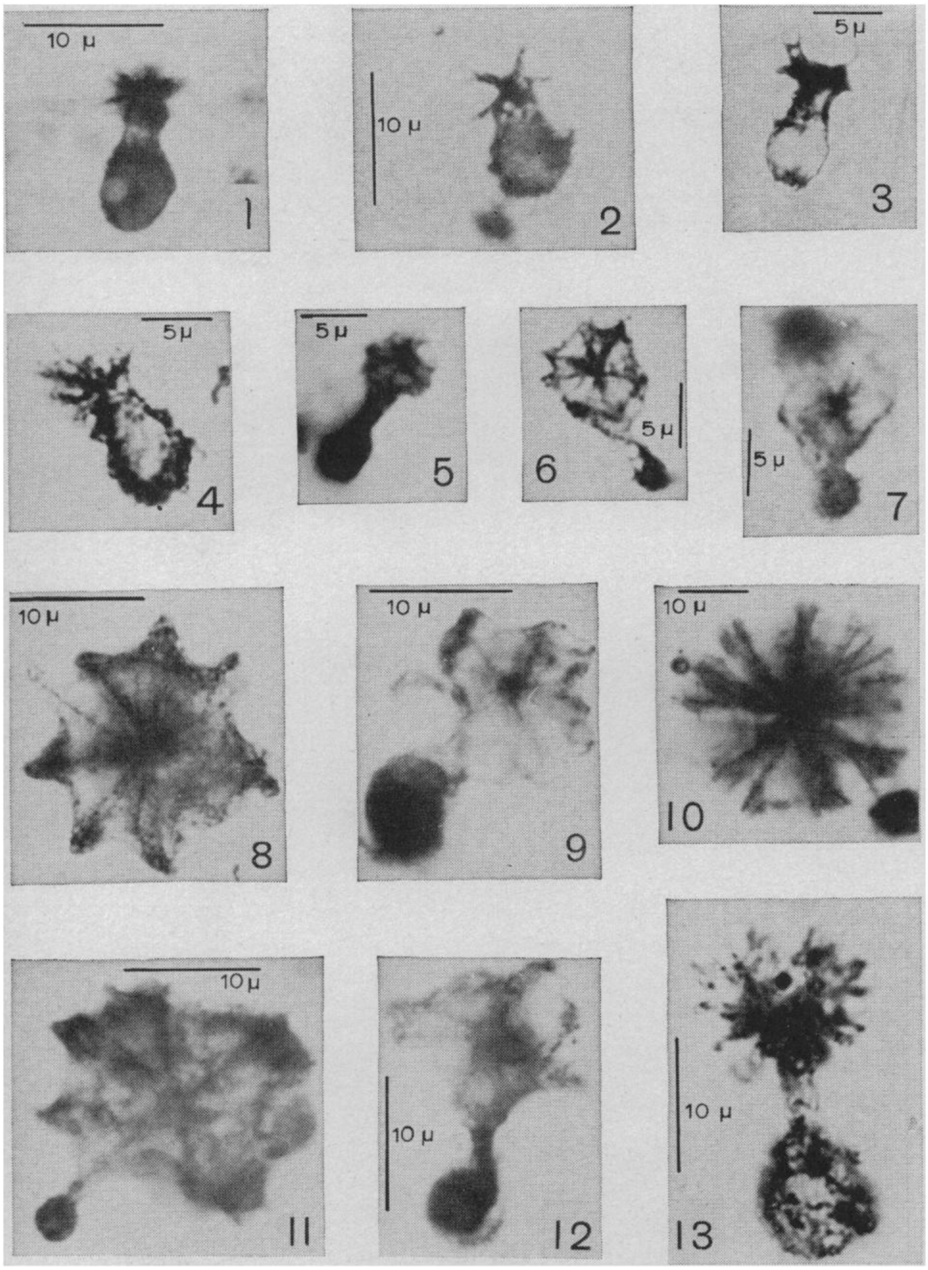


Fig. 7. *Kakabekia umbellata* Barghoorn, an organism of uncertain affinity, in thin sections of rock, photographed in transmitted light. The series of parts 1 through 13 is interpreted as representing different ontogenetic stages of the same organism. The basic morphology consists of a tripartite division into bulb, stipe, and crown of umbrella-like shape. As noted in the text, no counterpart to this organism has been observed among the dinoflagellates (living or fossil), among the chitinozoans, among the protozoans, or among the myxobacteria. The structures are exceptionally abundant in chert from the Kakabeka Falls locality and appear to be limited, generally, to the lower algal chert from that location. Structure 1, about × 1763; slide K-7B; Paleobotanical Collection, Harvard, No. 58280. Structure 2, about × 1763; slide 55-23-3; No. 58281. Structure 3, about × 1804; slide Sch-56-48; No. 58282. Structure 4, about × 1804; slide K-8; No. 58283. Structure 5, about × 1763; slide K-4-Y; No. 58284. Structure 6, about × 1763; slide K-4-Z; No. 58285. Structure 7, about × 1763; slide K-4-Y; No. 58286. Structure 8, about × 1763; slide K-4-Z; No. 58287. Structure 9, about × 1763; slide K-4-Z; No 58288. Structure 10, about × 935; slide K-4; No. 58289. Structure 11, about × 1763; *K. umbellata* Barghoorn, type specimen, slide K-7-A; No. 58290. Structure 12, about × 1763; slide K-19-5; No. 58291. Structure 13, about × 1763; slide 55-23-1; No. 58292.

The most abundant organisms in the Gunflint assemblage are filaments ranging from 0.5 to 6.0 μ, or occasionally more, in diameter. The filaments vary greatly in length. Some of them are fragments which resulted from segmentation of the larger filaments, apparently before death and mineralization; others are several hundred microns long. The maximum length of the filaments is difficult or impossible to ascertain, inasmuch as they are distributed in an undulating fashion in the chert matrix and pass in and out of the section interface, where parts of the filaments have been ground away during preparation of the thin section. The best-preserved filaments are found to be both septate and nonseptate (compare Fig. 3, parts 1–3, with Fig. 3, part 4, and Fig. 5, parts 5–8). Although in many cases it is difficult to determine with certainty whether the filament was septate or devoid of cross walls, because of postdepositional changes in the organic residue or deposition of pyrite granules, the grossly septate filaments are here placed in the new genus *Gunflintia* (see appendix), and are divided into two species, *G. grandis* (Fig. 4, parts 1 and 4) and *G. minuta* (Fig. 4, part 8) on the bases of filament diameter and regularity of cell size. Certain of the finely septate types exhibit a basic morphology comparable to that found in certain extant filamentous blue-green algae, such as *Oscillatoria* and *Lyngbya*; these forms are here placed in the new taxon *Animikiea septata* (Fig. 3, parts 1–3) (see appendix). Among the nonseptate filaments there occur, although very rarely, forms showing internally contained spores or endogonidia (Fig. 3, part 4; Fig. 4, parts 2 and 5); these organisms are here grouped in the new taxon *Entosphaeroides amplus* (see appendix). Structures morphologically comparable to these occur in a few extant genera of the blue-green algae and also in the iron bacteria (*Crenothrix*).

Filaments which show evidence of branching are exceedingly rare, and in the few cases in which any vestige of branching has been found the filaments are devoid of cross walls or septae. These occasionally branched, nonseptate, coarse or ropelike filaments are here placed in the new taxon *Archaeorestis schreiberensis* (Fig. 5, parts 5–8) (see appendix).

As noted earlier, the cross-sectional diameters of the filaments range from approximately 0.5 to over 6.0 $\mu$. Measurements of 1000 filaments (Fig. 9, left) reveals the fact, however, that nearly 50 percent of the 1000 filaments are in one size class—1.1 $\mu$. It is probable, although certainly not definitely demonstrable, that this preponderance of one size class represents the near-dominance of one "species" of blue-green alga. By analogy with mixed populations of modern blue-green algae from a variety of environments it seems reasonable to infer that the size range exhibited by the Gunflint algal assemblage represents a mixed population of blue-green algal species and not the size range to be expected in random sampling of a single species (Fig. 9, left). The establishment of three new genera and four new species to include the filamentous forms of the assemblage is consistent with the observed size range.

The spheroidal sporelike bodies which are ubiquitously but irregularly distributed through the chert matrix exhibit a wide range of size, wall thickness, external wall structure, and, to a certain extent, shape. The range in size of the sporelike bodies is from approximately 1 to over 16 $\mu$ (Fig. 9, right). Their shape varies from spherical (Fig. 3, part 4; Fig. 4, parts 3 and 7) to ellipsoidal (Fig. 5, parts 1 and 4). The wall is highly variable in thickness, ranging from an almost diaphanous membrane to a relatively thick or coarsely reticulate one (Fig. 3, part 4; Fig. 4, parts 2, 5–7; Fig. 5, parts 1, 3, and 4). The differences induced by mode of preservation or precipitation of pyrite adjacent to the wall are difficult to distinguish from differences which existed in the original biological structure. However, it is apparent that the sporelike bodies are of diverse and heterogeneous origin. Several of the more reasonable possibilities are that they are (i) unicellular blue-green algae similar to the *Chroococcus* type among living forms; (ii) endogenously produced endospores of filamentous blue-green algae or iron bacteria; (iii) free-swimming dinoflagellates; or (iv) fungus spores. The latter possibility seems quite remote in view of the absence or extreme scarcity of filamentous structures resembling those of fungi—that is, freely branching hyphae. Because of their great variation in size and the lack of clear relationship to other members of the assemblage, these sporelike bodies are

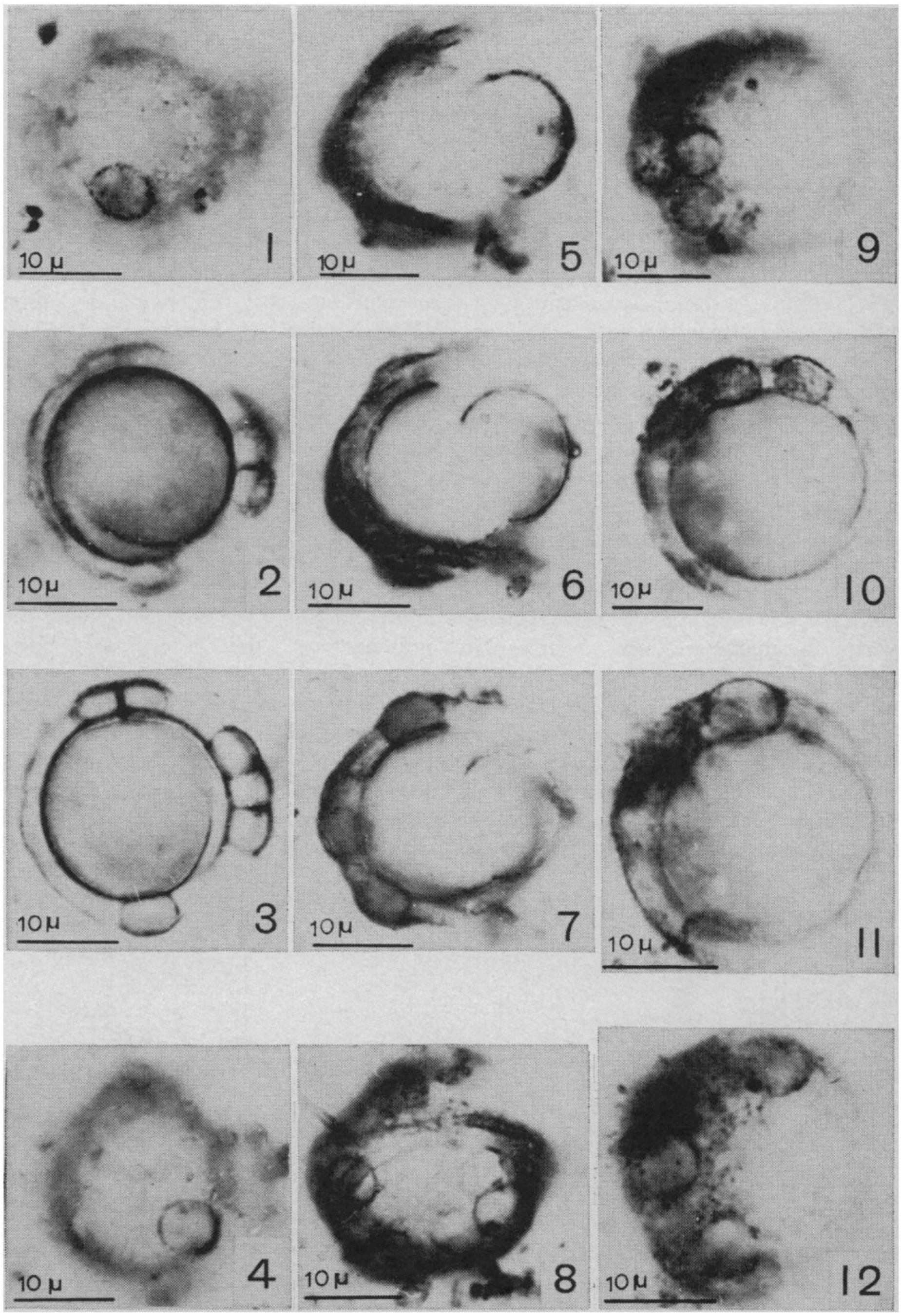


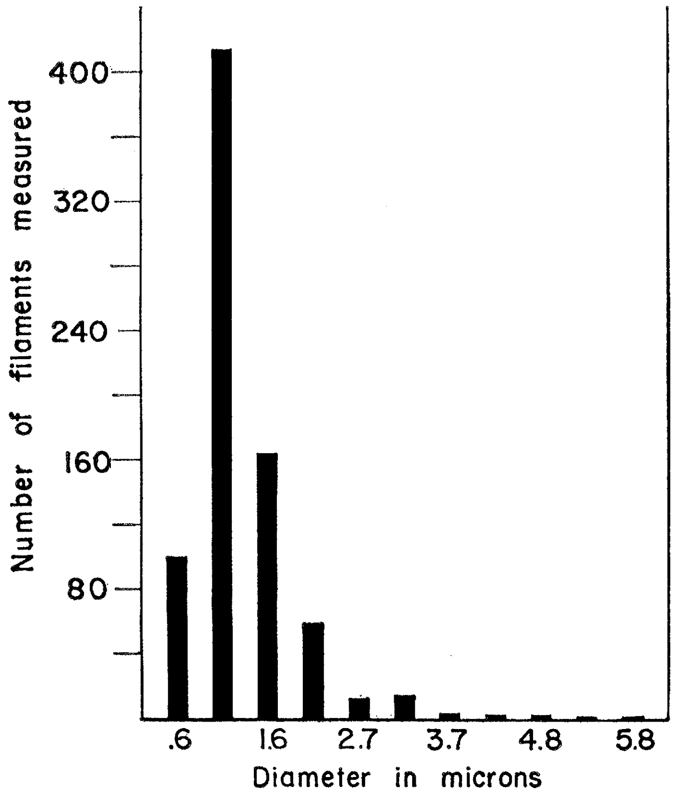
Fig. 8. *Eosphaera tyleri* Barghoorn, in thin sections of rock, photographed in transmitted light. Parts 1 to 4, A series of photomicrographs taken at four levels of focus, optically sectioning the organism, whose median or equatorial plane is shown in part 3. Photomicrographs 5 to 8 and 9 to 12, respectively, show two additional organisms of the same morphology but less perfectly preserved, photographed at four levels of focus. The organism occurs only in the Schreiber locality; in the study discussed, more than 800 thin sections of the chert-155 specimens were observed. The structure of the organism is that of a sphere within a sphere, the two spheres being separated by the tubercle-like spheroids which are attached to the inner, thick-walled sphere. The outer sphere is very thin and usually is partially ruptured as seen in parts 3, 6, and 10. The number of tubercles observed on 100 specimens varies from none to as many as 15. The biological affinity of this structure is entirely problematical, a fact of much interest in view of its quite complex morphology and its occurrence in this ancient assemblage. Parts 1 to 4, *E. tyleri* Barghoorn, type specimen, about × 1335. Parts 5–8, about ×1335; slide 67; Paleobotanical Collection, Harvard, No. 58294. Parts 9 and 10, about × 1200. Parts 11 and 12, about × 1468; slide Sch-E-8A; No. 58295.

here placed in the new form genus *Huroniospora* (see appendix) and are subdivided on the basis of wall-sculpturing pattern into three species: *H. macroreticulata* (Fig. 5, part 3), *H. microreticulata* (Fig. 5, part 1), and *H. psilata* (Fig. 5, part 4).

Among the more distinctive-looking organisms which are of even more uncertain biological affinity to living forms or groups are those shown in Fig. 6, parts 2–8, Fig. 7, and Fig. 8. The organized filamentous actinomorphic structures shown in Fig. 5, part 2, and Fig. 6, parts 2–8, are of uncertain affinity. These organisms, apparently ubiquitous throughout the fossiliferous zone of the formation, are characterized by segmented or septated filaments of variable number radiating irregularly from a central structure of poorly defined morphology. The radiating, frequently sinuous filaments are usually unbranched, although true bifurcation has been observed (Fig. 5, part 2; Fig. 6, parts 7 and 8). The central junction of these filaments varies in character from an irregular opaque mass of organic material (Fig. 5, part 2; Fig. 6, parts 7 and 8) to a diaphanous, membranous body of poorly delineated morphology (Fig. 6, parts 5 and 6). The diameter of the structures, measured in longest dimension, varies from about 8 to 25 μ. The diameter of the filaments and their generally segmented nature are reminiscent of the algal-like filaments shown in Fig. 4, parts 1, 4, and 8, and Fig. 6, part 1. For this reason it might be suggested that these structures actually represent filaments in a state of random aggregation. However, the uniform length of filaments radiating from particular centers (Fig. 6, parts 4, 6, and 8), the occasional bifurcation of these filaments (Fig. 5, part 2; Fig. 6, parts 7 and 8), and the mass of organic material apparently in organic connection with the filaments always present at the center of radiation (Fig. 5, part 2; Fig. 6, parts 2–8) render this interpretation untenable. The general starlike shape of these organisms appears similar, on superficial examination, to the umbrella-like process present in an organism of problematical affinity described below (Fig. 7). However, the very limited areal distribution (primarily the Kakabeka Falls locality) of the organism shown in Fig. 7, as contrasted with the presence of the asteroidal bodies throughout the fossiliferous zone of the Gunflint formation, and the presence of membranous connections between the "veins" of the umbrella-shaped mantle in the former organism (Fig. 7, parts 5–12), as contrasted with the lack of any such membrane between the radiating filaments of the asteroidal bodies, make any postulated genetic relationships between these two morphological types highly dubious. The actinomorphic structures may be related to other members of the assemblage, but no clear evidence for such a relationship has been discovered.

In gross organization the actinomorphic structures are morphologically comparable to certain modern actinomycetes and to certain of the myxobacteria. Although these ancient star-shaped microfossils probably represent a single genus and are almost certainly of plant origin, to relate them to any presently known living group appears unwarranted. For this reason, and because of lack of evidence clearly indicating affinity to other members of the assemblage, these filamentous asteroidal bodies are here placed in the new form genus *Eoastrion* (see appendix) and subdivided, on the basis of the form of the radiating filaments, into the two species *E. bifurcatum* (Fig. 5, part 2; Fig. 6, parts 7 and 8) and *E. simplex* (Fig. 6, parts 2–6).

The distinctive organism shown in Fig. 7 is almost entirely restricted, among the known Gunflint chert outcrops, to the locality near Kakabeka Falls. In the dense black chert from this locality the structures may be observed by the thousands in a relatively



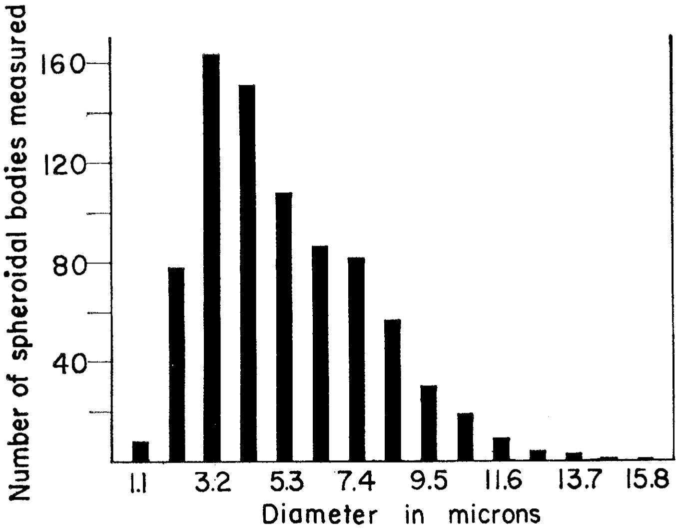


Fig. 9. Histograms showing size distribution of spheroidal bodies and of algal filaments in the Gunflint chert. The size classes were selected on the basis of discrimination by ocular micrometer units, and it is evident that the range in size between the smallest and the largest is continuous. A size distribution of this type indicates a diversity of organisms or entities rather than a normal distribution of a single "species" or entity.

few thin sections of the rock. The morphology is distinct, showing a tripartite organization of basal bulb, slender stipe, and crown of umbrella-like shape. The relative sizes of these three units of the organism vary widely, although in general the size of the basal bulb varies inversely with the size of the umbrella-like crown or mantle. The crown or mantle possesses distinct veinlike thickenings, varying in number from six to eight or more; the commonest number is eight. The "veins" sometimes dichotomize and terminate in the points of the mantle. The organisms range in diameter from 12.0 to slightly over 30.0 $\mu$. They occur within a particular thin section in all directions of orientation, and, when viewed from directly above, the mantle appears somewhat similar in form to that of discoasters (*16*). It is difficult to assign an affinity of this organism to a living counterpart, provided any exists. In shape and basic organization the structural features are reminiscent of certain coelenterates, particularly the hydrozoans. The organism is extraordinarily small, however, and if size is a criterion of prime importance, classification of the organism as a coelenterate must be excluded. It should be pointed out, however, that the true size of this organism in life may have been three to four times its present size owing to shrinkage in the transition from the hydrated silica gel to the chalcedonic phase of the silica matrix. Efforts to find analogies to this structure among the dinoflagellates (living and fossil), the chitinozoans, the protozoa, and the myxobacteria have been unsuccessful. This organism of uncertain affinity is here assigned to the new taxon *Kakabekia umbellata* (Fig. 7) (see appendix).

We face a similar problem when we seek an existing biological counterpart for the organism of Fig. 8. This organism occurs only in the Gunflint chert outcrops at the Schreiber Beach locality, and there it occurs very infrequently in the dense black cherts. Detailed observation of several hundred thin sections has revealed only 155 organisms which show this general organization. Of these a number are incomplete, although over 100 fairly intact specimens have been examined in detail. The basic organization consists of a central relatively thick walled sphere on which spheroidal tubercle-like bodies are distributed in varying numbers, and the entire structure is surrounded by a tenuous outer layer which is almost invariably ruptured in one hemisphere or in parts of both hemispheres. The structure is essentially a sphere within a sphere, the two spheres being separated by the tubercle-like spheroids. The number of the latter varies from none to as many as 15. The tubercles are distributed over the surface of the inner sphere in no discernible geometric pattern, as may be ascertained by optically sectioning the object. When there are few or no tubercles the outer sphere is fragmented and often undetectable. The structures, if intact, range in diameter from approximately 28.0 to 32.0 $\mu$, and many of them show a tendency to flatten to a rounded lenticular shape, although they are never highly compressed.

Table 1. Hydrocarbons obtained by pyrolysis of Gunflint chert at 400°C.

| Hydrocarbon | Parts per million* |
|---|---|
| Methane | 87.0 |
| Ethane | 4.0 |
| Propane | 0.8 |
| Normal pentane | .2 |
| Cyclopentane | .1 |
| 2-Methyl pentane | .1 |
| Normal hexane | .5 |
| Cyclohexane | .1 |
| Normal heptane | .07 |
| Normal octane | .01 |
| Benzene | .34 |
| Toluene | .15 |
| Xylene | .45 |
| Isopropyl benzene | .13 |

* Data provided by John Hunt, previously of Jersey Production Research, Tulsa, Oklahoma, now of the Woods Hole Oceanographic Institution.

I know of no objects similar to this among living organisms. Other observers have drawn analogies to oogonia of aquatic fungi and to certain colonial algae. However, none of these comparisons withstand close scrutiny. It is probable that the structure was a free-floating colonial photosynthetic organism, and it is possible that the small tubercles had a role in vegetative reproduction. Despite careful search in many thin sections of the chert from the Schreiber locality, no intermediate or what might be called ontogenetic stages have been found. This organism of uncertain affinity is here placed in the new taxon *Eosphaera tyleri* (see appendix).

It should be noted that the organisms shown in Figs. 2 to 8 do not represent the total range of structures which have thus far been found in the Gunflint chert. They do represent some of the commonest and most distinctive forms thus far observed. All organisms shown are indigenous to the rock, as evidenced by their presence within the solid translucent silica matrix of chalcedonic chert.

## Chemical Studies of the Organic Matter

The antiquity of the organic matter in the Gunflint chert and its definite biogenic origin lend much interest to various chemical aspects of the Gunflint formation, particularly with reference to problems of the ultimate antiquity of life and the nature of very ancient organic matter. Inasmuch as the Gunflint formation is probably the least metamorphosed Middle Precambrian formation now known in the geologic record, the possibilities of securing meaningful biogeochemical data are attractive. With this end in view, a number of studies have been made, some of which are summarized here.

The organic fraction of the darker and more highly carbonaceous samples of the chert ranges from 0.2 to 0.6 percent (dry weight), the average for the darker samples being 0.37 percent, or 3700 parts per million. Although there is some presumptive evidence of the presence of amino acids, careful reruns have yielded such low values that the data are inconclusive.

Destructive distillation of the chert at 400°C yielded hydrocarbons in the relative proportions given in Table 1.

The organic residue of the Gunflint chert, after demineralization in hydrogen fluoride, yields small amounts of extractable compounds when eluted with benzol and methanol. The extractives fluoresce strongly in ultraviolet light. Data recently obtained by W. G. Meinschein show the following extracts secured by eluting the organic residue from 1824 grams of chert after dissolution of the silica: N-heptane eluate, 2.1 mg; carbon tetrachloride eluate, 1.3 mg; benzene eluate, 0.3 mg; and methanol eluate, 10.9 mg. Of these extractables the heptane and carbon tetrachloride fractions are presumably all alkane hydrocarbons, and the benzene eluate is presumably made up of aromatic hydrocarbons, probably consisting primarily of phenanthrenes, as shown by ultraviolet absorption. The methanol nonhydrocarbon eluate was subjected to infrared absorption studies, with the result shown in the spectrum of Fig. 10. The infrared absorption spectrum indicates the presence of carbonyl bonding and alcohol and ester linkages.

One very interesting aspect of the carbon chemistry of the Gunflint organic matter is the nature of its stable carbon isotopic composition. Several determinations have been made of the $C^{13}/C^{12}$ ratio of the organic fraction. By using the Peedee belemnite standard and correcting for $O^{17}$, S. R. Silverman secured a $C^{13}/C^{12}$ ratio of $-33.1$ per mil $\delta$. This value falls close to the low end of the range for solid and liquid contemporary biogenic carbon (that is, organic matter photosynthetically depleted in $C^{13}$). Such a $C^{13}$ content is putative evidence that the Gunflint organic matter was produced by photosynthesis, from analogy with contemporary photosynthetic products such as wood or with known fossil products of photosynthesis, such as peat, lignite, and coal (*17*). Further evidence in this direction was secured by T. Hoering in analysis of the $C^{13}/C^{12}$ ratio in the organic carbon of the Gunflint and comparison of this ratio with the $C^{13}/C^{12}$ ratio of the carbonate fraction in the same rock sample. The value for the organic carbon was $-29.2$ per mil $\delta$, and the value for the inorganic $CaCo_3$ fraction was $-11.63$ per mil $\delta$ (the values refer to the Solenhofen Limestone National Bureau of Standards reference sample No. 20). The differences here between the values for reduced (organic) carbon and the $CaCO_3$ carbon attest further to the photosynthetic origin of the Gunflint chert organic matter and are of interest in speculation on whether the paleoenvironment of Gunflint time was oxidizing or reducing.

## Paleoenvironment of Deposition

It is generally recognized that the Precambrian banded, siliceous, iron-bearing formations such as the Gunflint are sedimentary deposits, but there is no general agreement as to the source, method of transportation, and manner of deposition of the iron and silica. Interpretation of paleoenvironment is based to a large extent upon knowledge gained from the study of the physical and chemical processes operating in similar environments today. In the case of the siliceous iron formations of the Precambrian type, there exists no modern example; nor is there known a single place where sediments of this type are being deposited today. Furthermore, similar sediments are either very rare or nonexistent in Paleozoic, Mesozoic, and Cenozoic stratigraphic sections. Thus, reconstruction of the paleoenvironment of the siliceous iron-bearing sediments depends upon circumstantial evidence limited only by the laws of physics and chemistry. This situation has led to a wide variety of interpretations and controversial points of view.

Van Hise and Leith (*18*) concluded that in the Lake Superior region the iron and silica were derived partly by weathering of pre-existing basic igneous rocks and partly by direct magmatic contribution or reaction of sea water with hot lavas. The weathering hypothesis has since been strongly supported by Gruner (*19*), Woolnough (*20*), Sakamoto (*21*), James (*22*), Alexandrov (*23*), and Hough (*24*). The direct-magmatic or hot-spring hypothesis has received support from Collins, Quirke, and Thompson (*25*), Moore (*26*), Magnüsson (*27*), Dunn (*28*), Goodwin (*8*), and Oftedahl (*29*).

There seems to be general agreement that the Precambrian iron formation accumulated in a subaqueous environment. The specific nature of this environment is open to question. The site of deposition of the iron formation is specified by Van Hise and Leith (*18*) and Oftedahl (*29*) as the sea; by Gruner (*19*) and Moore and Maynard (*26*) as lakes or the sea; by Tyler and Twenhofel (*30*), James (*22*), and Goodwin (*8*) as marginal basins with restricted connections with the sea; by Woolnough (*20*), Sakamoto (*21*), Alexandrov (*23*), and Hough (*24*) as lakes; and by Collins, Quirke, and Thompson (*25*) as pools, ponds, and irregular flow of water over a surface intermittently exposed to the air.

An intensive study of the physical and chemical attributes, such as chemical composition, mineralogy, grain morphology, textures, structures, and relationships to other sediments, should provide the clues necessary to define the environment of deposition of the iron formation. The chemical composition of these rocks is rather well known (this is true only with respect to the major constituents) in areas which have stimulated economic interest, but there are extensive areas for which we have little or no information. Thus, a statistical approach to the composition of the siliceous iron formations is heavily weighted by economic concepts and does not provide the basic information necessary for interpretation in terms of paleoenvironments.

Minerals are rather sensitive indicators of environment; hence the occurrence of specific minerals or mineral associations might be expected to have important environmental significance. This type of approach holds great promise from a theoretical point of view, but there are formidable practical difficulties. The Precambrian iron formations are very old rocks. In most areas these rocks have suffered metamorphism of some type during their history, and thus the present mineralogy may date largely from this period rather than from the time of deposition of the sediment. Iron-bearing sediments are particularly sensitive to oxidizing and reducing environments that may have existed at any time throughout their history; therefore the present oxidation state of the iron may not reflect conditions at the time of deposition. These factors must be taken into consideration in any study dealing with paleoenvironmental interpretation. Van Hise and Leith (*18*) concluded from their extensive studies of iron formation in the Lake Superior region that the original minerals were "greenalite, siderite, chert, and perhaps some hematite, magnetite and limonite. . . ."

James (*22*), as the result of studies in the Iron River district of Michigan, extended the sedimentary facies concept originally proposed by Van Hise and Leith (*18*) to include the oxide and sulfide facies. James considers magnetite, which is a major component of his oxide facies, as a primary mineral. He also redefines iron formation so as to include graphitic, pyritic slates as the dominant component of the sulfide facies. James (*22*) assumes that the minerals which occur in the areas of lowest metamorphic grade (in Michigan and Minnesota) are primary minerals. This assumption is not necessarily valid, for there is no compelling reason why unmetamorphosed iron formation should occur in these areas. The eastern portion of the Gunflint range contains what is probably the least metamorphosed iron formation known. This area is truly a window through the Precambrian metamorphic veil. The minerals present in the Gunflint formation have suffered a minimum amount of change and thus more nearly reflect the original environment of deposition than minerals in other areas.

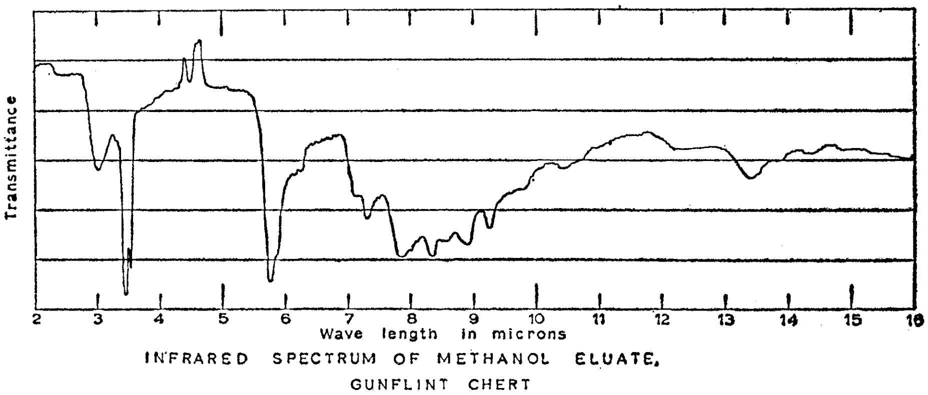


Fig. 10. Infrared absorption spectrum of the methanol eluate secured from the organic fraction (freed by means of hydrofluoric acid) of the Gunflint chert. The peaks above 10 indicate highly condensed ring structures.

It seems certain that the Gunflint waters were rich in silica. However, the source of this silica, the manner of transportation, and the mechanism of deposition are unknown. Krauskopf's studies (*31*) indicate that silica is soluble to the extent of about 120 parts per million at 25°C in both fresh and sea water in the *p*H range from 0 to 9. Any silica that occurs in excess of this amount will be present in the colloidal state. Most silica-bearing solutions in nature are very dilute (5 to 30 parts per million) except for certain connate waters (20 to 60 parts per million) and hot-spring waters such as those in Yellowstone Park, where the silica content may reach 700 parts per million. Colloidal silica may be deposited by evaporation, by freezing, by co-precipitation with other colloids, and by electrolytes. Organisms such as diatoms, radiolaria, and some varieties of sponges have the ability to precipitate silica from very dilute solutions. The silica which now occurs in the form of chalcedony and quartz in the Gunflint formation may have been deposited by organisms in the form of silica gel. Such a hydrous gel would slowly lose water through syneresis, passing into opal and finally crystallizing as chalcedony and quartz.

Interpretation of primary textures and structures of the Precambrian iron formation in terms of environment has received inadequate attention. The Gunflint iron formation contains granular, oolitic, and dense nongranular cherts. The granules range from far less than 0.1 millimeter to 1.0 millimeter or more in diameter and show no regular internal structure. Van Hise and Leith (*18*), Gruner (*19*), and Gill (*7*) concluded that the granules represent colloidal globules or aggregates that were deposited in the gelatinous state. Hotchkiss (*32*) and Huber (*33*) suggest that the wavy-bedded granular cherts on the Gogebic range were formed in shallow waters under conditions of strong wave activity.

The granular cherts in the lower algal zone of the Gunflint contain chert oolites and chert granules, I M muscovite granules, pyroclastic granules, and occasional clastic quartz grains. The morphology of the granules and the intimate association with clastic grains suggest that the granular particles were not deposited as colloidal globules or aggregates but that they are clasts which were deposited in an environment of strong wave or current activity. Goodwin (*8*) has noted well-developed cross-laminated units in the Lower East Taconite facies of the Gunflint. Similar structures may be observed in the lower cherty horizon on the Mesabi Range. The occurrence of cross-laminated units in the granular cherts indicates that the granules behaved as clasts and that currents were responsible for their transportation and deposition.

The occurrence of large numbers of algal domes in the lower algal zone of the Gunflint formation indicates that the waters were sufficiently shallow (probably less than 18 meters deep) to allow light to penetrate to the water-sediment interface. The presence of granular chert associated with oolites and quartz clasts in this zone suggests current activity. The cherts of the lower algal zone are dominantly black, gray, or green, with red and white cherts occurring in subordinate amounts. The black, gray, and green colors are due to the presence of pyrite, organic matter, and iron-bearing carbonates. The algal domes and the granular cherts suggest shallow agitated waters. The pyrite, the organic matter, and the iron-bearing carbonates indicate reducing conditions.

The local conditions of the environment as they affected the organisms preserved in the Gunflint chert are amenable only to inferential generalizations. The assumption that the filamentous structures constituting much of the organic fraction in the chert were truly algal and hence photosynthetic is based on the following deductions: (i) their morphology is similar to that of existing primitive filamentous blue-green algae; (ii) the gross structure of the domes containing the organisms conforms to that of similar algal domes or biostromes of blue-green algae extant today in shallow waters; and (iii) the fractionation of the stable carbon isotopes, as determined in the organic carbon of the chert, is most reasonably explained on the basis of photosynthetic fractionation. The oxygenous environment produced by photosynthesis in the Gunflint sedimentary basin might have been localized and adjacent to the algal colonies only. If heterotrophic oxygen-consuming organisms were among the mixed population of the organisms observed, this might well account for the evidence (based on mineralogy) of oxidizing and reducing conditions closely adjacent to each other. Such contrasts can be found in many biologically highly active sedimentary environments today.

To draw conclusions about the nature of the gaseous composition of the earth's atmosphere during Gunflint time on the basis of the paleontologic evidence is scarcely justifiable. However, one is tempted to consider the possibility that, if the Gunflint assemblage was largely a photosynthetic biosystem and if it was representative of a geographically more widespread or a worldwide biosystem of photosynthetic organisms, Gunflint time may represent an intermediate stage in the evolution of the highly oxygenic atmosphere which must have prevailed at the beginning of Cambrian time. In addition, the Gunflint chert is of unusual interest in the study of the history of life in that it provides a diversity of information concerning the most ancient organisms known at the present time.

# Appendix: Taxonomic Treatment of Genera and Species from the Lower Algal Chert, Gunflint Formation, Animikie Series, Ontario, Canada

### Genus **Animikiea** Barghoorn, n. gen.

Multicellular unbranched filaments straight or curved, with closely spaced septae. Individual cells much wider than long. Enclosing sheath of filament, distinct, thick-walled, and granular. Width of filament, 7 to 10 μ. Length may be greater than 100 μ.

1) Type species: *Animikiea septata* Barghoorn, n. gen., n. sp.; Fig. 3, parts 1 to 3.

*Description*: Salient characters as described for genus.

*Possible specific characters*: Cell length, 1/6 to 1/10 the diameter of filament.

*Locality*: 6.4 kilometers west of Schreiber, Ontario.

*Type specimen*: Fig. 3, part 2. Slide 67-S; Paleobotanical Collection, Harvard, No. 58253.

### Genus **Entosphaeroides** Barghoorn, n. gen.

Nonseptate unbranched filaments, straight or curved. Randomly distributed sporelike bodies present in the lumina of the filaments. Filaments 5 to 6 μ in diameter; may exceed 100 μ in length. Sheath enclosing filament is distinct, not conspicuously granular.

1) Type species: *Entosphaeroides amplus* Barghoorn, n. gen., n. sp.; Fig. 3, part 4; Fig. 4, parts 2 and 5.

*Description*: Salient characters as described for genus.

*Possible specific characters*: Sporelike bodies spherical-to-ellipsoidal, 2.5 to 3 μ on long axis.

*Locality*: 6.4 kilometers west of Schreiber, Ontario.

*Type specimen*: Fig. 3, part 4. Slide Sch-W-57-CF-10; Paleobotanical Collection, Harvard, No. 58255.

### Genus **Gunflintia** Barghoorn, n. gen.

Multicellular filaments, straight or curved, unbranched. Septae distinct and may be variably spaced. Diameter of filaments varies from less than 1 μ to 5 μ; individual filaments of generally uniform diameter throughout. Cells equidimensional or longer than wide. Filaments may exceed 300 μ in length.

1) Type species: *Gunflintia minuta* Barghoorn, n. gen., n. sp.; Fig. 4, parts 6 and 8; Fig. 6, part 1.

*Description*: Salient characters as described for genus.

*Specific characters*: Filaments less than 1 μ to 2 μ in diameter, usually about 1.1 μ. Cells generally of uniform size and shape.

*Localities*: Throughout the fossiliferous zones of the Gunflint formation. Particularly abundant at the locality 6.4 kilometers west of Schreiber, Ontario, and at road cut 1.2 kilometers northwest of Kakabeka Falls, Ontario.

*Type specimen*: Fig. 4, part 8. Slide Sch-72; Paleobotanical Collection, Harvard, No. 58263. Type specimen from locality 6.4 kilometers west of Schreiber, Ontario.

2) Species: *Gunflintia grandis* Barghoorn, n. gen., n. sp.; Fig. 4, parts 1 and 4.

*Description*: Salient characters as described for genus.

*Specific characters*: Filaments 2.5 to 5 μ in diameter, usually about 3.5 μ. Cells vary from equidimensional to 2 to 3 times longer than wide. Filaments may be conspicuously constricted at septae.

*Localities*: Throughout the fossiliferous zones of the Gunflint formation. Particularly abundant at the locality 6.4 kilometers west of Schreiber, Ontario.

*Type specimen*: Fig. 4, part 1. Slide Sch-W-CF-11; Paleobotanical Collection, Harvard, No. 58256. Type specimen from locality 6.4 kilometers west of Schreiber, Ontario.

### Genus **Archaeorestis** Barghoorn, n. gen.

Nonseptate tubular, occasionally branched filaments, commonly with rugose walls. Bulbose swellings of the filament wall can be present at random intervals. Filament diameter varies from 2 to 10 μ; filaments of relatively constant diameter except at bulbose swellings. Filament may exceed 200 μ in length.

1) Type species: *Archaeorestis schreiberensis* Barghoorn, n. gen., n. sp.; Fig. 5, parts 5 to 8.

*Description*: Salient characters as described for genus.

*Possible specific characters*: Bulbose swellings less than twice the diameter of the filament.

*Localities*: 6.4 kilometers west of Schreiber, Ontario, and road cut 1.2 kilometers west of Kakabeka Falls, Ontario.

*Type specimen*: Fig. 5, part 8. Slide K-4-Z; Paleobotanical Collection, Harvard, No. 58271. Type specimen from Kakabeka Falls locality.

### Genus **Huroniospora** Barghoorn, n. gen.

Spheroidal-to-ellipsoidal unattached bodies varying in length of long axis from 1 to 16 μ. Wall sculpture pattern varies from psilate to murate and is commonly reticulate. Ellipsoidal bodies may exhibit a minute aperture at the more constricted end.

1) Type species: *Huroniospora microreticulata* Barghoorn, n. gen., n. sp.; Fig. 5, part 1.

*Description*: Salient characters as described for genus.

*Specific characters*: Wall thick, with sculpture pattern regularly reticulate.

*Localities*: Throughout the fossiliferous zones of the Gunflint formation. Particularly abundant at the locality 6.4 kilometers west of Schreiber, Ontario.

*Type specimen*: Fig. 5, part 1. Slide Sch-72; Paleobotanical Collection, Harvard, No. 58264. Type specimen from locality 6.4 kilometers west of Schreiber, Ontario.

2) Species: *Huroniospora macroreticulata* Barghoorn, n. gen., n. sp.; Fig. 5, part 3.

*Description*: Salient characters as described for genus.

*Specific characters*: Wall thick, wall pattern regularly murate.

*Locality*: Road cut 1.2 kilometers northwest of Kakabeka Falls, Ontario.

*Type specimen*: Fig. 5, part 3. Slide K-25; Paleobotanical Collection, Harvard, No. 58266.

3) Species: *Huroniospora psilata* Barghoorn, n. gen., n. sp.; Fig. 5, part 4.

*Description*: Salient characters as described for genus.

*Specific characters*: Wall relatively thin and unornamented.

*Locality*: Road cut 1.2 kilometers northwest of Kakabeka Falls, Ontario.

*Type specimen*: Fig. 5, part 4. Slide K-25; Paleobotanical Collection, Harvard, No. 58267.

### Genus **Eoastrion** Barghoorn, n. gen.

Septate filaments of variable number radiating irregularly from a central body. Filaments commonly sinuous and of approximately equal length from central attachment. Filaments may be single or branched. Central body varies in character from irregular and opaque to membranous. Filament diameter about 1.5 μ; filament length varies from 3 to 18 μ; long axis of central body, 2 to 8 μ or occasionally longer.

1) Type species: *Eoastrion simplex* Barghoorn, n. gen., n. sp.; Fig. 6, parts 2 to 6.

*Description*: Salient characters as described for genus.

*Specific characters*: Radiating filaments unbranched; diameter of central body 1/5 to 1/3 the length of filaments.

*Localities*: 6.4 kilometers west of Schreiber, Ontario, and road cut 1.2 kilometers northwest of Kakabeka Falls, Ontario.

*Type specimen*: Fig. 6, part 6. Slide K-4-Z; Paleobotanical Collection, Harvard, No. 58277. Type specimen from Kakabeka Falls locality.

2) Species: *Eoastrion bifurcatum* Barg-

hoorn, n. gen., n. sp.; Fig. 5, part 2; Fig. 6, parts 7 and 8.

*Description*: Salient characters as described for genus.

*Specific characters*: Radiating filaments bifurcate; central body usually opaque and variable in size.

*Localities*: 6.4 kilometers west of Schreiber, Ontario, and road cut 1.2 kilometers northwest of Kakabeka Falls, Ontario.

*Type specimen*: Fig 6, part 7. Slide K-4-Z; Paleobotanical Collection, Harvard, No. 58278. Type specimen from Kakabeka Falls locality.

Genus **Kakabekia** Barghoorn, n. gen.

Structure showing tripartite organization consisting of spheroidal bulb, slender stipe, and crown or mantle of umbrella-like shape. Radiating, veinlike, occasionally dichotomously branched thickenings, present in mantle, are often tetramerous. Overall length from distal end of bulb to apex of mantle varies from 12 to 30 $\mu$. Diameter of mantle varies from approximately 5 to 30 $\mu$. Size of bulb commonly varies inversely with size of mantle.

1) Type species: *Kakabekia umbellata* Barghoorn, n. gen., n. sp.; Fig. 7.

*Description*: Salient characters as described for genus.

*Possible specific characters*: Mantle perimeter varies in shape from scalloped (Fig. 7, parts 6, 8, 11), to lacerate (Fig. 7, part 10), to tentacular (Fig. 7, part 2).

*Localities*: Abundant at road cut 1.2 kilometers northwest of Kakabeka Falls, Ontario, very rare at locality 6.4 kilometers west of Schreiber, Ontario.

*Type specimen*: Fig. 7, part 11. Slide K-7-A; Paleobotanical Collection, Harvard, No. 58290. Type specimen from Kakabeka Falls locality.

Genus **Eosphaera** Barghoorn, n. gen.

Complex spheroidal structure consisting of a thick-walled inner sphere on the outer surface of which occur rugose spheroidal tubercles of varying number and random distribution. The inner sphere and tubercles are encompassed by an outer thin-walled spherical membrane. The thick-walled inner sphere is discontinuous at some point on its periphery, forming a distinct invagination. Radius of inner sphere, approximately 10 to 12 $\mu$. Radius of outer sphere, about 14 to 15 $\mu$. Tubercles, about 2.5 $\mu$ on long axis.

1) Type species: *Eosphaera tyleri* Barghoorn, n. gen., n. sp.; Fig. 8.

*Description*: Salient characters as described for genus.

*Possible specific characters*: Number of tubercles varies from none (in which case no outer sphere is present) to 15. Degree of completeness of outer sphere, highly variable.

*Locality*: 6.4 kilometers west of Schreiber, Ontario.

*Type specimen*: Fig. 8, parts 1 to 4. Slide 56; Paleobotanical Collection, Harvard, No. 58293.

The specific name is in honor of the late Professor Stanley Tyler of the University of Wisconsin.

### References and Notes

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