valley have been found (*13, 14*) three pools of hot acidic brines with heavy-metal concentrations as high as 50,000 times those in normal ocean waters. Red Sea water is normally 20°C at *p*H 8.5; the deep brines at 2000 m may be as hot as 56°C at *p*H 4. Under the hot pools is a sedimentary layer consisting mainly of metal oxides and sulfides that is 10 to 100 m thick (*14*). The pools appear to be large natural chemical laboratories in which metals that have migrated from the upper mantle, through faults, are concentrated and precipitated, from colloidal suspension, on the sea floor. The Coeur d'Alene mining district was used (*14*) to show that the value of ore was probably greater in the Red Sea sediments.

The graben structure of and a similar origin for Coeur d'Alene have been discussed (*15*), as have the subsequent diagenesis, metasomatism, and metamorphism (*16*). Areas similar to the Red Sea pools have been found over the East Pacific Rise and its extensions into continental North America (*17*).

I suggest that the strata-form deposits at Kimberley originated within the bounds of the Precambrian rift that crosses western Canada. The method of ore concentration may have been similar to that now occurring in the Red Sea hot brines. Lead isotopes from the Sullivan body (*18*) yield an age of 1340 ± 50 million years for the time of mineralization. Model lead ages of 1340 to 1500 million years have been calculated by me from older measurements (*19*) from nearby in British Columbia and from the Coeur d'Alene district. A syngenetic origin is supported by a rubidium-strontium isochron age of 1315 ± 35 million years (*20*) from rocks from the lower part of the Belt Series in Montana; the intercept of the isochron has an initial $Sr^{87}:Sr^{86}$ ratio of 0.7075, which is consistent with a subsialic or mantle origin for the strontium (*21*).

Thus there is evidence that strata-form deposits, and possibly some having characteristics of a hydrothermal origin, were formed in active rift valleys or in areas under so much tension that fractures extended into the mantle to form channels for mineralizing solutions. The lead-isotope ratios for such deposits may be interpreted with a simple single-stage model (*11*). Measurements (*22*) on a sample from the Red Sea brine shows that the model lead age is zero as it should be. However, if the crust is very old and thick, some modification of the lead-isotope ratios may be anticipated because of contamination with lead formed in a sialic environment having highly variable lead, uranium, and thorium ratios. If rifting and the formation of hot pools were under a deep sea, the sulfur-isotope ratio would probably be close to the meteoritic value, since only chemical fractionation is involved. Under shallow seas, biogenic activity may be important, and the sulfur ratios may show large amounts of fractionation.

Perhaps the most significant finding is that the seismic-reflection method may be used to discover and map an ancient rift zone. In the search for oil it is used indirectly to locate suitable structural or stratigraphic traps. If major ore deposits lie within the confines of rift zones, seismology may be successful in mining exploration also.

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Alga-Like Forms in Onverwacht Series, South Africa: Oldest Recognized Lifelike Forms on Earth

Abstract. *Spheroidal and cupshaped, carbonaceous alga-like bodies, as well as filamentous structures and amorphous carbonaceous matter occur in sedimentary rocks of the Onverwacht Series (Swaziland System) in South Africa. The Onverwacht sediments are older than 3.2 eons, and they are probably the oldest, little-altered sedimentary rocks on Earth. The basal Onverwacht sediments lie approximately 10,000 meters stratigraphically below the Fig Tree sedimentary rocks, from which similar organic microstructures have been interpreted as alga-like microfossils. The Onverwacht spheroids and filaments are best preserved in black, carbon-rich cherts and siliceous argillites interlayered with thick sequences of lavas. These lifelike forms and the associated carbonaceous substances are probably biological in origin. If so, the origins of unicellular life on Earth are buried in older rocks now obliterated by igneous and metamorphic events.*

The search for evidence of early terrestrial life in the better preserved, old Precambrian sedimentary rocks has revealed a wide variety of unequivocal fossils as well as problematical structures and carbonaceous materials of uncertain origin (*1*). Some of the microstructures referred to as exhibiting "alga-like" and "filamentous" morphologies occur in carbonaceous argillites, siltstones, and cherts from South Africa that are more than 3 eons (3×10^9 years) old (*2, 3*).

The oldest unequivocal fossils are

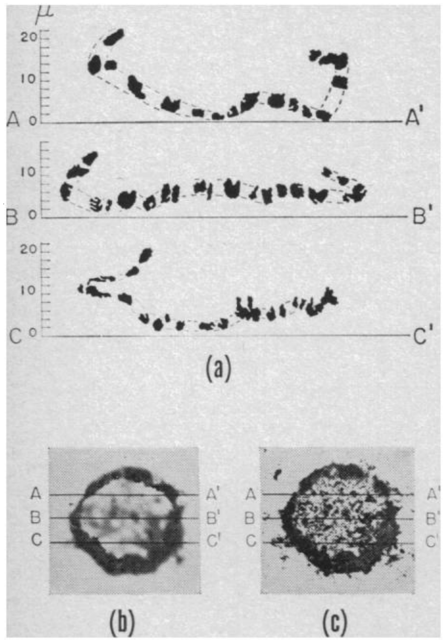

Fig. 1 (left top). (a–c) Photomicrograph and optical cross sections of one of the carbonaceous spheroids freed from the mineral matrix of the lower Onverwacht chert zone SF-77 by acid maceration; largest diameter, 74 μ. (a) Three cross sections constructed along lines *A–A′*, *B–B′* and *C–C′* from a total of 38 photomicrographs taken partly at 1-μ and partly at ½-μ intervals vertically through the object. (b) The same object at 4 μ above the base.

probably the laminated algal stromatolites found in carbonate rocks of the Bulawayan Series near Bulawayo, in southern Rhodesia (*4*). Although the age of the Bulawayan stromatolites is arguable and is based on a correlation of the Bulawayan type series with similar rocks approximately 300 km east-northeast, the geological relations in this region strongly suggest that these algal remains are at least 2.7 eons old, and possibly more than 3 eons old (*5*).

Recently, however, very old microfossil-like forms and carbonaceous matter have been found in the sedimentary rocks of the Fig Tree Series (*2, 3*). The Fig Tree is the middle member of the Precambrian Swaziland System, which is well exposed some 650 km south-southeast of Bulawayo, in the Barberton-Badplaace region of the eastern Transvaal, South Africa. In this region, (the Barberton Mountain Land) the Swaziland System is demonstrably older than 3 eons (*6*). Spheroidal organic bodies (that range from 5 to 25 μm in diameter) and filamentous wisps of carbonaceous matter are present in the Fig Tree Series. Rodlike to filamentous forms having the appearance of bacteria (*7*) and concentrically laminated "oolites" possibly of algal origin (*8*), have also been reported from the Fig Tree sediments. The Fig Tree spheroids have been interpreted as fossil algae by Pflug (*3*) and as alga-like microfossils by Schopf and Barghoorn (*2*); the carbonaceous filaments also may be algal in origin (*2, 3*). The spheroidal forms that Schopf and Barghoorn regard as remnants of unicellular, noncolonial, alga-like organisms, have been named *Archaeosphaeroides barbertonensis* (*2*). We observed similar organic spheroids and filaments in the Fig Tree beds and also in successively lower stratigraphic zones in the very thick underlying Onverwacht Series. The sedimentary rocks in the Onverwacht are probably the oldest exposed, well-preserved beds in South Africa and are perhaps the oldest exposed beds on the earth.

We note herein (i) the stratigraphic features and interrelations of the several rock series in the Swaziland System, (ii) the occurrence and morphology of abundant carbonaceous alga-like and filamentous forms in the Onverwacht sediments, and (iii) the presence of inorganic, siliceous spheroids that are morphologically suggestive of alga-like microfossils but definitely not of organic origin in associated basaltic lavas. These inorganic spheroids are illustrated to indicate the extreme caution necessary in the interpretation of the origin and occurrence of cell-like microscopic structures that occur in many rock types of diverse ages and origins throughout the Precambrian rock systems.

The Swaziland System is a remarkably complete, well-preserved, oceanic to island-arc and continental borderland sequence of volcanic and sedimentary rocks in the Rhodesian or South African

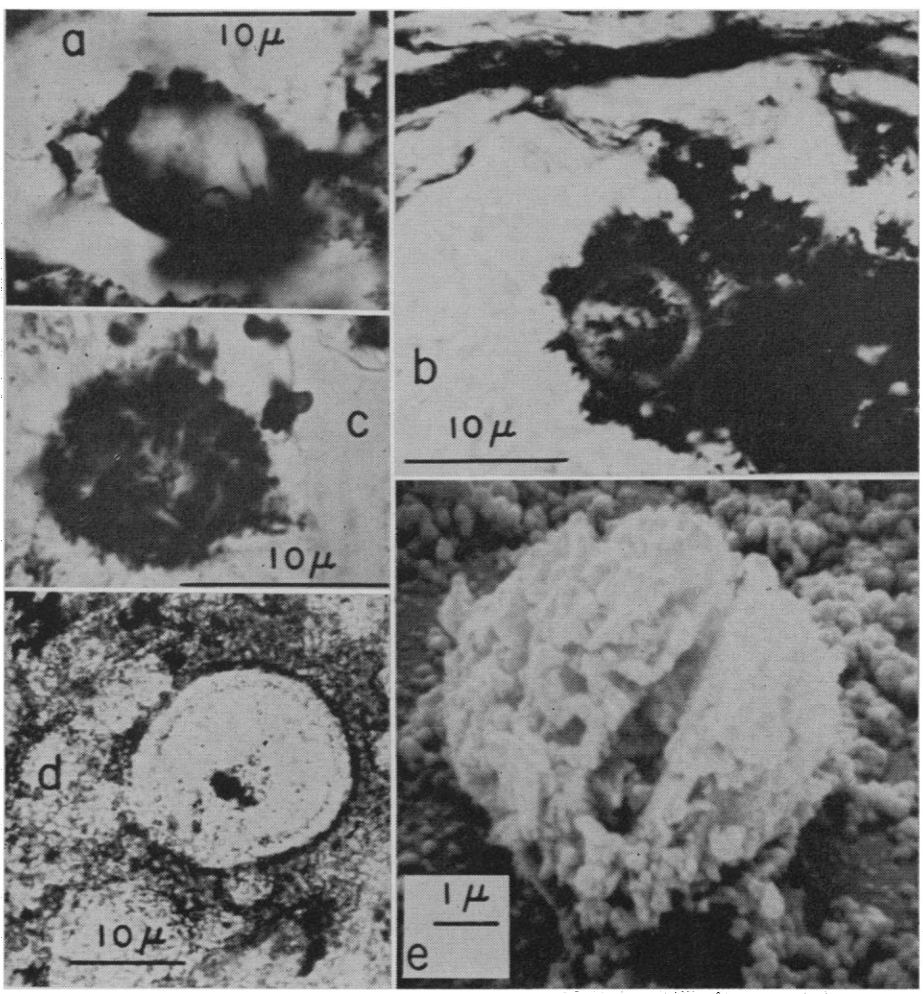

Fig. 2. (a) Thin section showing a spheroid from the lower chert zone SF-77. (b and c) Thin sections of carbonaceous argillite with spheroidal and filamentous forms from the upper Onverwacht sedimentary zone ACS-14; detailed microscopic examination of the round particle in (b) suggests it is cupshaped. (d) Thin section of Onverwacht pillow lava showing an inorganic spheroidal microstructure with a pseudo-"double wall" and central body. This is definitely nonbiological in origin. (e) An "organic" body from the lowest chert zone SF-77. This particle was freed from a preparation of powdered, carbonaceous chert by treatment with hot 6*N* HCl and hot 48 percent HF for 1 hour and was then coated with a thin layer of gold-palladium.

shield (9). Rocks of this system are in part sheared and faulted and in part undeformed. Most of the system is metamorphosed, commonly to the greenschist facies, although some segments, especially the marginal contacts with granitic rocks, are reconstituted into the amphibolite facies. In a few scattered areas, constituent igneous and sedimentary rocks are relatively free of metamorphic overprint. The Swaziland System is subdivided into three rock series. In order of decreasing geologic age these are: (i) Onverwacht Series, (ii) Fig Tree Series, and (iii) Moodies Series (9).

During the past 5 years the Onverwacht Series has been carefully studied and mapped by M. and R. Viljoen at and near the type locality (9). One of us (A.E.J.E.) has examined in detail many of the better exposed parts of the Onverwacht Series. In and near the Komati River Valley, 15 to 30 km east of Badplaace, many of the initial sedimentary and volcanic structures and textures are well preserved. The series consists largely of successions of ultramafic and mafic lavas with quite subordinate layers of dacitic agglomerate, tuff, chert, and clastic sediments. Beds of carbonaceous argillite and carbonate occur as interlayers with the cherts in the lower, middle, and upper Onverwacht.

The amounts of carbonate sediment are crudely proportional to the amount of chert and argillite. The lowermost sedimentary zone is largely tuff, with thin lenses of laminated, carbonaceous and white chert. Most of the sedimentary beds and the lavas were deposited in water. This is clearly indicated by graded- and cross-bedding, detailed and uniform laminations, and scour and fill structures in the sediments, and by numerous and widespread pillows in the associated lavas. The thickness of the Onverwacht at and near the type locality varies up to about 11,000 m.

The Onverwacht Series is overlain, in part unconformably, by the Fig Tree Series. The Fig Tree varies in thickness up to approximately 3600 m and consists largely of graywackes, carbonaceous argillites, arkoses, and argillaceous sandstones with subordinate amounts of banded, iron-bearing and carbonaceous cherts, tuffs, and conglomerates (9). Volcanic rocks are rare, except for the tuff components in the finer-grained clastic sediments.

The Fig Tree Series is, in turn, overlain unconformably by the Moodies Series, which consists mostly of arkosic sandstones, shales, and thick orthoquartzites which are in part recycled (9). The thickness of the Moodies also appears to vary up to approximately 3600 m.

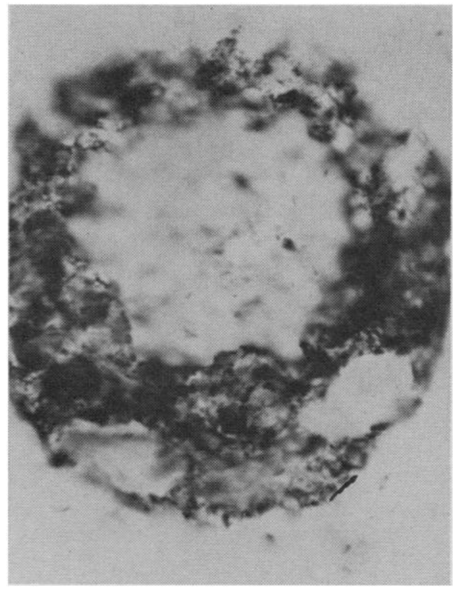

Fig. 3. Lifelike form, 106 μ in diameter, typical of many forms found in carbon-rich, siliceous sedimentary rocks of the Onverwacht series in South Africa.

In conjunction with detailed petrographic and chemical studies of sedimentary and igneous rocks of the Swaziland System, one of us (C.G.E.) isolated both siliceous and carbonaceous particles and carbonaceous filaments from cherts, argillites and carbonate beds. In the acid-resistant residues, filamentous and spheroidal alga-like forms of the types described from the Fig Tree (2, 3) were abundant. The Fig Tree and Onverwacht microstructures are similar in morphology, but the Onverwacht spheroids are commonly larger in size than the spheroidal bodies in the Fig Tree Series (2).

From studies to date, gradations in both size and form in the organic spheroids from the lowest Onverwacht beds to the lower Fig Tree rocks are suggested. The carbon-bearing filamentous forms are of diverse morphology.

Our morphological studies have been concentrated largely in two stratigraphic zones: (i) the lowermost sedimentary rocks in the Onverwacht (hereafter referred to as lower chert zone SF-77) which occurs 350 to 600 m above the contact of granitic gneisses and granodioritic plutons with the oldest recognizable Onverwacht lavas, and some 10,000 m below the base of the Fig Tree, and (ii) carbonaceous chert and argillite in the upper Onverwacht (referred to as ACS-14) roughly 2500 m below the base of the Fig Tree Series and approximately 7500 m stratigraphically above the lower chert zone SF-77. Several studies have been made of the organic geochemistry of the Fig Tree sediments (10). Our analysis of the Onverwacht carbonaceous matter is incomplete. They are involved mainly with the insoluble kerogen fraction because

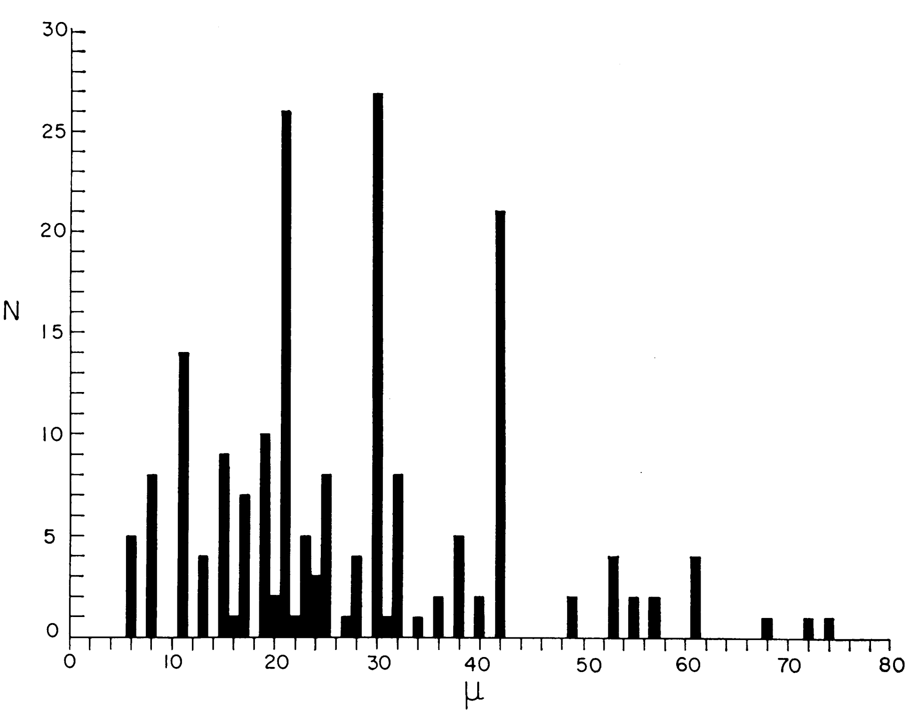

Fig. 4. Size distributions of 190 spheroidal particles in the Onverwacht lower chert zone SF–77. Note the large range in diameter of the 190 spheroids measured and what may be a polymodal size-frequency distribution.

solutions percolating through the beds during geologic time may contaminate these sediments with soluble organic material of younger geologic age. Initial analyses indicate a kerogen which is largely aromatic in composition. In contrast, much of the Fig Tree kerogen is essentially aliphatic (*11*).

In both the carbonaceous chert zones (SF-77 and ACS-14) spheroidal forms are more common than the filamentous forms. The microstructures were studied in thin sections of the rocks and in powdered preparations. Some of the powdered rock was treated with hot 6*N* HCl and then with hot 48 percent HF for 1 hour, and then the acid-resistant residues were examined. Most of the spheroidal structures found in powdered preparations and in thin sections are cupshaped (Fig. 1, a–c). The Fig Tree spheroids reported by Schopf and Barghoorn have a maximum size of 24 μm and a mean of about 19 (*2*). The largest Fig Tree spheroids we have seen are about 30 μm in diameter. Many spheroids in the Onverwacht are much larger (Fig. 3). The spheroidal particles in both Fig Tree and Onverwacht are definitely indigenous to the sedimentary beds as is indicated by their presence in thin sections of the rocks [Figs. 2 (a–c) and 3].

Thin sections of the Onverwacht lavas also contain inorganic spheroids that approach in morphology the alga-like forms in the associated sediment (Fig. 4). Many of the spheroids in the lavas tend to be precisely shaped and they possess distinctive, if pseudo, double walls. Several microbiologists who examined the thin sections, but who were not told that the enclosing rock is of igneous origin, interpreted these forms found in the pillow lavas as definite remains of unicellular life. A photomicrograph of one of these pseudomicrofossils with a double wall is shown in Fig. 2d. Two of us (C.G.E. and A.E.J.E.) have observed a wide variety of equally lifelike mineral artifacts in diverse rock types. Bramlette (*12*) has noted the problem, and most petrographers and some micropaleontologists are aware that fossillike forms are commonly produced by inorganic processes. It is impossible that any of these forms in the altered igneous rocks are fossil remnants of life. It could be inferred that some of the lifelike microstructures in the Onverwacht and Fig Tree sedimentary rocks may have had their source in weathered or tectonically disintegrated and eroded igneous rocks, or as products of other nonbiological processes.

However, the spheroids within the carbonaceous Onverwacht sediments not only have the morphologies of fossils, but also are intimately associated with the kerogen-bearing carbonaceous substances which appear to form parts of their walls and interiors. They are also closely associated with kerogenbearing, filamentous forms which have the appearance of microfossils (*2*). These features and relations suggest that the enclosed carbonaceous, spheroidal, and filamentous forms may be microfossils.

Difficulties of interpretation of the carbonaceous filaments are, however, apparent from inspection of Fig. 2b. The filamentous layers in this carbonaceous argillic chert are of diverse morphology, many remarkably lifelike, similar to those found in the Fig Tree (*2*). Some of these filaments are probably carbonaceous material of accidental form, distributed unevenly and also in regular geometric patterns along the bedding planes by sedimentary and diagenetic processes. But many appear to be true fossils, although less well preserved than those found in younger Precambrian sediments (*1*).

Establishing the presence of biological activity during the very early Precambrian clearly poses difficult problems. Although the Fig Tree and Onverwacht organic spheroids and filaments are probably of biological origin, skepticism about this sort of evidence of early Precambrian life is appropriate. Unfortunately, little-altered sedimentary rocks as old or older than the Onverwacht chert SF-77 are unknown on Earth. If the carbonaceous forms in the Onverwacht are fossils, the origin of unicellular life presumably has occurred in still older rocks destroyed by superimposed igneous and metamorphic episodes in the evolving earth.

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