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The Geological Setting of the Earliest Life Forms

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Summary. Life on Earth may have begun about 4×10^9 years (4 Ga) ago. Plate tectonics probably operated in the early Archaean, with rapid spreading at mid-ocean ridges, a komatiitic (magnesium-rich) oceanic crust, active volcanic arcs and the development of extensional basins on continental crust. Shallow water environments would have been more restricted and probably shorter-lived than in later geological times; however, extensive shallow seas existed in the later phases of the development of extensional basins. Bacterial communities—presumably photosynthetic—have probably existed in such shallow-water settings and probably at shallow depths in the oceans for at least 3.5 Ga. Because the mid-ocean ridges were probably subaqueous, hydrothermal systems would have been very vigorous and would have offered suitable habitats for early chemo-autotrophic bacterial communities. Early life forms probably also occupied vesicles in lavas, pumice and volcanic breccias, and pores in soft sediments, living in the constant flux of fluid flushing through permeable strata. Other, similar habitats would have existed in volcanic island arcs and in extensional basins.

Key words: Early life — Stromatolites.

Introduction

Life on Earth seems to have begun around or before 4×10^9 years (4 Ga) ago. There is evidence that life was flourishing 3.6 GA ago (Buick et al. 1981), and weak evidence for life 3.8 Ga ago (Schidlowski 1980), but it is difficult to imagine how life could have existed on Earth in the earliest part of the planet's history. Probably, life began between 3.8 and 4.2 Ga ago (Nisbet 1980; Nisbet and Pillinger 1981). Since that time, living organisms have influenced or controlled the environment of the Earth's surface, avoiding the perils of both a runaway 'greenhouse' (as on Venus) and runaway glaciation (as on Mars).

In the past decade substantial advances have been made in the geological understanding of the Archaean Earth in the period 3.8–2.5 Ga ago. The purpose of this paper is to review this geological information gained from the study of very old terrains, and to make available to biologists a variety of geologically based speculations while warning them that most geological speculation about the Archaean is precisely that; proof is exceedingly difficult.

Offprint request to: E.G. Nisbet

Geological Setting

It is fairly certain that the dichotomy between continents and oceans is as old as the geological record. Well established continental nuclei 3.8–3.6 Ga old are preserved in Australia, Southern Africa and Greenland. Metamorphic and sedimentological assemblages in some areas (see, e.g., Chinner and Sweatman 1968; Bickle et al. 1975; Boak and Dymek 1982) imply that the continents were thick and in some places probably had considerable relief. Mountains of moderate height may have existed, although the hotter and less viscous mantle (McKenzie and Weiss 1978) may not have supported relief contrasts as great as are found today. The relatively cool metamorphic temperatures in the continents can be interpreted as implying that the Earth's heat loss occurred mainly by active volcanism in the oceans (Bickle 1978).

In the modern Earth the majority of the total heat loss from the interior of the planet is dissipated by the process of plate tectonics. New material rises up from the mantle at ca. 1350°C, reaches the surface at mid-ocean ridges, cools and spreads away in mechanically strong plates overlying a viscous 'asthenosphere.' The cool strong lid, or 'lithosphere,' becomes denser than the underlying hot mantle as it cools, and eventually falls back into the mantle in subduction zones (Richter and McKenzie 1978).

This process is responsible for most modern volcanoes. Bickle (1978) demonstrated that the Earth's thermal budget in the Archaean would have demanded much more vigorous plate creation and destruction than occurs today, in order to dissipate some of the heat transported from the hot Archaean mantle, which contained 3–4 times as much radioactive K, U and Th as it does today and may also have retained considerable heat from the accretion of the Earth. Nisbet (1982), Arndt (1983) and Nisbet and Fowler (1983) have pointed out that in Archaean time the primary igneous melts rising up from the mantle were probably not at 1350°C as today, but may have been as hot as ca. 1700°C or more. Young modern oceanic crust is basaltic in its upper layers, whereas Archaean oceanic crust was probably komatiitic, a lava type erupted at higher temperature and with a more magnesian composition.

This thermal history has major biological implications. Current estimates are that in the modern Earth a quarter of the total global heat loss occurs by hydrothermal cooling of the lavas erupted at mid-ocean ridges. In order that this may take place, the equivalent of the entire volume of sea water is circulated through the mid-ocean ridge lavas every 8–10 million years (see, e.g., van Andel 1983). In the Archaean, with more heat dissipated from a komatiitic oceanic crust, and with an ocean deep enough to cover the ridges (Nisbet 1984), this circulation time could have been as much as an order of magnitude less: The equivalent of the total volume of sea water probably passed through the mid-ocean ridges every million years or so. This is based on the assumption that the Archaean mid-ocean ridges were subaqueous, as today, an assumption supported by the available geological evidence (Nisbet 1984). The significance of the hydration of the ridges is discussed below.

Various authors (e.g., Edmond and von Damm 1983) have shown that a principal control on the chemistry of modern sea water is the exchange with basalt during hydrothermal circulation. Such circulation would have been much more intense in the Archaean and for most chemical species would have dominated more minor factors such as continental runoff. In the Archaean the volume and the chemistry of sea water, and probably the amount of free CO_2 on the Earth's surface, would have depended heavily on the reactions taking place during this circulation.

On continental margins, processes in the Archaean were probably broadly analogous to modern equivalents. Subduction, the process whereby the oceanic lithosphere is destroyed, probably took place very rapidly and vigorously, with relatively thin (in comparison to today) slabs of lithosphere plunging into the hot, low-viscosity asthenosphere. Thick sequences of calc-alkaline lavas and granites (rocks similar to lavas and intrusions found today in the western margins of the Americas) are found in Archaean geological terrains; some of these may have been produced by eruptions above subduction zones (e.g., see Wilson 1979).

Within the Archaean continents sedimentary basins existed, including basins with extensive shallow-water environments (Barley et al. 1979). McKenzie et al. (1980) suggested that many of these basins were formed by extension of the lithosphere. In highly extended basins volcanism would begin (Le Pichon and Sibuet 1981). Various authors (e.g., McKenzie et al. 1980) have suggested that this is the setting in which were formed the Archaean rocks now preserved in some 'greenstone belts.' Greenstone belts (Condie 1981) are assemblages of Archaean volcanic and sedimentary rocks that sometimes include very well-preserved Archaean biogenic sediments. Figure 1 is a general sketch of the various geological environments on the surface of the Archaean earth.

The Location of Early Life

Oceanic crust is not usually preserved in the geological record. The ocean floor is created, lasts a hundred million years or so, and is then destroyed. With just possibly two exceptions, in Barberton, South Africa (de Wit 1982), and in the West Pilbara, Australia (Nisbet and Chinner 1981), no Archaean oceanic crust is preserved or suspected to be preserved. Thus our evidence for early life comes from continental rocks, and the geological record is thereby biassed.

Most of the evidence for early life available to the geologist comes from the study of stromatolites (Fig. 2). These are structures formed in carbonate rocks that were laid down in shallow water or in intertidal settings. They are thought to have been produced, in the main, by cyanobacteria. Modern analogues exist and have been studied in detail, especially in Shark Bay, Western Australia, where stromatolite forms occur that are very closely comparable to the Archaean examples (Walter 1977).

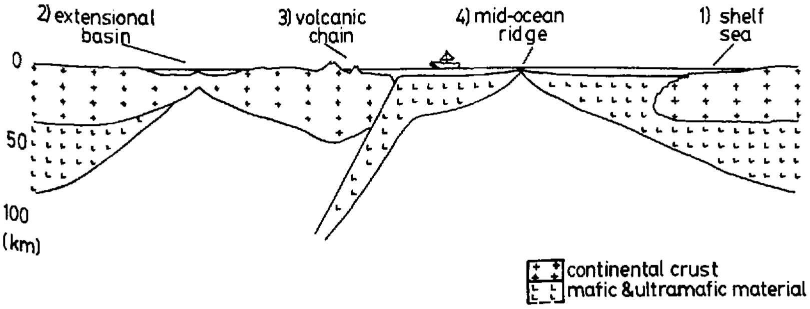

Fig. 1. Sketch illustrating possible settings in which early life forms may have lived. There is good evidence to suggest that extensive deep oceans existed on the Archaean Earth (Campbell and Taylor 1983). Thus pelagic life depending on photosynthesis in the top few tens of metres of water could have existed over much of the Earth's surface. (1) Shallow shelf seas on continental margins. Continents and shallow water sediments are as old as the geological record, though shelf seas may not have been as extensive in the Archaean as in much of the more recent geological record. Life in this setting would depend on photosynthesis and would occupy the shallow sea floor. (2) Extensional basins. Many Archaean sedimentary basins probably formed during subsidence following extension of continents. Figure 4 gives a more detailed sketch of this setting. (3) Volcanic chains on continental margins above subduction zones, or as island arcs above subduction zones within oceans. Here hydrothermal systems would have been active and long-lived, and associated with areas of shallow sea floor if the volcanoes were subaerial. Chemo-autotrophic life could live around the volcanoes, and photosynthetic life on the shallow parts of the surrounding sea floor. (4) Mid-ocean ridges. Hydrothermal systems on Archaean mid-ocean ridges may have supported flourishing communities of chemo-autotrophic life

Stromatolites are well developed in 2.7-Ga-old strata (Martin et al. 1980), and there have been various claims that stromatolites have been identified in 3.5- to 3.6-Ga-old rocks (Walter et al. 1980; Buick et al. 1981; de Wit et al. 1981). The discussion by Buick et al. (1981) is thorough and rigorous; one may conclude that in some of the claims for 3.5-Ga-old life, the evidence is good enough for us to be fairly confident (although not totally sure) that *life in shallow water* did indeed exist 3.5 Ga ago. However, most claims about the morphology of 3.5-Ga-old bacteria or about their kerogen *should be discounted*; *the evidence is too poor*. Schopf and Walter (1983) considered the 43 categories of putative microfossils reported from Archaean rocks and showed that at least 41 should be discounted. Buick et al. (1981) strongly attacked one of the surviving claims (from the Pilbara), which leaves only a single as-yet-undisputed example of old microfossils, from the Fortescue Group (Schopf and Walter 1983). This latter example is of early Proterozoic or latest Archaean age (Blake 1984). The better evidence that has been left to us in stromatolites consists not of microfossils, but rather of the degraded products of mat structures that grew in shallow coastal environments.

Calcareous sediments of Archaean age are very rare, and constitute only a minor component of the Archaean geological record. However, this rarity is probably in large part a consequence of chance of preservation in the Archaean tectonic regime. Thus, though Archaean stromatolites are rare, it is probable that, at least by the late Archaean, bacterial life occupied all available niches. As a modern parallel, California, for instance, has few shallow-water limestones in its geological record, yet there is no evidence that life in California has been either sparse in character or unusual in its behaviour (at least until recently).

It is probable, then, that life occupied much of the Archaean coastline where conditions were sufficiently protected from terrigenous detritus to allow bacterial mats to grow. It is also probable, though there is as yet only tenuous evidence, and no macroscopic evidence, that other environmental settings allowed biological activity. For instance, Schidlowski (1979) has argued that the bulk of the sulphate in Archaean oceans was probably produced by photosynthetic sulphur bacteria. Isotopic evidence from banded ironstones (Schidlowski 1979) and the presence of sulphate evaporites 3.5 Ga ago (Buick et al. 1981) thus imply the widespread existence of life, although much of it may have lived in environments where there was little chance of preservation, such as at shallow levels in the oceans. The setting was probably mildly oxidizing.

Corliss et al. (1981) have recently pointed out that Archaean life could have existed in a quite different environment: in submarine hydrothermal systems. They argue strongly that this is the most probable birthplace of life [if indeed life did begin on Earth (see Crick 1981)]. However, any geological evidence that is used to support this argument is controversial in the extreme. It is safer to assume that there is as yet no generally accepted geological evidence for organic remains in hydrothermally deposited early Archaean rocks. This is not to dispute Corliss et al.'s proposal; rather, it is to point out that the proposal is so seductively attractive to the geologist that any evidence adduced in its favour must be examined with great caution.

Archaean oceanic hydrothermal systems cannot

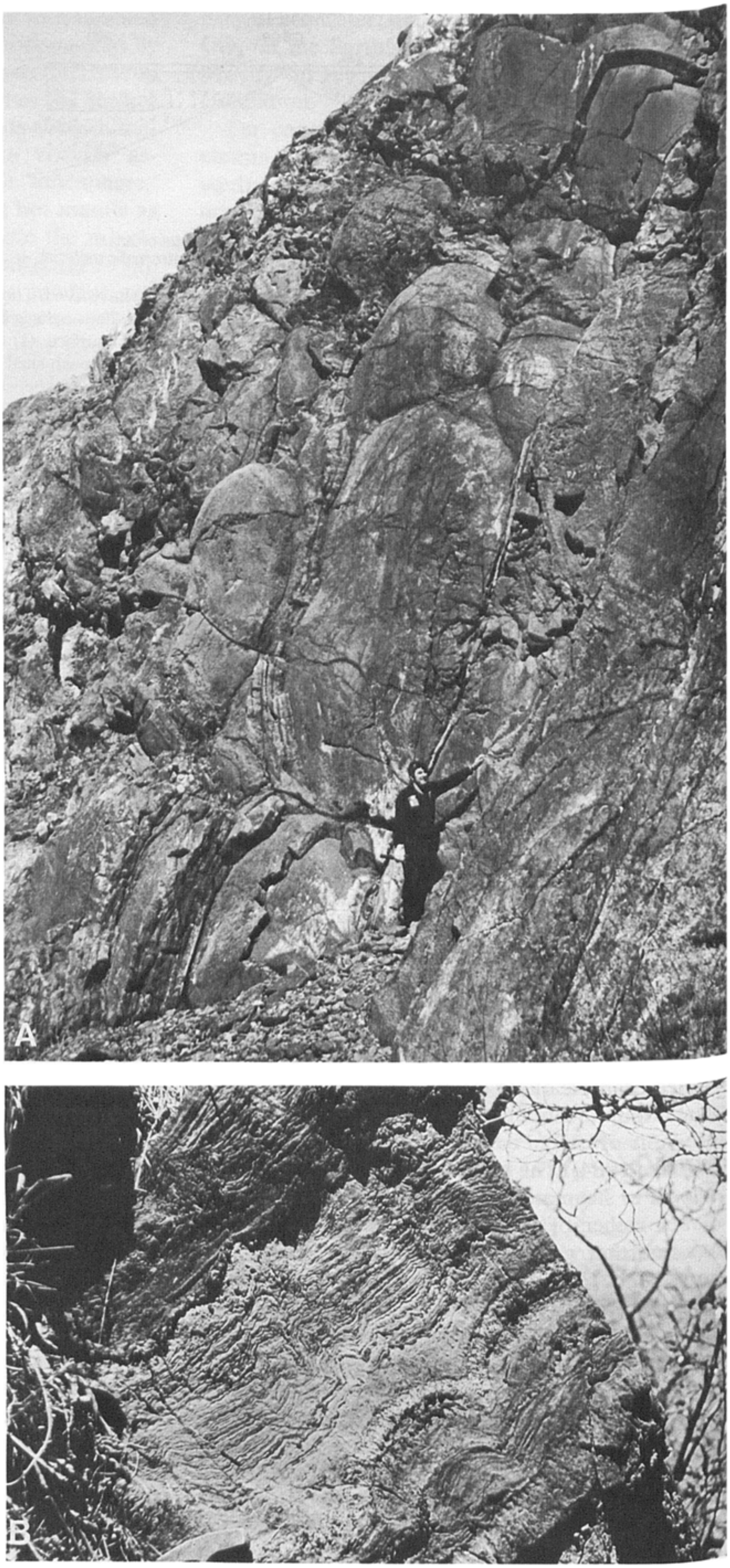

Fig. 2a, b. Examples of stromatolites from well-preserved Archaean rocks. **a** Large-scale stromatolite domes, Steep Rock Lake, Canada, approximately 2.7 Ga old. Bedding dips steeply as a result of deformation. Original way up is to the left. **b** Detail of stromatolite morphology, Cheshire Formation, Belingwe Greenstone Belt, Zimbabwe, 2.7 Ga old. Scale is given by hammer at bottom left. Preservation of original fabric in the rock is excellent; photo by MJ Bickle

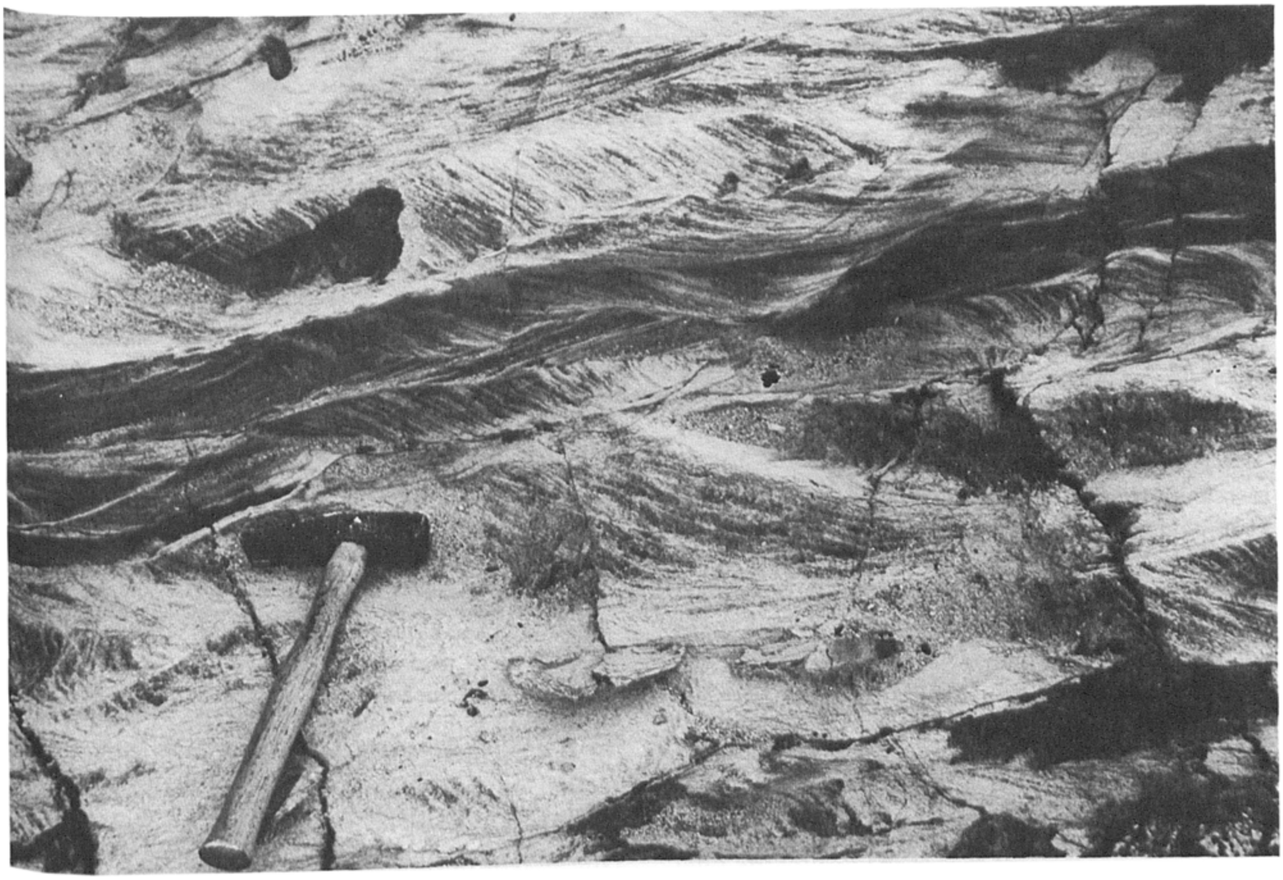

Fig. 3. Shallow-water sediment, Barberton Greenstone Belt, South Africa, ca. 3.5 Ga old. Note similarity to modern cross-bedded sands

have been preserved except by extraordinary accident, since Archaean oceans were destroyed, probably by plate tectonics (Nisbet and Fowler 1983). However, hydrothermal systems in greenstone belts *have* been preserved (e.g., Fripp 1976). Although, as stated above, there is no generally accepted evidence for organic remains in Archaean hydrothermal vein deposits, there are widespread occurrences of 'graphite' (black, carbonaceous matter) in Archaean volcanogenic or exhalative mineral deposits. Corliss et al. (1981) pointed to these as possible evidence of life. For example, Worst (1956) reported extensive 'graphite' in the Agincourt mine, Belingwe Greenstone Belt, Zimbabwe, in what appears to be an auriferous and sulphide-rich vent of a hydrothermal system. This system, at the top of a thick volcanic unit, appears to have been very slightly older than the nearby lagoonal stromatolites (Martin et al. 1980). If the 'graphite' is indeed organic in origin, it is quite probable that in the Belingwe area the growth of 'cyanobacteria' in a coastal lagoon took place at the same time that other bacterial communities were thriving in the contemporaneously active hydrothermal vents nearby. A similar association between carbon-rich sulphide deposits and stromatolites occurs at Steep Rock Lake, Canada.

Too much weight should not be placed on this or other unproven examples, but the Archaean association of hydrothermal systems (whether or not the graphite is organic in origin) with nearby stromatolites (e.g., Jolliffe 1955) is especially interesting in view of the very small number of Archaean stromatolites known. Corliss et al.'s (1981) speculation remains speculation, but it is of very great interest.

Specific Settings in which Life May Have Flourished during the Archaean

Figure 1 shows several settings in which Archaean life may have flourished. These settings are regarded as the environments most likely to have contained abundant communities of bacteria, as in these settings the prerequisites for such life—free energy and water—would most readily have been available. Other settings, especially in the surface layers of the oceans, may well have hosted abundant life, but are not now geologically accessible except by stable-isotope detective work.

1. Shallow Waters

Continents have existed since the beginning of the geological record. Since erosion tends to reduce them

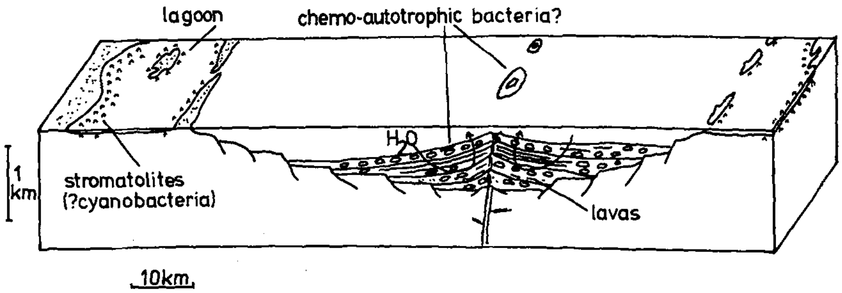

Fig. 4. Environmental settings in an extensional basin on Archaean continental crust. Some greenstone belts may have formed in basins similar to this as a result of stretching of the continental lithosphere. Note shallow-water lagoonal conditions on margin of basin, in which photosynthetic cyanobacterial communities producing stromatolites may have grown (see, e.g., Martin et al. 1980). In centre of basin the volcanic axis would have hosted active hydrothermal systems that may have sustained communities of chemo-autotrophic bacteria

to sea level, throughout geological time there has been shallow water around the edges of continents and in basins where the continents have been pulled apart. Figure 3 shows a 3.5-Ga-old example of a very-shallow-water sandy sediment from the Barberton Mountain Land. The stromatolites grew in shallow-water settings protected from excessive sedimentation (Figs. 2 and 4). Cyanobacteria probably formed most of the biota; sulphate reduction probably took place (Schidlowski 1979) and it is possible that diverse bacterial communities existed wherever the conditions were right. By the late Archaean thick, reeflike bodies of carbonate rock were being formed in areas such as Belingwe.

This bacterial community would have relied on photosynthesis, but would not have existed solely at the sediment–water interface, building upwards: Bacteria would probably also have lived in the soft sediment below the interface. In intertidal settings there is a constant flux of water of varying temperature, oxidation state and salinity through the unconsolidated sediments. If organic molecules were present in the water, they would have been trapped in the sediment filter.

Shallow-water rocks do stand a chance of being preserved in the geological record, though all have undergone some degree of metamorphism that has degraded the biological information in them. Nevertheless, despite the degradation, the close similarity between ancient and modern stromatolites and the existence of ancient stromatolites in shallow-water settings (Martin et al. 1980; Buick et al. 1981) argues strongly for photosynthesis being a process at least 3.5 Ga old. This is consistent with the isotopic evidence available (Schidlowski et al. 1983).

2. *Volcanism in Extensional Basins*

Some years ago it was pointed out that many (though not all) of the preserved sequences of Archaean sediments may have been formed in extensional basins similar to the modern North Sea basin (McKenzie et al. 1980). In such basins regional tensional forces pull apart continental crust and the underlying lithosphere. The consequence is immediate rapid subsidence in the extended region, followed by infilling by sediment and then a long period of slow deposition in widespread shallow waters. If the degree of stretching is great, volcanism begins in the centre of the basin and volcanoes are built up on continental crust, erupting through and over the early sediment infill. The stratigraphy of the Belingwe Greenstone Belt has been interpreted in this way (McKenzie et al. 1980), as have successions in the Pilbara and Witwatersrand (Bickle and Eriksson 1982).

In such basins life probably existed in shallow water as described above. However, non-photosynthetic life may also have existed. At the volcanic centres, the hydrothermal circulation would have developed around active volcanic vents. Water would have entered on the flanks of submarine volcanoes and exited close to the axis of the volcano. In modern volcanoes, especially those of the mid-ocean ridges, biological activity plays a major role in controlling the chemistry of the fluids passing through and out of such hydrothermal systems. Sulphate from the sea water entering the systems reacts with iron in the rock to produce hydrogen sulphide and iron oxides, while sulphide minerals in rock are dissolved. Consequently, the water rising back to the surface to leave the system is heavily charged with sulphide. The water leaves at distinct vents on the sea floor, where hydrogen sulphide is absorbed by the bacteria that also take up oxygen from the surrounding sea water (this oxygen being of photosynthetic origin). The sulphide-to-sulphate reaction drives the bacterial metabolism (Edmond and von Damm 1983).

Could this have taken place in the Archaean? The answer is most probably yes. As noted above, bacterial sulphate reduction may be as old as the geological record (Schidlowski 1979). The association

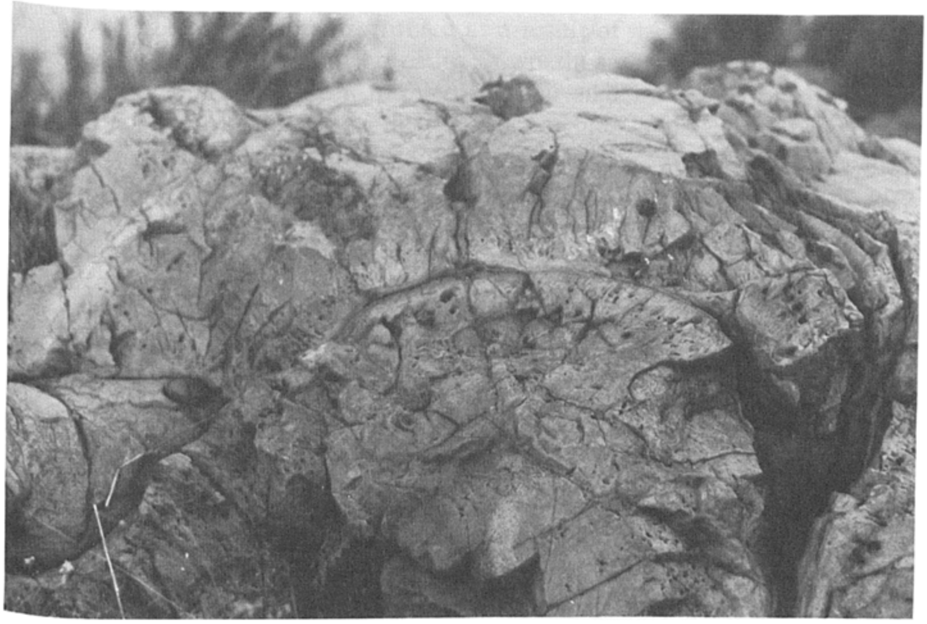

Fig. 5. Submarine pillow lava, Barberton Greenstone Belt, 3.5 Ga old. Note vesicles (holes). Most sea floor volcanic debris is far more fractured, permeable or vesicular (e.g., pillow breccia, pumice, explosion debris, tuff). Lens cap (left) gives scale

between stromatolites and active volcanic centres has already been commented upon. In the Belingwe belt extensive stromatolites vertically overlie thick mafic volcanics that show in places the effects of extensive hydrothermal alteration (Martin et al. 1980). In the Steep Rock deposit, Ontario, stromatolites and volcanic centres are intimately juxtaposed. This is not to imply that stromatolites grew only in close association with active volcanism, but it is interesting that a chemical cycle of modern aspect may have existed in the later Archaean.

3. *Volcanism in Island Arcs*

Today long chains of volcanic islands exist above subduction zones where oceanic crust is consumed. Examples include the Aleutian Islands and many of the western Pacific islands. In these settings active volcanism takes place in the same place for millions of years, and volcanoes are built up from the ocean floor to shallow depths or as subaerial piles. Hydrothermal circulation develops around active volcanoes. In similar settings in the Archaean a bacterial community could have existed consisting of anaerobic chemo-autotrophs deriving their energy from oxidation–reduction reactions with hydrothermally transported gases.

In further discussing hydrothermal systems, it is important to note that most high-level igneous rocks are to some extent porous. Lavas that erupt and cool on the seabed are typically vesicular (Fig. 5); that is, they contain abundant small pores created by degassing during cooling. More than that, some island arc volcanism is characteristically explosive; the rock is often fractured and becomes a breccia. This is a characteristic feature of some massive sulphide deposits, in which hydrothermal systems preferentially 'choose' fractured and porous rocks as flow pathways. The volumes of fluid passing through the rock are immense, and even in unfractured rock vast volumes of fluid permeate and extensively alter the mineralogy of the rock. A significant feature of island arc volcanism is that this process can be long-lived in some places, in contrast to similar hydrothermal processes at mid-ocean ridges, described below. Although some Archaean arcs of this nature may have been preserved, there is as yet no clear evidence for (or against) the presence of life in them. Hydrothermal systems have been widely identified, because they often host gold mines (see above), and graphite is a common component of these systems. However, no evidence has been found to show whether the graphite had an organic origin, although Schidlowski (1980) considers the carbon cycle to have been controlled by organisms since 3.8 Ga ago.

4. *Mid-ocean Ridges*

The sulphide deposits and bacterial communities of modern mid-ocean ridges are very well known (Edmond and von Damm 1983). Active spreading centres probably existed in the Archaean, but may have been komatiitic rather than basaltic in character. In other words, a more magnesian and much hotter igneous liquid may have fed the volcanism. Sea floor spreading rates would probably have been rather higher, with the amount of heat loss annually to the sea by hydrothermal cooling much more than it is today.

The mid-ocean ridge hydrothermal circulation is today one of the most important of the factors controlling sea water chemistry and, by association, at-

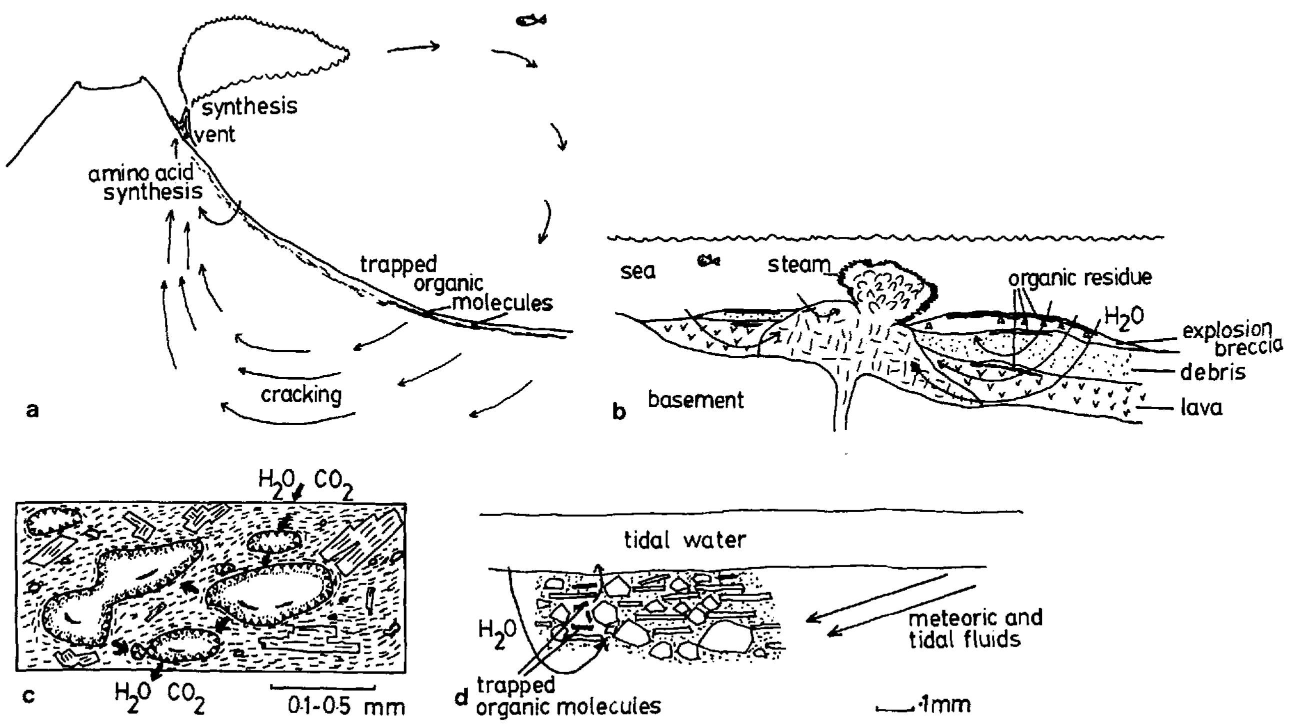

Fig. 6a–d. a Hydrothermal circulation around sea-floor vent in underwater setting. b Silicic volcanism on sea floor. Note explosion debris. c Fluid movement through vesicular or brecciated rock. Rock consisted of crystalline laths (e.g. feldspar, pyroxene) and altered glassy matrix. Longer organic molecules would have been trapped in open spaces. d Water circulation through soft sediment in shallow or intertidal setting

mospheric chemistry. In the Archaean the ridge circulation would most probably have been a dominant control on the abundance of many chemical species in sea water. Any primordial organic 'soup' would have rapidly (in geological terms) been passed through the ridges. Organic molecules would have been trapped in the pores of the intake network of the hydrothermal systems or would have penetrated rapidly to regions with temperatures of several hundred degrees centigrade. Pyrolysis there would have been rapid. The fluids would have left under pressure at temperatures close to the boiling point. For a soup to have existed in the open ocean, production of organic molecules by ultraviolet radiation, lightning, etc. would have to have been faster than destruction of the soup at the ridge. Otherwise (and probably) the soup would have been reduced to a most tenuous consommé of floating molecules, something interesting but not life-nourishing.

Corliss et al. (1981) have pointed out that the ridge environment probably sustained a flourishing community of anaerobic chemo-autotrophs. Indeed, this may have been the dominant early Archaean biological community and the particular home of a wide variety of bacteria, especially archaebacteria (Fox et al. 1980; Woese 1981; Kaine et al. 1983). Moreover, Corliss et al. (1981) suggested that life may have begun in this setting. Although the subject of this review is the setting, not the origin, of Archaean life, it is worth digressing here to consider the problem of the origin of life, to discuss and amplify Corliss et al.'s suggestion. If the first life were chemo-autotrophic, where would it have begun? The most likely sites are in the exit chimneys of the hydrothermal systems, at the sediment–water interface above the intakes of such systems, or in vesicles in the rock (Fig. 6) through which large quantities of fluid passed; all three of these sites were in the hydrothermal systems, not in the ocean. Corliss et al. showed that amino acids could have been synthesized and preserved in exit vents; simultaneously, organic molecules in the water would have been trapped by filtration through the intake regions, thus building up deposits of complex organic compounds.

Cairns-Smith (1982) has pointed out the possible role of clay minerals and zeolite minerals in assembling proto-life chains of nucleotides. For life to have begun in open water, it would need to have been encapsulated ab initio in some sort of containing membrane of lipids (unless it was seeded from outside the planet). On the other hand, life could have begun in a small vesicle or cavity in porous rock or within permeable sediment in a hydrothermal system. Such a cavity would have sat in a steady flux of CO_2, H_2O, H_2S, short-chain organic molecules and minerals dissolved in the circulating brine. If, as Cairns-Smith has suggested, complex chains of nucleotides were assembled as a result of catalysis by minerals lining the cavity, then those long chains would have been trapped by their size within that cavity. If a self-replicating system had formed, it would thus have maintained access to its long daughter molecules during replication, in contrast to the situation in the open ocean, where a replicating molecule would not necessarily have been born within a containing membrane. Periodically in an active volcano or spreading centre, earthquakes and eruptions would have opened inter-pore gaps; thus a self-replicating system born in a rock vesicle could colonise a large region around its birthplace in pores in soft sediment, pumice breccia or lava. In such a setting, mineral catalysis might later have become a capricious nuisance to self-replication. A system that could surround itself with lipids would thus have been at a great evolutionary advantage: It would have been pre-adapted to life in the open ocean.

Oceans, Continents, Life—A Mutual Dependence?

Earth is the most extraordinary of planets; not least amongst its extraordinary features is that it is covered by oceans of water and has been so covered for as long as there is geological evidence. Campbell and Taylor (1983) recently suggested that it is only because water is present above mid-ocean ridges that the continents exist: Without water, there would be no granites; without granites, there would be no continents. Puddles of water, or water as ice or vapour, would not have done—the oceans must have been deep enough to cover the mid-ocean ridges, which would have stood 1.5–2 km higher than the abyssal plain in Archaean time. Only then would hydrothermal systems have been able to introduce water to the oceanic crust, and only then would the crust have been able to take water down subduction zones to produce granites. In this context, the processes by which the Earth's surface temperatures were controlled within the range at which water is liquid are of great interest. Henderson-Sellers and Cogley (1982) considered the possibility that during the 7×10^8 years preceding the deposition of the oldest sediments self-regulating inorganic mechanisms prevented runaway glaciation or a runaway greenhouse; they considered both gradual outgassing and a massive CO_2 atmosphere unlikely. This inorganic self-regulation is perhaps consistent with the anthropic principle. However, although rapid degassing took place soon after the accretion of the Earth, there is strong evidence for continuous outgassing of CO_2 throughout the Earth's history (Javoy et al. 1982). Various authors (e.g., Schidlowski 1980; Margulis and Stolz 1983) have pointed out that there is evidence for Lovelock's Gaia hypothesis that life has maintained a homeostasis: It has controlled CO_2 levels for at least the last $3.5–4 \times 10^9$ years. If this is so, then the continued existence through geological time of oceans and continents is in a sense dependent on the presence of life on Earth; thus the three may be mutually interdependent. Life needed oceans to begin, and then complex organisms needed shallow water on continental edges and much later subaerial environments on the continents to flourish, but once life had begun and had passed the first crisis of CO_2 balance (posed by the appearance of life), it may have been instrumental in maintaining and creating those conditions most suitable for itself. Again the anthropic principle enters: On how many planets has life managed the first enormous hurdle, i.e., replicating, only to destroy its protective greenhouse or to remain confined to shallow oceans on a landless, continent-free planet on which mid-ocean ridges are subaerial?

All this is interesting but unprovable. Geology is a science that has as its experiment the ruins of time. It is as if, after some nuclear cataclysm, an extraterrestrial visitor were attempting to reconstruct all of molecular biology from a miraculously preserved pile of submitted manuscripts in the basement of the office of the *Journal of Molecular Evolution.* The information would be partial; furthermore, some would need rejecting; some would be correct. The surface of the modern Earth is reasonably well understood, but most of our models of the Archaean Earth are simply that—models, not fact. The facts are in part available in the geological record, but the models are simply hypotheses, 'respectable' but not proven, in contrast to our knowledge of the modern Earth. To illustrate this point, we need only consider that it is mainly Occam's razor that deters the hypothesis that the dinosaurs—the last of which were very advanced—in their last few thousand years became intelligent and thereby managed to destroy themselves. With our present evidence it would be difficult to disprove such a theory, but it is contrary to our uniformitarian intuition, so the theory is not entertained (though it is entertaining). The Archaean models proposed are stronger, in that they are consistent with both evidence and intuition. Further detailed field work and detailed experimental investigation (especially of hydrothermal systems) can provide evidence with which to test the hypotheses; eventually a detailed geological understanding of the Archaean geological environment may provide the substrate for a molecular explanation of how life began.

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