Archaean Soils, Lakes and Springs: Looking for Signs of Life

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Abstract

Microbial life in Archaean non-marine settings like soils, lakes and springs would have faced several challenges. These would have included exposure to UV light; aridity, salinity and temperature changes; and nutrient availability. Current understanding is that none of these challenges would have been insurmountable. Microbial organisms of Archaean marine environments are likely to have been similar in their lifestyles and habits to those of the Archaean terrestrial world. Non-marine stromatolites, microbial filaments, microbial borings and microbially-induced sedimentary structures might therefore have been preserved. But Archaean subaerial surfaces would have been very prone to erosion by wind and rain, so the oldest fossil 'soils' of subaerially weathered surfaces (up to 3.47 Ga) are mostly identified using geochemistry. However, some ancient duricrusts like calcretes have been reported. Archaean lacustrine microbial life may have included stromatolites of the Tumbiana Formation of Western Australia. The case that these were lacustrine rather than marine is critically assessed, with the conclusion that the stratigraphy provides the strongest supporting evidence here. Archaean terrestrial hot springs, though often mentioned in origin of life studies, are not yet known from the rock record. In the Palaeoproterozoic to present these silica and carbonate-precipitating environments are commonly found in proximity to volcanic sediments and faults, where the deposits form terraced mounds, fissure ridges and hydrothermal lakes. It remains plausible that life could have existed and even evolved in these hypothesised Archaean hot-spring settings, and there is cause for optimism that the evidence for this might one day be found.

13.1 Introduction

Archaean lakes have been linked with early life since Charles Darwin first imagined a 'warm little pond' full of primordial soup in his 1871 letter

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to Joseph Hooker. But does current knowledge still allow this hypothesis of life in Archaean lakes to be entertained? Could life have evolved or even survived in Archaean non-marine environments, and if so, where and how are the signs of life likely to be preserved?

The radio-isotopically dated lunar cratering record (e.g. Tera et al. 1974) shows a cataclysmic impacting event occurred around 3.9 Ga (±200 Ma), meaning terrestrial environments were likely inhospitable at that time. The sedimentary record only extends to around 3.8 Ga. However it is generally but cautiously (Sweetlove 2011) accepted that the record of (marine) life on Earth extends to at least 3.5 Ga (e.g. Schopf 2006), supported by recent candidates for sulphur metabolising cells in beach sandstones of the Strelley Pool Formation (Wacey et al. 2011). Continued claims that carbonaceous artefacts in the hydrothermal Apex Chert are biogenic microfossils (Schopf and Kudryatsev 2012; 2013) are still refuted on the basis of multiple tests (Pinti et al., in press; Marshall and Marshall, in press), including detailed mapping and petrographic interpretation (M.D. Brasier et al. 2011). The first recorded land surface and possible palaeosol dates to 3.47 Ga (Buick et al. 1995). This review is, therefore, primarily concerned with the possible record of life in non-marine environments in the billion year interval from 3.5 to 2.5 Ga. The volume of literature covering the many topics touched upon here is vast, so only an introductory overview can be presented in such an article as this. Therefore a short summary of the physical challenges that life would face in Archaean non-marine environments is followed by a reminder of what to look for if one is to find any signs of life in Archaean soils, lakes and springs. Some examples of likely Archaean terrestrial sediments and evidence of Archaean terrestrial life are also given, with some predictions and suggestions for future research.

13.2 Hostility of Archaean Non-Marine Environments

Microbes attempting to survive in the Archaean terrestrial world would have faced several challenges, including exposure to ultraviolet (UV) light; aridity and salinity changes; temperature fluctuations; and problems associated with access to nutrients. Nevertheless there would have been many local niches where conditions would have been more habitable (Fig. 13.1).

13.2.1 Ultraviolet Light

The existence of Archaean terrestrial (non-marine) life might have been challenged by a high flux of DNA-damaging UV light in the absence of an ozone layer (e.g. Rothschild 1999). But there is considerable uncertainty on the Earth's early atmospheric composition, and hence it is not easy to judge how hazardous UV light exposure would have been to subaerial life at ground level. One hypothesis, for example, speculates that an atmospheric organic haze (similar to that found around Saturn's moon Titan) might have protected Archaean surface environments from UV radiation (e.g. Domagal-Goldman et al. 2008). In Archaean oceans, life would have been protected by the inability of UV light to penetrate below the surface waters. This would also have been true in deep lakes. The fossil record shows that microbial mats survived in periodically exposed coastal settings around 3.5–3.3 Ga (Westall et al. 2006). UV barriers in coastal environments likely included layers of dust, snow, evaporite minerals and dead organisms (Westall et al. 2006). Glover (1992) similarly suggested shields of mud would have protected coastal microbes. These are all UV shields that could also have been found in fully terrestrial environments. Endolithic niches within the sediment or in primitive 'soils' may have been quite safe for early microbes. For example Cockell and Raven (2007) determined that a thin (mm-thick) layer of ferric iron sediment is also an effective barrier to harmful UV light, and reasonably concluded that this challenge would therefore have been resolvable by Archaean terrestrial life.

13.2.2 Aridity and Salinity

The hazard of desiccation is a particular challenge to be overcome in terrestrial environments. Extra cellular polymeric substances

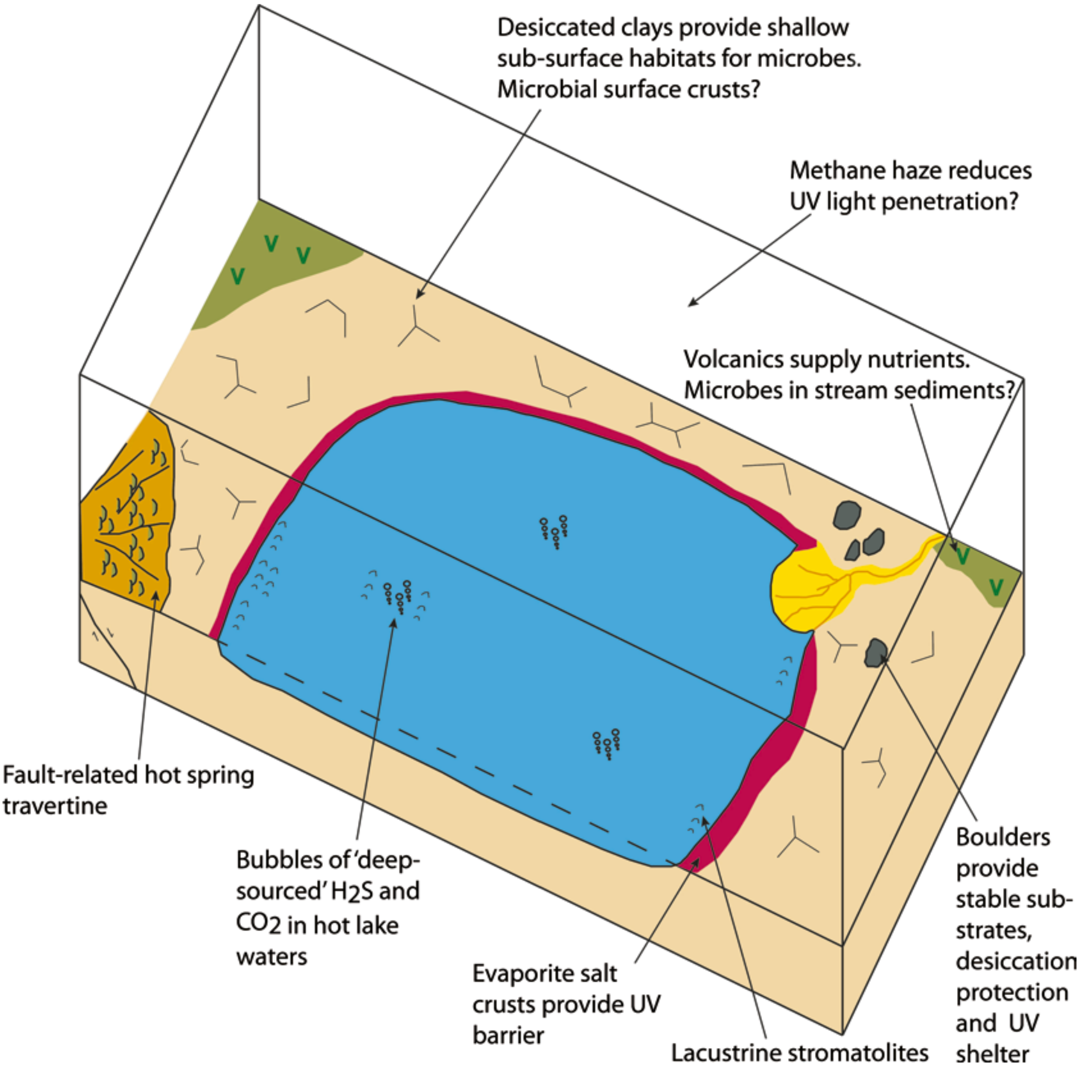


Fig. 13.1 Life in the Archaean terrestrial world, showing some likely habitable niches. Note the presence of volcanics supplying nutrients; salt crusts, desiccated clays and boulders for UV shielding (plus a potential organic haze atmosphere) and protection from desiccation. Extremes of temperature would have affected soils more than sub-aquatic niches

(EPS) produced by bacteria can help to reduce moisture loss and act as an osmoprotectant, as observed in some modern Alpine bacterial colonies (the latter described by Horath and Bachofen 2009). An endolithic life habit would also minimise water loss, while organisms inhabiting large Archaean lakes would perhaps have been less afflicted by desiccation. But they may have had to cope with fluctuations in lake salinity, particularly in near-coastal brackish systems. On timescales much longer than the lifespan of individual micro-organisms (perhaps thousands of years) then even the most stable of lake systems could have been prone to drying out. Life habits and cycles that enabled survival in any of freshwater rivers, brackish lakes and the sea would likely have been beneficial to the long-term survival of early lacustrine genera. Notably some modern cyanobacterial species like *Schizothrix calcicola* are able to live in all three of these settings. It seems reasonable to assume this phenomenon might also have applied to Archaean microorganisms with similar life habits and trophic strategies.

13.2.3 Temperature

There is a dispute over the likely temperature of Archaean oceans (with implications for temperatures of terrestrial environments), stemming from interpretation of oxygen isotope values of marine carbonates and cherts (e.g. Knauth and Lowe 1978, 2003; Muehlenbachs 1998). Low chert oxygen isotope values around 7–22 ‰ VSMOW point towards hot ocean surface temperatures (55–85 °C according to Knauth 2005), whereas temperatures above 37 °C are intolerable to several (but not all) groups of organisms. Most palaeontologists (particularly those working on Phanerozoic rocks, where a discrepancy still exists between temperatures calculated from chert and carbonate oxygen isotope values and expected temperatures) therefore prefer an Archaean world with ocean temperatures no higher than around 37 °C. Even if Archaean oceans were extraordinarily hot, their temperatures would presumably have been more constant (and therefore more bearable to thermophilic bacteria?) than those of most terrestrial surface environments. Large lakes and perhaps some endolithic niches could have provided suitable refugia for organisms intolerant of dramatic temperature fluctuations.

13.2.4 Nutrient Availability

The majority of essential nutrients are found in volcanic rocks and volcanic gases (e.g. CO_2, SO_2, H_2, NO_2 etc) and could therefore be obtained from volcanic rocks, sediments or the atmosphere, while phosphorous could be obtained by osmotrophic organisms directly from minerals like apatite. Fungi are particularly adept at the latter. Whether any microorganisms had evolved this capacity as early as the Archaean is unknown. It is, therefore, possible that living organisms would have depended on dissolved (or volcanically-emitted) nutrients in lakes and ground waters, hindering the colonisation of drier environments until the Neoproterozoic arrival of fungi (Lücking et al. 2009).

13.3 Looking for Fossil Evidence of Ancient Terrestrial Life

The features and lifestyles of organisms that inhabited Archaean terrestrial settings are likely to have been identical or very similar microorganisms to those which inhabited coastal marine or even deep water hydrothermal settings. Therefore many of the features that would identify life in Archaean lakes or soils, for example, are the same as those that apply to the widely studied marine sedimentary record. These include stromatolites, microbial filaments preserved in cherts or carbonates, microbial borings and microbially-induced sedimentary structures (MISS).

13.3.1 Stromatolites

Stromatolites have been the subject of numerous recent reviews (for example Riding 2011; McLoughlin et al. 2013). Often assumed to be biogenic where palaeontological data are sparse (see discussion in Schopf 2006) this is not necessarily the case (McLoughlin et al. 2008). McLoughlin et al. (2013) critically evaluated several criteria used to establish the biogenicity of stromatolitic fabrics. They concluded that a biogenic origin is most easily established in stromatolites with complex morphologies that bear organic remains. There is increasing evidence that microbial assistance commonly aides calcite crystal nucleation in modern non-marine stromatolite-forming settings (Rogerson et al. 2008), yet even some Quaternary laminar carbonates formed around cool water springs are currently hard to conclusively establish as a product of microbial activity (A.T. Brasier et al. 2011a).

13.3.2 Microbial Filaments

Microbial filaments are commonly best preserved in siliceous fabrics (see Cady and Farmer 1996), as these are less prone to early diagenetic recrystallisation than those of carbonate minerals. For example modern *Phormidium* seasonally banded tufas are commonly comprised of low magnesian calcite that precipitated around the external surfaces of cyanobacterial filaments (Andrews and Brasier 2005; Brasier et al. 2010). The high initial porosity of these *Phormidium* tufas results from early decay of the organic filaments themselves, and only occasional entombed filaments are found. Chert fabrics have long been seen as more favourable for preservation of organic microbial remains (e.g. Tyler and Barghoorn 1954; Cady and Farmer 1996; Konhauser et al. 2003), although still susceptible to diagenetic alteration (Hinman and Walter 2005) and organic matter preservation still seems to be the exception rather than the rule (see Walter 1996). Even where carbonaceous matter is found in cherts, there are disputes over its possible biogenicity. As with carbonate precipitation (Rogerson et al. 2008) it might well be that silica precipitation around hot springs is facilitated by microbes, or the latter may just provide a stable substrate for mineral growth (Cady and Farmer 1996; Guidry and Chafetz 2003a; Konhauser et al. 2003). Abiogenic silica precipitation can occur as a result of cooling of the depositing waters, evaporation or abrupt raising or lowering of pH (see Jones et al. 1997 and references therein).

13.3.3 Microbial Borings

In the absence of immaculately preserved organic remains, traces like endolithic microbial borings (see McLoughlin et al. 2009; Jones 2010; Cockell and Herrera 2008) are potentially diagnostic signs of ancient primitive life. Such borings as might be preserved in the rock record have been described from modern speleothem-precipitating caves (Jones 2010). These can be produced by several bacterial groups. Dolomite-inhabiting endolithic communities of the Alps, for example, include Cyanobacteria, Actinobacteria, Alpha Proteobacteria and Acidobacteria. As with examples found in modern Antarctica (Friedman 1982), endolithic habits in the Archaean could have afforded microorganisms direct access to nutrients (through osmotrophy), protection from UV light, and respite from desiccation. In younger (Neoproterozoic; Lücking et al. 2009) terrestrial rocks, borings by fungal groups might one day be found. But when seeking fossil endolithic borings, it is important to distinguish between inclusion trails of abiotic origin (Lepot et al. 2009) and ancient bacterial excavations.

13.3.4 Microbially-Induced Sedimentary Structures

Microbially-induced sedimentary structures (MISS; Noffke et al. 1996) are found in tidal flat and shelf sandstones, including those of Archaean age (see for example Noffke et al. 2008). Microbial (mostly photosynthetic cyanobacterial; Noffke 2009) growth, binding, bio-stabilisation, baffling and trapping produce the seventeen types of MISS recognised by Noffke (2009; her Fig. 13.3). To increase confidence that a given MISS occurrence is of a biological origin, Noffke (2009) proposed that six criteria must be met. Briefly these are that the rocks should not have been metamorphosed beyond lower greenschist facies; that stratigraphically, the MISS should occur at the turning points in regression-transgression cycles; that MISS should be found in facies conducive to their formation and preservation (often quartz sands of high purity); that the spatial distribution of MISS corresponds to the ancient 'average hydraulic pattern'; that uniformitarian comparisons with modern examples suggest a biological origin; and that one of nine specific MISS micro-textures is present.

The aim of applying these criteria in a strict way is to reduce the number of doubtful claims of Archaean microbial life where an abiotic process might have caused MISS-like structures. Not all of these criteria can be fairly applied to the non-marine realm. In particular, Noffke (2009) suggests that in all of her sections studied to date, MISS developed 'exclusively' on wide tidal flats during shoreline transgressions. If microbially-induced sedimentary structures are the result of the physical effects of biofilms and microbial mats on sediment stabilisation, baffling and trapping then it seems unlikely that MISS are truly exclusive to shallow marine tidal flat settings, nor does there seem an *a priori* reason why MISS should be exclusive to any particular point in global sea-level cycles. Although seemingly not yet found (Noffke 2009), some forms of MISS –perhaps not identical to or as easily recognisable as the seventeen forms now known from tidal settings—must surely exist and have existed where microbes abounded in sandy lakes, streams, springs and even soils. Ancient terrestrial examples will not necessarily have developed during episodes of global sea-level rise. However humid, wet time intervals (linked to sea-level highstands?) may still have provided more spatially widespread lake and stream habitats for microbes than available during the drier episodes of Earth history. Further, the spatial distribution of terrestrial MISS types is likely to be very complex and less predictable than found in marine lagoonal and tidal flat deposits (described by Noffke 2009), reflecting the relatively high frequency and rapidity of tectonically and climatically-related environmental changes in non-marine settings.

When making claims of ancient terrestrial life, in addition to meeting the several criteria associated with establishing biogenicity (such as Brasier et al. 2005; Noffke 2009; McLoughlin et al. 2013), one must further establish that the setting was non-marine or subaerial at the time the organisms were alive. In the absence of diagnostic fossils this is not always easy or incontrovertible.

13.4 Identifying Archaean 'Soils'

Archaean 'soil' differed from its modern counterparts that are products of biological processes. Retallack (2007) included "rocks altered by hydrolitic weathering" under the palaeosol heading. Often this broad definition is useful in astrobiology and 'deep-time' research, facilitating study of subaerially exposed and weathered surfaces (including Brasier et al. 2013a). The use of soil taxonomy (terms like 'Aridisol' and 'Mollisol') to classify palaeosols in the same way as those of the modern world is highly contentious (see for example Mack et al. 1993; Dahms and Holliday 1998; Retallack 1998). This is because many of the defining characteristics of modern soils require accurate measurement of specific environmental conditions that could only ever be inferred for palaeosols. Nevertheless, the scheme of Mack et al. (1993) was intended for use on soils of all ages and has been quite widely adopted. It has often proven useful in Quaternary palaeoenvironmental studies (e.g. Leeder et al. 2008). Caution is urged in inferring, for example, climatic conditions from a particular soil characteristic because the (potentially and even likely invalid) uniformitarian assumptions that must be made—particularly in studies of pre-Silurian rocks—cannot be overlooked. This may be less of an issue from the late Palaeozoic to the present.

Criteria are required to identify an Archaean soil, and Rye and Holland (1998) applied the following:

1. the unit must be developed on a homogenous parent rock and have been preserved in place;
2. the unit must exhibit changes in mineralogy, texture and chemical composition from the parent rock to the top of the soil that are consistent with soil forming processes;
3. there must be identifiable soft-sediment deformation features (e.g. re-worked soil clasts) along the contact between the unit and the immediately overlying rocks.

To distinguish 'soils' from hydrothermally altered rocks, Grandstaff et al. (1986) recommended the following criteria, some of which are similar to those adopted by Rye and Holland (1998):

1. palaeosols are stratiform, found parallel to bedding;
2. palaeosols are relatively thin (usually <20 m);
3. palaeosols have transitional lower boundaries and sharp upper boundaries, the latter due to a disconformity or unconformity;
4. palaeosols often exhibit colour variations;
5. palaeosols exhibit the destruction of primary rock textures, often accompanied by the formation of 'soil' textures including clay coatings on grains ('cutans'), calcite or silica nodules, or iron and manganese crusts;
6. palaeosols exhibit the destruction of primary minerals to form clay minerals;
7. palaeosol elemental distributions often show depletion of most cations and enrichment of Al, Ti, Zr and other elements forming insol-

uble compounds. However, this pattern can change according to the geochemical conditions during soil formation, such as with calcrete and silcrete formation;

8. palaeosols may include neptunian dykes of sediment washed down into desiccation cracks;
9. palaeosols may be found as rip-up clasts in overlying sediments

There must be good reason to believe that chemical alteration took place in a subaerial setting and not later during burial. This evidence may come from the stratigraphy, as with the late Archaean Dominion Group palaeosol of South Africa. This palaeosol is directly overlain by fluvial sediments (Grandstaff et al. 1986). These criteria of Grandstaff et al. (1986) and Rye and Holland (1998) are good for identifying subaerially weathered surfaces, if not necessarily 'soils' *sensu stricto*.

If using the criteria of Rye and Holland (1998) then each of the "changes in mineralogy, texture and chemical composition" that are to be expected in an Archaean 'soil' must be defined by the observer. Rye and Holland (1998), for example, looked for 'soils' developed on igneous rocks, and found they usually became increasingly sericite-rich towards their tops. They decided this was a useable criterion for identifying 'soils' amenable to geochemical reconstruction of Archaean palaeoatmospheric compositions. They also looked for invariant ratios between immobile elements (like Ti/Zr and Ti/Al) from the parent rock to the top of the identified 'soil', coupled with loss of the more soluble, mobile elements like Ca, Mg and (in an atmosphere with little free oxygen) Fe^{2+} from the 'soil' tops. The obvious assumption here is that the identified 'soil' is simply comprised of the weathered surface of the bedrock (see Fig. 13.2). This definition excludes 'soil' examples that contain allochthonous materials like wind-blown dust or organic matter. Allochthonous desert dusts constitute a significant proportion of many modern soils (e.g. Goudie and Middleton 2001), and many modern soils are formed in alluvial and fluvial sediments. This might not have been the same in the Archaean because of the absence of plant roots to bind these loose materials together, since these surface materials might easily have been eroded (Fig. 13.2). For the geochemical palaeoenvironmental reconstruction purposes of Rye and Holland (1998), avoiding these allochthonous materials was in any case desirable.

What these Archaean palaeosols or weathered surfaces (e.g. Grandstaff et al. 1986; Rye and Holland 1998) actually tell us about the level of free oxygen in the early atmosphere is not the central focus of this review. However, it is worth noting that iron can be retained in chemically weathered rocks even in reducing conditions: the haematite of Martian dust is a likely example of this. Explanations for production of haematite in the absence of free atmospheric oxygen on Mars include oxidation of iron in hydrothermal environments, where water thermally dissociates and H_2 gas is lost from the system (e.g. Catling and Moore 2003). Iron retention in a palaeosol is therefore not necessarily an indicator of free atmospheric oxygen.

There are rare cases where 'un-weathered' subaerial exposure surfaces are preserved, such as the ashfall tuffs of the Ventersdorp Supergroup, South Africa, which purportedly exhibit the impressions of Archaean raindrops (Som et al. 2012). The lack of their removal by weathering and denudation is testament to the short time these surfaces were exposed to the atmosphere prior to burial. Conceivably the several voids in such rocks could have been inhabited by microbes hiding from UV exposure and desiccation, though that has not been reported in this case.

13.4.1 Morphological Characteristics of Archaean 'Soils'

Many of the features of modern soils would not have been present in the Archaean, making such ancient examples harder to identify (see also Brasier et al. 2013a). Fossil roots, 'one of the best criteria for recognition of paleosols in sedimentary rocks' (Retallack 2007), will not be found in the Precambrian. Vertical horizonation, a feature of modern soils, will also be harder to identify in the most ancient cases. The topsoil ('A') horizon of a modern profile might be dark coloured and

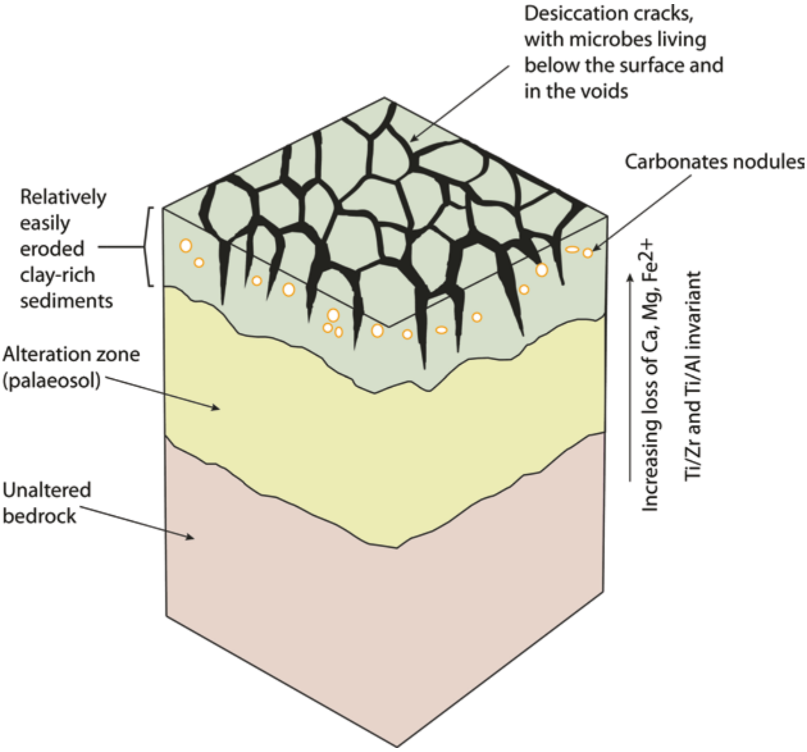
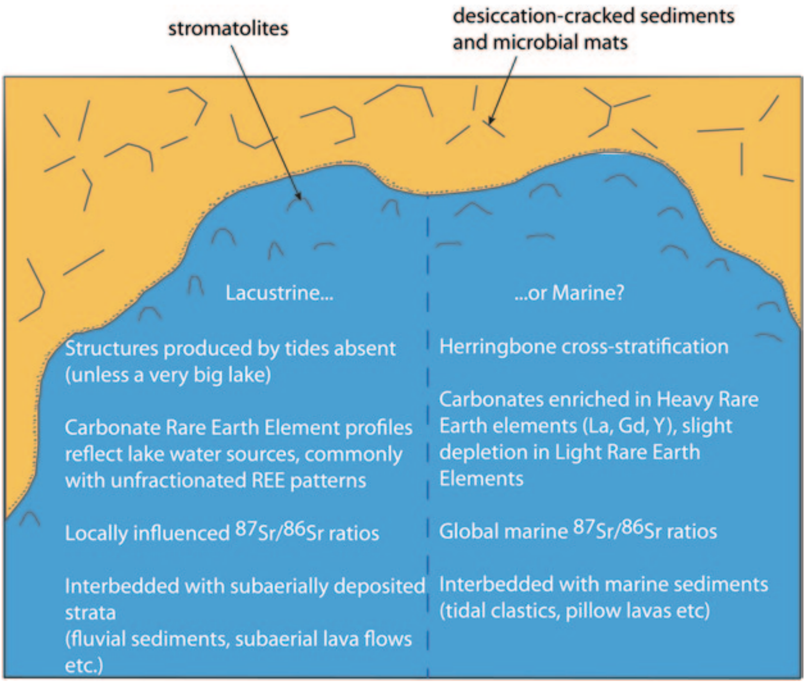


Fig. 13.2 Features of an Archaean soil. Unaltered bedrock passes transitionally into altered 'soil', with increasing loss of Ca, Mg and Fe^{2+} ions towards the soil top (except where duricrust layers form). Unconsolidated sediment would have been easily eroded without the stabilising effect of plant roots, so most Archaean soils are now identified geochemically

organic-rich, and possibly underlain by eluviated (E) and illuviated (B) horizons, becoming transitional (C horizon) to the partially weathered bedrock (R horizon). In the absence of plants, their roots and symbiotic fungi, most Archaean 'soils' would have been more like modern Entisols (or Protosols of Mack et al. 1993): showing only weak development of horizons (Fig. 13.2). However, this does not mean Archaean soils entirely lacked features such as aggregates of clay minerals ('peds') with slickensides and grain-surrounding clay layers ('cutans'), which form through the shrinking and swelling of clay minerals. Nodules or glaebules and pisoliths of authigenic precipitates, commonly carbonates and silica, might also have been present in Archaean soils (see Fig. 13.2 and Brasier 2011). But when searching for an Archaean soil, one must consider the preservation potential of these fabrics. Without plant roots to bind the sediment and remove excess moisture, the unconsolidated surface regolith will have been prone to regular removal by strong winds and rains. Duricrusts like calcretes and silcretes (Brasier et al. 2013a) have a relatively high chance of surviving weathering, denudation, burial and even metamorphism. They might even preserve textural and geochemical evidence of microbial habitation of Earth's early land surfaces (for example Watanabe et al. 2000). This issue of preservation could be the central reason why Archaean soils have so far mostly been identified using geochemical techniques to identify zones of alteration beneath unconformities.

13.4.2 Archaean 'Soil' Examples

The oldest reported exposed land surface (3.47 Ga) belongs to the Pilbara Craton, Western Australia (e.g. Buick et al. 1995; Johnson et al. 2009). This is an angular unconformity beneath rocks of the Warrawoona Group. Chert beds beneath the unconformity surface form steep ridges draped by the overlying succession, indicating at least 10 m of sediment were eroded (Buick et al. 1995). Underlying igneous rocks are more altered (felsics more kaolinitic, mafics less chloritic) within 50 m of the contact, and Buick et al. (1995) suggested



Lacustrine...	...or Marine?
Structures produced by tides absent (unless a very big lake)	Herringbone cross-stratification
Carbonate Rare Earth Element profiles reflect lake water sources, commonly with unfractionated REE patterns	Carbonates enriched in Heavy Rare Earth elements (La, Gd, Y), slight depletion in Light Rare Earth Elements
Locally influenced ^{87}Sr/^{86}Sr ratios	Global marine ^{87}Sr/^{86}Sr ratios
Interbedded with subaerially deposited strata (fluvial sediments, subaerial lava flows etc.)	Interbedded with marine sediments (tidal clastics, pillow lavas etc)

Fig. 13.3 Some criteria for differentiating between lacustrine and marine strata

this alteration zone might be interpreted as Earth's oldest known 'palaeosol'.

Rye and Holland (1998) summarised fifty possible cases of subaerially weathered horzions ('soils') of pre-Devonian age, concluding that fifteen of these met their criteria to be considered 'definite soils'. Of these, the oldest two examples developed on the 2.765 ± 0.1 Ga Mount Roe Basalts, and they were named Mount Roe #1 and Mount Roe #2. The basalts are highly vesicular and do not contain pillow structures, and hence they were interpreted as having erupted subaerially (Rye and Holland 2000). The palaeosols were indentified using the geochemical criteria of Rye and Holland (1998) described above. Expanding on their description and interpretation, Rye and Holland (2000) suggested that Mount Roe #2 contains evidence for terrestrial habitation and even methanotrophy in the form of organic carbon with distinctly light δ^{13}C compositions (−33 to −51 ‰ VPDB). They suggested the carbon might represent methanotrophs that were present in the soil, or could originally have been deposited in a hypothesised nearby lake.

Palaeosols of Mpumalanga Province, South Africa, are said to be between 2.7 and 2.6 Ga old (Watanabe et al. 2000). At the Schagen locality, 2.7 Ga serpentinised dunites have been interpreted as having undergone Archaean subaerial alteration to produce a 17 m thick palaeosol including void-filling precipitates of calcite, dolomite and quartz (Watanabe et al. 2000). These authors believed the calcium to be allochthonous (CaO up to 54 %); magnesium to be derived from the serpentinites; and bicarbonate ions from the atmosphere, and this may be so. However, carbonatisation of serpentinite to produce dolomite and calcite (sometimes termed 'ophicalcite') could explain the carbonate features Watanabe et al. (2000) describe. Unlike pedogenic calcrete formation, this carbonatisation is a process akin to 'groundwater calcrete' formation, which does not require subaerial exposure or a seasonal climate (see for example Wright and Tucker 1991; Brasier 2011).

Watanabe et al. (2000) claimed 2.6 Ga terrestrial biogenic organic matter in the purported palaeosol they described. The organic matter, which has measured δ^{13}C of − 17.4 ‰ to − 14.3 ‰ PDB, is found closely associated with clay layers that are presumed to be depositional or derived from a depositional texture. The organic matter is not concentrated in fissures, potentially reflecting its origin as terrestrial microbial mats formed on the surface of a 'soil' 2.6 billion years ago. Further, Watanabe et al. (2000) claim the crystallinity and H/C index of the organic matter show that it is unlikely to be of hydrothermal origin, and predates a metamorphic event at around 2.0 Ga.

13.5 Lakes

Differentiating Archaean and Proterozoic lacustrine deposits from their marine equivalents is notoriously challenging (Fig. 13.3). The suggestion of continent-flooding epeiric seas (e.g. Kamber et al. 2004) and giant lakes (e.g. Awramik and Buchheim 2009) in the Archaean adds to this complexity. In the absence of diagnostic palaeontology, arguments must be made using sedimentology, stratigraphy, geochemistry, physics or a combination of these. The distinction between marine and non-marine environments is important because this impacts on ones interpretation of the local versus global nature of organism populations and geochemical events.

Westall et al. (2006) claimed anoxygenic photosynthesisers likely built the desiccation-cracked mats of the Josefsdal Chert (Barberton Greenstone Belt) in a coastal marine setting that was periodically subaerial. If so, then life should have been able to withstand the transition from coastal, periodically exposed settings to lakes, streams and soils. Some workers (e.g. Glover 1992) have even postulated that life may have originated in coastal or coastal lacustrine sands. The hypothesis of Glover (1992) was that radiation from heavy minerals concentrated within the sands would provide the necessary heat for polymerisation of organic molecules. Glover (1992) reasonably suggested looking for fossil microbes in the silica cements of such sandstones.

13.5.1 Archaean Lakes: The Tumbiana Formation as an Example?

Stromatolites of the 2.7 Ga Tumbiana Formation (Fortescue Group), Western Australia, have been variously interpreted as lacustrine (Buick 1992; Bolhar and van Kranendonk 2007; Awramik and Buchheim 2009) and as marine (Packer 1990; Thorne and Trendall 2001; Sakurai et al. 2005). These stromatolites were undoubtedly deposited in very shallow waters, as deduced from desiccation cracks, ripples and the topographic relief of the stromatolites themselves.

Buick (1992) suggested that lack of evidence for sulphates in an evaporitic setting reflected a lacustrine rather than marine environment for the Tumbiana Formation. Yet one could ascribe this lack of evidence for sulphate minerals to the low level of free oxygen at this early point in Earth history. The first widespread marine sulphates are not found in the rock record until after 2.4 Ga (e.g. Kah et al. 2004; Melezhik et al. 2005; Schröder et al. 2008; A.T. Brasier et al. 2011b). Further, there is a debate surrounding the presence (e.g. Sakurai et al. 2005) or absence (e.g. Awramik and Buchheim 2009) of sedimentary indicators of (marine) tidal currents, such as herringbone cross-stratification in the Tumbiana Formation.

Packer (1990) reported relatively invariant carbonate carbon isotope values close to 0 ‰ PDB, and suggested these support a marine origin for the Tumbiana Formation. However, this carbon isotope evidence is not diagnostic. First, in the absence of abundant terrestrial plants, it is likely that marine carbonate (or in some settings volcanic) carbon dominated the dissolved inorganic carbon of Archaean terrestrial waters. Therefore, Archaean terrestrial carbonates are likely to have carbon isotope compositions between approximately 0 and −6 ‰ VPDB. Cambrian calcretes, for example, have compositions between −1 and −3 ‰ VDPB (Buggisch et al. 2003). Second, meteoric waters that have long residence times in marine carbonate bedrock are likely to precipitate carbonates with carbon isotopic compositions close to 0 ‰ VPDB.

Rare Earth Element (REE) patterns cannot on their own allow distinction between marine and lacustrine carbonates (see for example Johannesson et al. 2006), but have been muted as supporting evidence for a lacustrine origin of the Fortescue Group stromatolites by Bolhar and van

Kranendonk (2007). The latter authors believed their shale-normalised REE patterns to have resisted diagenetic alteration, and to show similarities with those of the lacustrine Eocene Green River Formation carbonates. These Fortescue Group stromatolites display no enrichment in either heavy or light rare earth elements relative to the 'post-Archaean Australian shale' they used as a baseline. In contrast, modern marine carbonates are normally enriched in heavy rare earth elements.

Probably the strongest reported evidence that the Tumbiana Formation stromatolites can plausibly be interpreted as non-marine comes from their stratigraphic context, sandwiched between two subaerially-erupted basalts and in close proximity to fluvial sediments (see Buick 1992; Awramik and Buchheim 2009).

13.5.2 Other Potential Archaean Lakes

Kamber et al. (2004) examined the REE and strontium isotope geochemistry of the Archaean Mushandike limestone (Masvingo Greenstone Belt, Zimbabwe), demonstrating a correlation between the REE and Sr data. The $^{87}Sr/^{86}Sr$ values were relatively radiogenic (the lowest being 0.7184), implying input from 3.8 to 3.5 Ga, Rb-rich Archaean gneisses of south-central Zimbabwe. The Mushandike limestone REE pattern was interpreted as reflecting input of locally derived detrital grains to a continent-flooding (marine) epeiric sea.

Stromatolites of the Ventersdorp Group of South Africa reported as terrestrial by Buck (1980) date from around 2.7 Ga (Armstrong et al. 1991). The palaeoenvironmental interpretation of Buck (1980) envisages these stromatolites forming in pools formed by depressions on fluvial floodplains. The evidence for this is based on sedimentary textures and stratigraphy. For example, ripple cross-lamination; 'mud-flake' conglomerates and desiccation cracks require a shallow water to subaerial setting. Poorly-sorted conglomerates and sandstones interpreted as debris flow deposits (partly re-worked by ephemeral streams) are interbedded with the stromatolitic horizons. The stromatolites themselves are commonly desiccated and comprised by layers of either dolomite or chert alternating with mud laminae.

13.6 Terrestrial Springs

Silica or carbonate precipitating (hot) springs can be excellent environments for preservation of (thermophilic) bacterial fossils (see for example Walter and Des Marais 1993; Cady and Farmer 1996; Konhauser et al. 2003). Several authors have suggested life could have thrived or even originated around deep sea hydrothermal vents, including Corliss et al. 1981; Baross and Hoffman 1985; Walter 1996; Ueno et al. 2004; Hoffman 2011, amongst several others. Walter and Des Marais (1993) even suggested looking for Martian thermal springs and their precipitates in the search for extra-terrestrial life. Much less is known or reported of subaerial and sublacustrine hydrothermal springs than submarine examples in 'deep time', with no or very few described Archaean cases and only a few likely deposits documented from Proterozoic rocks (see Brasier 2011). It is noticeable that most recorded ancient spring precipitates were either silica-depositing systems or are now at least part silicified carbonate, perhaps reflecting that most depositing springs precipitated silica, but likely also reflecting the better chances of preservation of a primary silica or silicified deposit.

Heat flow on the young Earth would have been high, and therefore Archaean hot springs should have been common (Walter 1996). On the modern Earth, one can make a distinction between 'ambient temperature' meteogene springs where water is sourced from rainfall, and 'thermogene' springs where a 'deep source', commonly of hot water is involved (see Pentecost 2005). This difference has an important effect on the biology and chemistry of the spring, and therefore on the facies, petrographic and mineralogical properties of any resulting precipitates. In the Archaean it is plausible that all springs would have been 'hot' to any inhabiting organisms (likely >35 °C), and therefore such a distinction is not easy to make and arguably not required (Brasier 2011; Brasier et al. 2013b).

Modern and Phanerozoic hot springs are associated with igneous bodies, commonly with a fault as a conduit for 'deep sourced' fluids rising to the surface. Dissolved H_2S concentrations may be high in such scenarios, as found in some modern Italian cases (Chafetz and Folk 1984). Classic modern examples include Mammoth Hot Springs of Yellowstone National Park in the USA (Tilden 1897; Walter 1976a, b; Pentecost 1990; Fouke 2000; Guidry and Chafetz 2003a, b). Here, regional groundwaters are heated to around 100 °C by near-surface magma chambers and travel to the surface along two major faults. Surface temperatures of the waters are up to around 95 °C (Chafetz and Folk 1984), cooling down with increasing distance (metres or tens of metres) from the spring as they flow over aprons and terraces (see also Walter and Des Marais 1993; Jones et al. 1998; Brasier et al. 2013b). Walter (1976a, b) found that silica 'geyserite' precipitation in Yellowstone National Park springs does not proceed at temperatures below 73 °C. This temperature is commonly taken as the limit above which only thermophilic bacteria are expected (e.g. Jones et al. 1997), with cyanobacteria and thermophilic bacteria found where waters have been able to cool sufficiently.

In carbonate-precipitating 'terraced mounds' (Chafetz and Folk 1984; Guidry and Chafetz 2003a), facies proximal to the spring vent comprise aragonite needle botryoids, with sheets of calcite, calcified bubbles and feather crystals found more distally (Fouke et al. 2000). If Archaean surface temperatures were closer to values found around the vents, then one might not expect such strong temperature-related gradients (and thus aragonite to calcite transitions) around Archaean 'hot' spring mounds. However, chemical gradients, with higher ionic strength solutions proximal to the vent than found in distal locations, might be anticipated. It is, therefore, plausible that bacteria with different trophic strategies would have inhabited their own specific zones around Archaean terrestrial spring vents. Indeed, such chemical gradients might have actively encouraged microbial diversification.

Several different types of 'hot spring' settings have been documented. Facies models relevant to early Earth history described by Brasier et al. (2013b) were inspired by models like those of Pedley (1990), Pentecost and Viles (1994), Jones et al. (1998) and Guidry and Chafetz (2003a) that are of most relevance to the Quaternary. Archaean settings could include 'terraced mounds' similar to those of Mammoth Hot Springs, but also 'fissure ridges' (elongate, narrow ridges from which waters escape and precipitate minerals) and 'hydrothermal lakes' (Brasier et al. 2013b). Where no deep-sourced fluids were involved (as might be interpreted where there are no volcanic sediments in the stratigraphy, or no fault conduit for fluids) then the 'perched springline', 'fluviatile' and 'lacustrine' facies models of Brasier et al. (2013b) might be more relevant. However, Brasier (2011) noted that high atmospheric pCO_2 levels on the early Earth would not have favoured carbon dioxide degassing (and thus carbonate precipitation) from surface waters. Some calcite precipitation might still have occurred around springs where the precipitating waters had very high pCO_2 from 'deep sources' like subducted sediments or volcanics. Silica precipitation also seems to be more common in settings with significant volumes of volcanic rock, so it is likely that the majority of Archaean terrestrial hot springs that could have preserved evidence of ancient terrestrial life were 'hot spring-like' settings in volcanic areas.

Some selected petrographic features of spring carbonates that might be observed in any Archaean examples are tabulated in Brasier (2011). Petrographic studies of modern silica 'geyserite' precipitates have revealed columnar and stratiform stromatolitic fabrics (Walter 1976a; b; Jones et al. 1997, 1998; Hinman and Walter 2005) plus spicules, oncoids, peloids and breccias (Campbell et al. 2001; Guidry and Chafetz 2003b; Konhauser et al. 2003).

Diagenesis of siliceous precipitates involves transformation from opal-A to opal-CT and quartz, often as a result of exposure to high temperatures. Hinman and Walter (2005) compared siliceous hot spring deposits of Artist Point, Yellowstone National Park with those of Steamboat Springs, Nevada. They found that the latter exhibited similar but fewer 'original' petrographic characteristics, and ascribed this to differences in the early diagenetic histories of the two deposits. Hot springs can have complex diagenetic histories because of heating of facies deposited at 'cooler' temperatures by hot waters (even affecting facies only a few centimetres below the surface); temporal fluctuations in the amount of hot-spring activity; and contributions from subsurface waters of different compositions and temperatures (Guidry and Chafetz 2003b).

Stratigraphically underlying the mineral precipitates of an ancient hot spring, one might look for hydrothermal breccias. In silica-depositing environments these are likely to be chert cemented, as found in a Jurassic example from Patagonia (Guido and Campbell 2009). As a further example of the field occurrence of an ancient 'hot-spring' deposit, the succession containing the famous Devonian Rhynie Chert and its flora and fauna includes a lava flow preserved beneath subaerially deposited tuffaceous sandstones. In turn, these underlie the interbedded shales and thin sandstones that contain the Rhynie Chert (Trewin and Rice 1992).

13.6.1 Archaean Spring Examples?

For all that is written of hydrothermal activity in the Archaean, the oldest reported hydrothermal travertines are Palaeoproterozoic, with seemingly no reports of any Archaean terrestrial springs (Melezhik and Fallick 2001; Pirajno and Grey 2002; Rainbird et al. 2006). The Kuetsjärvi Sedimentary Formation travertines of the Pechenga Basin, Fennoscandian Russia, were documented by Melezhik and Fallick (2001), Melezhik et al. (2004) and Brasier et al. (2013b). They date from between 2.2 and 2.06 Ga. Purported hydrothermal travertines include laminated dolomitic carbonate sheets of 1–15 cm thickness, and dolomitic mounds of 1–10 cm height. Some silica in these specimens was also interpreted as an original 'sinter' precipitate (Melezhik and Fallick 2001). The interpretation that the fluids were likely 'deep sourced' and hot-spring-like is based on association with volcanic sediments and carbon isotope values around −6‰ VPDB (Melezhik and Fallick 2001).

The pervasively silicified Bartle Member of the Killara Formation of Western Australia also contains some interpreted Palaeoproterozoic terrestrial hot spring sediments (Pirajno and Grey 2002). Chert veins within continental tholeiitic volcanics lower in the Killara Formation were interpreted as evidence for the conduits of hydrothermal fluids that fed chert layers of the Bartle Member (Pirajno and Grey 2002). These authors also reported that the cherts contain 'microdubiofossils'. The 1.79 Ga Kunwak Formation of northern Canada includes likely hydrothermal travertine, interpreted as such and described as laminar colloform calcite by Rainbird et al. (2006). Swallow tail shapes of gypsum crystals are consistent with H_2S-rich depositing waters, and there is also an association between hot spring deposits and volcanic sediments here.

13.7 Discussion: Finding Signs of Life in Archaean Soils, Lakes and Springs

Returning to the question asked at the beginning of this review, it seems likely that life could have survived (perhaps even evolved) in Archaean nonmarine environments. Big Archaean lakes like that envisaged by Awramik and Buchheim (2009) could have provided reasonably stable environments for microorganisms to flourish. Individual lakes would have grown their own disparate populations, each facing specific geochemical conditions unique to their environment, and therefore helping to drive evolution and increase global diversity through natural selection. Notably one does not require global glaciations or meteorite impacts to cause a crisis in a lake of any size. Major catastrophes in terrestrial environments could have been a change in the direction from which rainfall arrives; the incision of a river; a succession of cold winters. These are all factors that can dramatically affect the physical characteristics of a lake, challenging life to adapt and evolve, and are common occurrences in geological history.

But with the exception of some plausible lacustrine stromatolites, well-preserved evidence of early terrestrial life (even early terrestrial soil) is scarce. There is a time gap of around 800 million years between (carbon isotopic and stromatolitic) suggestions of life on land at around 2.7 Ga and the likely maximum age for life on land at around 3.5 Ga. Given that most recorded Archaean terrestrial deposits are siliceous or silicified, carbonaceous microbial filaments are most likely to be found in silicified lacustrine or fluvial sandstones. Hopefully, further searching in such environments will help to uncover some of this missing record.

13.8 Conclusions

The challenges faced by life in coastal marine environments from ~3.5 Ga onwards would have been very similar to those faced by microorganisms in Archaean lakes. These include exposure to UV radiation; desiccation, temperature fluctuations and access to nutrients. Current studies suggest that each of these challenges would have been resolvable, probably with endolithic and sub-aquatic life habits favoured over the most exposed surface settings. The features and effects of organisms that inhabited terrestrial Archaean environments will have been similar to those found in marine environments. Therefore, visual evidence to look for in non-marine settings should include stromatolites, microbial filaments (often in cherts), microbial borings and microbially-induced sedimentary structures.

There are some reports of truly ancient duricrusts like calcretes and silcretes, but without any protective vegetation cover the Archaean subaerial world would have been very prone to erosion by wind and rain. The more easily eroded Archean regolith is seemingly scarcely preserved. Archaean ‘soils’ or subaerially weathered surfaces, including an example as old as 3.47 Ga, are therefore most commonly identified using geochemical criteria.

It seems to be generally accepted that life could have survived in Archaean lakes. Yet differentiating lacustrine from marine environments is a major challenge in the Archaean. Stratigraphic evidence that an environment was lacustrine remains the most robust, backed up by potential geochemical indicators like strontium isotopes and rare earth element profiles of authigenic carbonates.

Hot springs are commonly mentioned in discussions of the origin of life, but despite well-reasoned suggestions that they should have been common, no Archaean terrestrial hot springs are yet known. The oldest likely cases are Palaeoproterozoic. Most ancient preserved hot spring deposits are siliceous or at least part silicified, generally associated with volcanic sedimentary rocks. Although themselves subject to diagenesis, siliceous fabrics are commonly more robust than those of carbonates. Whether or not life originated in the dynamic niches around ‘deep-sourced’ sub-lacustrine hot springs, there is hope that such deposits and their fossilised biota might one day be found.

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