



HAL
open science

Geodynamic and metabolic cycles in the Hadean

M. J. Russell, N. T. Arndt

► **To cite this version:**

M. J. Russell, N. T. Arndt. Geodynamic and metabolic cycles in the Hadean. *Biogeosciences Discussions*, 2004, 1 (1), pp.591-624. hal-00330217

HAL Id: hal-00330217

<https://hal.science/hal-00330217>

Submitted on 18 Jun 2008

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Biogeosciences Discussions is the access reviewed discussion forum of *Biogeosciences*

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

Geodynamic and metabolic cycles in the Hadean

M. J. Russell and N. T. Arndt

LGCA, Université de Grenoble 1, 1381, rue de la Piscine, 38400 St. Martin d'Herès, France

Received: 26 July 2004 – Accepted: 30 August 2004 – Published: 22 September 2004

Correspondence to: N. T. Arndt (arndt@ujf-grenoble.fr)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

Abstract

High-degree melting of hot dry Hadean mantle at ocean ridges and plumes resulted in a crust about 30 km thick, overlain in places by extensive and thick mafic volcanic plateaus. Continental crust, by contrast, was relatively thin and mostly submarine. At constructive and destructive plate boundaries, and above the many mantle plumes, acidic hydrothermal springs at $\sim 400^\circ\text{C}$ contributed Fe and other transition elements as well as P and H_2 to the deep ocean made acidulous by dissolved CO_2 and minor HCl derived from volcanoes. Away from ocean ridges, submarine hydrothermal fluids were cool ($\leq 100^\circ\text{C}$), alkaline (pH ~ 10), highly reduced and also H_2 -rich. Reaction of solvents in this fluid with those in ocean water was catalyzed in a hydrothermal mound, a natural self-restoring flow reactor and fractionation column made up of carbonates and freshly precipitated Fe-Ni sulfide and greenrust pores and bubbles, developed above the alkaline spring. Acetate and the amino acetate glycine were the main products, much of which was eluted to the ocean. Other organic byproducts were retained, concentrated and reacted within the compartments. These compartments comprising the natural hydrothermal reactor consisted partly of greigite (Fe_5NiS_8). It was from reactions between organic modules confined within these inorganic compartments that the first prokaryotic organism evolved. These acetogenic precursors to the Bacteria diversified and migrated down the mound and into the ocean floor to inaugurate the 'deep biosphere'. Once there the Bacteria, and the recently differentiated Archaea, were protected from cataclysmic heating events caused by large bolide impacts. Geodynamic forces led to the eventual obduction of the deep biosphere into the photic zone where, initially protected by a thin veneer of sediment, the use of solar energy was mastered and photosynthesis emerged. The further evolution to oxygenic photosynthesis was effected as catalytic $[\text{CaMn}^{4+}]$ -bearing molecules that otherwise would have been interred in the mineral ranciéite in the shallow marine manganiferous sediments, were sequestered and invaginated within the cyanobacterial precursor where, energized by light, they could oxidize water with greater efficiency. Thus, chemical sediments were

BGD

1, 591–624, 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

required both for the emergence of chemosynthesis and of oxygenic photosynthesis, the two innovations that did most to change the nature of our planet.

1. Introduction

The Earth's internal thermal energy is mainly degraded through convection. Heat is transferred to the surface by a convecting mantle, to be discharged through volcanoes and hydrothermal springs into the ocean and atmosphere (the volatisphere). Chemical disequilibrium between reduced mantle and oxidized volatisphere is focused at springs and seepages on land or on the ocean floor. In turn this chemical energy is degraded through metabolism. Today metabolism relies on convection for supply of nutrients in the ocean and on convection in the atmosphere for irrigation and chemical weathering of the land. The springs and seepages are oases of life in both realms.

At a broader scale and at slower rates, global geodynamic processes generate fresh, reduced rock surfaces that provide energy and supply nutrients to life. This coupling of metabolism to convection was directly implicated in the onset of life, which probably emerged at least 4 Ga ago at moderate temperature seepages (Russell et al., 1988, 1994).

Reconstruction of the conditions that drove life to emerge and evolve its metabolic cycles is the main task of this paper. We begin by considering what present-day processes offer to the understanding of the conditions on the surface and in the interior of the Hadean/Archaean Earth, then suggest a scenario for the onset of life and its colonization of the ocean floor. This journey from geodynamics, through geochemistry to biochemistry leads us to conclude that obduction of oceanic crust facilitated the evolutionary jump to photosynthesis.

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

2. The modern oceanic crust

2.1. Birth and death of oceanic crust

A complete plate tectonic cycle starts with the formation of crust at a ridge and ends with its recycling to the mantle at a subduction zone. Continental crust forms above subduction zones, a direct result of the dehydration of subducting oceanic crust which triggers partial melting in the overlying mantle and the development of hydrous magmas. Superimposed on the plate tectonic cycle is the formation of oceanic islands and oceanic plateaus, which are generated by partial melting in mantle plumes.

2.2. Modern hydrothermal systems – how they work

Five main types of hydrothermal fluids circulate through modern oceanic crust. Three high temperature types ($\leq 4^\circ\text{C}$) operate at oceanic ridges, above plumes or in back arc basins; an intermediate type occurs on ridge flanks ($\leq 75^\circ\text{C}$); and the last, far cooler, on the deep ocean floor (Anderson et al., 1977; Von Damm, 1990, Cathles, 1990; Sedwick et al., 1994; Kelley et al., 2001; Wheat et al., 2002) (Table 1).

The temperature of the very hot springs, driven by magmatic intrusion, is controlled largely by the two-phase boundary of water and its critical point (Bischoff and Rosenbauer, 1984). Temperatures in modern hydrothermal convective systems, which bottom at an overall water column depth of 4 km or so, tend to peak at $\sim 4^\circ\text{C}$. The fluids in the downdrafts become acidic (pH ~ 3) through the release of protons as Mg^{2+} is fixed as serpentine and brucite (Janecky and Seyfried, 1983; Douville et al., 2002). These acidic solutions dissolve, transport and exhale the transition metals, some phosphate, H_2S and H_2 , at black smokers (Table 1) (Von Damm, 1990; Kakegawa et al., 2002).

The temperatures and compositions of intermediate-temperature hydrothermal convection cells are controlled by exothermic reactions and the rheology of the newly serpentinized mafic to ultramafic rock of the conduits. So far the fluid from only one entirely submarine example of ultramafic interaction has been sampled, the “Lost City” field, 15

BGD

1, 591–624, 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

km from the Mid Atlantic Ridge (Kelley et al., 2001). The pH of this water approaches 10 as $\text{Ca}(\text{OH})_2$, HCO_3^- and H_2 are eluted, and the temperature is 70–75°C (Table 1) (Kelley et al., 2001). A cooler (72°C) alkaline (pH 10) fresh-water submarine spring in a fjord off the north coast of Iceland (Marteinsson et al., 2001; Geptner et al., 2002) is characterized by porous cones of Mg-rich clay (saponite) some tens of metres high (Table 1).

Still farther from ridges, even cooler circulation is driven by heat within the uppermost crust. Small closed convection cells are evenly spaced with a periodicity of about 7 km, with thermal cusps around 20°C (Anderson et al., 1977).

Data for columns 1 to 4 from Von Damm (1990), Douville et al. (2002), Kelley et al. (2001) and Marteinson et al. (2001). Elemental and molecular concentrations are in millimoles. Temperatures at the base of the convection cells developed at oceanic spreading centres and the off-ridge systems are presumed to be ~400°C and ~100°C, respectively.

3. Hadean/Archaean ocean/atmosphere, oceanic crust and global dynamics

3.1. The volatisphere

According to oxygen isotope analysis of the oldest known zircons, an ocean is assumed to have condensed on Earth by 4.4 Ga (Wilde et al., 2001). The atmosphere contained CO_2 and N_2 , some HCl, SO_2 , S^0 and minor amounts of H_2 and Ar (Kasting, 1993; Kasting and Brown, 1998; Pavlov and Kasting, 2002). Volcanogenic CO_2 and HCl, augmented by output from high temperature acid springs, rendered the early ocean acidulous (pH 5–6) (Maisonneuve, 1982; Sedwick et al., 1994; Kasting, 1993; Macleod et al., 1994). The proportion of CO_2 depended on the balance between inputs from volcanic emissions and redissolution in the deep ocean, and outputs via carbonation of the crust and of the dust thrown up by meteorite impacts (Alt and Teagle, 1999; Nisbet and Sleep, 2001). Transition metals and phosphate contributed by very hot springs

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

remained in solution in this acidulous ocean (Kakegawa et al., 2002). Particularly important is Fe^{2+} , some of which was photo-oxidized to insoluble flocs of FeOOH at the ocean's surface (Braterman et al., 1983; Gaffey, 1997; Russell and Hall, 2002).

3.2. Crustal structure and composition

5 Heat production in the Hadean was at least 5 times that of the present day and it is probable that the mantle was several hundred degrees hotter than today's mantle (Turcotte, 1980). Because the dehydration reactions that control the amount of water recycled to the mantle are temperature dependent, the Hadean mantle was drier than its modern counterpart. The ocean contained most of the Earth's water and its volume
10 may have been up to twice that of today's oceans (Bounama et al., 2001). Upwelling of hot, dry mantle at oceanic spreading centres generated an early Archaean crust about 30 km thick (Sleep and Windley, 1982) (Fig. 1). Oceanic plateaus more extensive than Ontong Java covered large parts of the oceanic crust with an additional 30 km of mafic and ultramafic igneous rock. Both oceanic crust and plateaus were internally
15 differentiated into an upper ~5 km-thick layer of magnesian basalt underlain by ~10 km of gabbros and troctolites and 10 km or more of ultramafic cumulates (Francis et al., 1999; Foley et al., 2003).

The volume of continental crust in the early Archaean was a subject of intense debate in the 1980's. Geochemists tended to the interpretation that continental crust
20 started to appear only around 3.8 Ga, the age of the oldest rocks known at that time. Since then several important discoveries have been made. The pre 4.2 Ga zircons provide evidence for the existence of granitic rocks in the Hadean (Froude et al., 1983; Compston and Pidgeon, 1986). Direct or indirect evidence for continental crust is becoming more abundant: the 4 Ga Acasta gneisses (Bowring and Williams, 1999) and
25 the recently discovered 3.8 Ga Porpoise Cove supracrustal rocks (Stevenson et al., 2003). Ultra-high-pressure metamorphic rocks indicate that portions of the continental crust are routinely cycled deep into the mantle. These discoveries provide mounting support for Armstrong's (1981, 1991) model of rapid early continental growth. In this

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

model, granitic continental crust was abundant by the end of the Hadean.

The topography of the Hadean planet differed radically from that of the modern Earth. Because Hadean granitic crust contained higher concentrations of radioactive elements it was hotter, less viscous, and thinner than modern continental crust (Sandiford and McLaren, 2004). And because the mantle also was hotter, the continental lithosphere was thinner. Oceanic crust, in contrast, was much thicker than modern oceanic crust; as thick or thicker than the early Archaean continental crust. The oceans were more voluminous and they flooded a greater portion of the Earth's surface. Most of the continents were submerged and only mountain ranges at convergent margins and vast volcanic plateaus occasionally breached the ocean surface (Arndt, 1999). Thus there was little subaerial weathering and erosion of the mainly submerged continental masses and therefore comparatively little clastic sedimentation.

Hydrated oceanic crust continually cycled back into the mantle. At the base of the thickest sections, where oceanic plateaus had erupted onto the oceanic crust, pressures were sufficient to convert plagioclase to garnet. The downward drag of these dense eclogitised segments and the underlying dense Fe-rich ultramafic cumulates initiated subduction. Once started, the entire basaltic and gabbroic portion of the crust converted to eclogite, and plunged into the mantle (cf. Holmes, 1931). The earliest subduction zones probably were steeply dipping, rather than shallow, as is commonly assumed (Fig. 1) (Karsten et al., 1996). The upper layers of the crust dehydrated and triggered the melting in the over-riding mantle that gave rise to the magmas parental to continental crust. The uppermost parts of the oceanic crust obducted to form accretionary prisms of the type discussed by Maruyama (1997) and Foley et al. (2003). These prisms obliterated any nascent oceanic trenches, a process that was highly significant, as we shall see, to the development of photosynthesis.

3.3. Hydrothermal circulation

If we assume that the 400°C springs developed at constructive plate margins were comparable to those emanating from the ultramafic crust at the Rainbow field, the highly

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

reduced acidic fluids would have carried about 20 mM of Fe^{2+} to the ocean (Von Damm, 2000; Douville et al., 2002; Allen and Seyfried, 2003) (Table 1). With negligible marine sulfate in the Hadean (Farquar et al., 2000) there were no spontaneously precipitated protective anhydrite chimneys, and no black smokers. Hydrogen sulfide, reacting first with zinc, produced soluble but stable ZnS clusters as the solutions cooled on exhalation (Luther et al., 1999). Given the high remaining metal to sulfide ratio (Walker and Brimblecombe, 1985), much of the Fe and minor Ni stayed in solution in the acidulous ocean, though photo-oxidation of a proportion of the Fe^{2+} generated flocs of FeOOH (Braterman et al., 1983).

In marked contrast, off-ridge springs had a similar temperature and chemistry to those of the present day ($<100^\circ\text{C}$ and pH 9–10, Table 1) (Shock, 1992; Macleod et al., 1994; Kelley et al., 2001; Russell and Hall, 2002; Foley et al., 2003). Similar solutions may have exhaled from faulted zones within the oceanic plateaus. Such alkaline solutions could have provided ~ 10 mM of HS^- to the seepage site (Macleod et al., 1994; Rahman, 2003). A mound of precipitates formed where these seepage waters met the acidulous ocean. The main precipitates were of iron, calcium and magnesium carbonates, with subsidiary ferrous and ferric oxyhydroxides and iron>nickel sulfides (Russell et al., 1988, 1998).

3.4. Ocean temperatures

The temperature of the Hadean ocean is uncertain. The effective radiative temperature of the Sun was about 70% of its present output (Bahcall et al., 2001) and only the presence of atmospheric CO_2 prevented the Earth from completely freezing over (Kasting, 1993). Indeed, temperatures may, on occasion, have approached 100°C . There were several effective sinks for CO_2 including the extensive volcanic plateaus and the dust raised by major bolide impacts (Nisbet and Sleep, 2001). These impacts may also have vapourised the ocean from time to time, though temperatures were never so high that a Venus-like atmosphere persisted. Very likely there were frequent oscillations from

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

hot (impact and green-house induced), to cold and partially frozen, a consequence of solar radiation masking by local or galactic dust clouds (Kasting, 1993; Kasting and Brown, 1998; Alt and Teagle, 1999; Nisbet and Sleep, 2001). Very cold conditions were short-lived because of continuous and widespread volcanicity and exhalations of CO₂.

Notwithstanding our earlier suggestion for a thermophilic start to life (Russell and Hall, 1997), because of the fragility of RNA we recognise that life is unlikely to have emerged at temperatures much above 40°C (Forterre, 1996; Moulton et al., 2000; Brochier and Philippe, 2002). And because a thermal gradient is required to drive convection, we suggest that life's emergence had to await a period, or "window of opportunity" when oceanic temperatures were low, perhaps around 20°C (but see Schwartzman and Lineweaver, 2004, for a contrary view). However, once life had emerged it had to survive the Hadean periods of high temperature. How this was done will have to be addressed in our hypothesis of life's emergence and early evolution.

4. Chemical contribution to the onset of life

4.1. The hydrothermal mound

Haeckel (1892, p. 414) considered life to have emerged from an "inorganic formative fluid" and Leduc (1911, p xv) suggested that "the chain of life is . . . a continuous one, from the mineral at one end to the most complicated organism at the other". In Leduc's view, the first compartments to store the potential energy that drove life to emerge were also inorganic. These prescient ideas were ignored, partly because they seemed to hark back to theories of spontaneous generation put paid to famously by Pasteur, and partly because scientists were loath to consider anything but an organic origin for any organic being. Although this organic view held sway for 75 years, the inorganic hypothesis has since been disinterred. Here we suggest that a stable, long-lived alkaline submarine seepage of moderate temperature satisfies Haeckel's expectations (Rus-

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

sell et al., 1988, 2003) and that Leduc's inorganic compartments may have comprised catalytic iron(nickel) sulfides generated at this same seepage, a suggestion given significance by the recognition that iron and sulfur comprise the active centres to proteins with the longest pedigree, the electron transfer agents known as the ferredoxins (Eck and Dayhoff, 1966; Hall et al., 1971; Russell et al., 1994).

Portions of a hydrothermal mound comprising freshly precipitated films of iron sulfide in the form of disordered nanometric mackinawite (Fe_{1+x}S) and minor greigite (Fe_5NiS_8) offered semipermeable and semiconducting containers for the synthesis and retainment of organic molecules (Russell and Hall, 1997; Filtness et al., 2003; Wolthers et al., 2003). Strong gradients developed at the outer margins of such a mound where the reduced alkaline hydrothermal solution interfaces with the cooler, more oxidized Hadean ocean. Potentials focused across the iron sulfide membranes were hydrodynamic (between buoyant hydrothermal solution and ocean), thermal ($<20^\circ$ to 100°C), chemical (between hydrothermal H_2 and CO_2) and electrochemical (between redox couples H^+/H_2 and $\text{Fe}^{3+}/\text{Fe}^{2+}$) (Russell and Martin, 2004). Electrons could also be gained from H_2S .

Reduction of HCO_3^- to CO with activated $[\text{H}]$ is assumed to take place on nanocrystals of mackinawite and greigite (Russell et al., 1998; Russell and Martin, 2004). Further reduction to methane thiol (CH_3SH), involving activated $[\text{H}]$ and HS^- , is thermodynamically favoured (Schulte and Rogers, 2004) and has been demonstrated by Heinen and Lauwers (1996). Huber and Wächtershäuser (1997) reacted at 100°C and at a pH of 6.4 the two products CO and CH_3SH to produce acetate ($\text{H}_3\text{C.COO}^-$) in yields of 40% with respect to the thiol. These chemical and physical states can be met in the hydrothermal mound. It appears then that the first product of reaction between an alkaline hydrothermal fluid and carbonic ocean water will be acetate. Indeed, acetate is the product of what is known as the acetyl coenzyme-A pathway – the most ancient of all metabolic pathways (Peretó et al., 1999; Russell and Martin, 2004).

In their experiments Huber and Wächtershäuser (1997) used a slurry of iron sulfide and nickel sulfide. However, Russell et al. (1998) pointed out that greigite and violar-

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

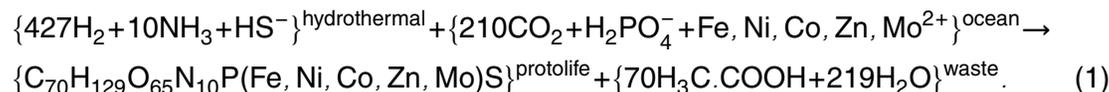
Print Version

Interactive Discussion

© EGU 2004

ite ($\text{Fe}_2\text{Ni}_4\text{S}_8$) are more likely to have been the catalysts. The high acetate yields are consistent with the thermodynamic calculations of Shock et al. (1998), who showed the reaction between of CO_2 and H_2 with the production of acetate to be extremely favourable (exergonic). The structure of greigite (Fe_5NiS_8) is strikingly similar to the active centres (e.g. Fe_4NiS_5) of the enzymes carbon monoxide dehydrogenase/acetyl co-enzyme-A synthase (CODH/ACS) (Dobbeck et al., 2001; Drennan et al., 2001; Darnault et al., 2003) that are presently involved in the reduction of CO_2 and the formation of acetate (Vaughan and Craig, 1978; Russell et al., 1994, 1998). The same enzymes have the facility to activate H_2 (Menon and Ragsdale, 2000).

The first microbes therefore used the energy and materials within the hydrothermal solution and the ocean to generate acetate (with water) as a waste product, i.e. it was an “acetogen” (Russell and Martin, 2004). The emergence of life and the generation of acetate waste within the natural hydrothermal reactor resembled mineral precipitation at a hot spring. As soon as organic molecules are formed in the process they have the effect of inhibiting mineral growth (e.g. Rickard et al., 2001): the active centres of the metalloproteins can be thought of as “still-born” mineral clusters. The approximate and highly simplified formula for “proto-life” used here [$\text{C}_{70}\text{H}_{129}\text{O}_{65}\text{N}_{10}\text{P}(\text{Fe},\text{Ni},\text{Co},\text{Zn},\text{Mo})\text{S}$] is gleaned from Redfield et al. (1963), Orr (1978), Morel and Hudson (1985), Faggebakke et al. (1996) and Macalady and Banfield (2003). The trace metal contents are exaggerated in keeping with their likely contribution to the first living cells. The reactions that generated this proto-life and waste can be put notionally as:



Note the high waste-to-protolife molecular ratio.

In this explanation, the hydrothermal mound can be viewed as a self-restoring catalytic flow reactor that synthesized acetate (Russell and Martin, 2004). More complex organic molecules were a minor by-product of the reaction, a by-product that optimized acetate production. Of particular significance was the amino acetic acid glycine

(H₂N.CH₂.COOH), which has been produced in hydrothermal experiments by Hennet et al. (1992). Once glycine appeared in the sulfide compartments, redox and pH gradients came into effect (Russell and Hall, 1997, 2002). The alkaline mounds constituted the hydrogen electrode, or cathode, and the photolytic Fe^{III} flocculants aggregated at the mound's exterior acted as a positive electrode. It is the Fe^{III} that provides the potential, augmented by the exterior protons, that results in polymerization (Russell and Hall, 1997, 2002). Fe^{III} accepted the electrons ultimately contributed by hydrothermal H₂. Most prokaryotes near the root of the evolutionary tree can use Fe^{III} as an electron acceptor, supporting the notion that this element was the first to fulfill this vital role (McFadden and Shively, 1991; Liu et al., 1997; Pace, 1997; Russell and Hall, 1997; Vargas et al., 1998; Reysenbach and Lovley, 2002).

Today the power of light drives metabolism. In the Hadean, photolytic Fe^{III} represented "borrowed light" that energized and helped drive life's emergence (Cairns-Smith et al., 1992; Russell and Hall, 2002). In theory, the electrochemical potential approaches one volt (Russell and Hall, 1997; Russell et al., 1998); in practice, Russell and Hall (2002) and Filtner et al. (2003) have demonstrated that an FeS membrane, spontaneously precipitated at the interface between solutions containing 10mM of Fe²⁺ >>Fe^{III} on the one side, and 10mM HS⁻ on the other, can hold a tension of 600 to 700 mV for several hours. The gradients had the potential to polymerize inorganic phosphate if water activity was low (Baltscheffsky, 1996). Polymerization may have taken place on the surfaces of closely packed mackinawite nanoclusters making up the inorganic membrane. In turn, and on the same surfaces, pyrophosphate might have polymerized glycine to form homopeptides. That amino acids may be polymerized on saponite clay has been demonstrated by Ferris et al. (1996).

Once formed the primitive peptides coordinated the building blocks of greigite (e.g. [Fe₂S₂]⁺, [Fe₄S₄]²⁺ and perhaps [Fe₄S₆Ni]⁺) that had been inhibited from further growth by organic sulfides such as ethane thiol (CH₃CH₂S⁻) (Bonomi et al., 1985; Stevens and Kurtz, 1985). This started the organic take-over of the mineral-based prebiotic chemistry (Milner-White and Russell, 2004). These peptides also formed a

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

proteinaceous membrane, more stable and flexible than its inorganic precursor, yet with sequestered sulfides and phosphate that were still able to gain electrochemical energy and nutrients from outside the individual cells.

4.2. Evolution in the mound

5 Evolution in the mound extended beyond mere optimization of the chemotrophic acetate reaction (Martin and Russell, 2003). The first step was adaptation to organotrophy, the digestion of the reduced carbon and energy to be found in dead cells. Newly evolved acetogens were the forerunners of the true Bacteria. A minority of cells, derived from those that emerged at around 40°C, exploited the potential offered at higher
10 temperatures deeper in the mound where the kinetic energy was greater and the activation energy required for reduction, through acetate all the way to methane, was lower. These first so-called methanogens may have evolved while still in the mound, where they exploited the greater energy to be had in the full reduction of CO₂ (Amend and Shock, 2001). Methanogenic Archaea derived energy by generating methane from the
15 acetate waste from neighbouring acetogens (Madigan et al., 2000):



Russell and Hall (2002) suggested that such methanogenic cells were the precursors of the Archaea, the sturdy but slowly evolving second domain of the prokaryotes (Woese et al., 1990). If so, the last common ancestor of life occupied the very hatchery in
20 which life first emerged, and the most significant of all cellular differentiations, that between the Bacteria and the Archaea, probably took place before the mound was evacuated (Koga et al., 1998; Martin and Russell, 2003). Up till this time of divergence, genes were shared like software in what may be called a cellular cooperative. Eventually the cells differentiated as opportunities for exploratory evolution in this previously
25 empty habitat presented themselves, a differentiation partly driven by entropy. Random changes in genes eventually gave mutually exclusive phenotypes (Wicken, 1987) and by this stage Mn^{IV} and S⁰ had joined Fe^{III} and CO₂ as electron sinks.

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

In summary we can say that Bacteria were initially suited to low to moderate temperatures, and the Archaea originally evolved to withstand the shock of relatively high temperatures (i.e. $\sim 55^{\circ}\text{C}$). But the propensity to live well above 40°C was passed back to the nascent bacteria through genetic transfer. A period of high ambient temperature, caused either by a bolide impact or a CO_2 greenhouse (Kasting and Akerman, 1986; Kasting and Brown, 1998; Nisbet and Sleep, 2001) could explain why the last common ancestor of all life may have been a thermophile, perhaps living at 50° to 60°C (Gaucher et al., 2003 but see Brochier and Philippe, 2002). Whatever the heating event, it was from the surviving community that the evolutionary tree was seeded.

Representatives of both domains found it advantageous to live syntrophically. Cells relied upon their neighbours to swap genes, provide some of the nutrients and to remove some of the waste. Unfortunates that were entrained within the hydrothermal solution and dispersed to the ocean could not have survived such dilution of nutrient (e.g. Bjerrum and Canfield, 2002). The only way out was down – down onto the ocean floor and into the warm chemical sediments and permeable basalts below.

4.3. Inauguration of the deep biosphere

Growth and expansion of the colonies of acetogens and methanogens followed the redox front laterally out of the mound and into the surrounding sediments. Colonization of the entire seafloor and upper crust was relatively rapid as microbial colonies were entrained in aqueous advection currents. H_2 continued to be the available fuel, diffusing into the sediments from hydrating crust and mantle (Apps and van der Kamp, 1993). H_2 was also provided by fellow metabolizing cells within the syntrophic communities (Wolin, 1982; Towe, 1996). CO_2 for biosynthesis was provided by downward percolating ocean water, and photolytic Fe^{III} , already deposited on the ocean floor, acted as the terminal electron acceptor to maintain electrochemical potential. At some stage fatty acids and lipids started to replace much of the protein in the membrane (Martin and Russell, 2003).

Once life had gained a foothold in the sediments and hydrated volcanics of the ocean

bottom, it would have been extremely hard to eradicate. Strong Earth tides resulting from the shorter day and lunar cycle and the closer moon continuously pumped the required nutrients from above and below (Davis and Becker, 1999). Only Fe^{III}, the main electron acceptor in the chemical sediments, may have been in short supply. Even so, a small flux of H₂ was enough to prevent decay of cellular material and racemization of peptides (Morita, 2000).

Thus the deep biosphere was born (Parkes et al., 1990, 1994; Pedersen, 1993; Thorseth et al., 1995; Wellsbury et al., 1997; Whitman et al., 1998; Kotelnikova and Pedersen, 1997; Furness et al., 2004). At this depth, as the thermal conductivity of saturated sediment and basalt is so low, the prokaryotes were well protected by a layer of insulating sediment and basalt from the effects of impacts, even of those that may have caused the entire ocean to volatilize.

5. Obduction and the emergence of photosynthesis

Given that conditions for life in the open sea were most inhospitable, how do we explain the emergence of photosynthetic organisms in the full glare of hard UV from the young sun (Canuto et al., 1982)? We suggest that obduction brought microbial consortia from the deep ocean floor into the photic zone. Because of the particular geometry of Hadean oceanic crust, chemical sediment overlying hydrated basaltic crust was obducted over the subducting, delaminated, eclogitised lower parts of the slab. Obduction of oceanic sediments, particularly of carbonates and hydrated oxyhydroxides precipitated on the margins of volcanic chains, and of the hydrated basalt beneath, passively transported the bacterial colonies into shallow water and into the photic zone. Cells were protected from deleterious solar radiation beneath a mineral coating, perhaps within a biofilm (Cockell and Knowland, 1999). In these conditions some Bacteria near the surface augmented their protective shield by developing a UV pigment protector from a ring of organic bases. Pigments comprising macrocyclic aromatic rings probably date back to at least 4 Ga (Pratt, 1993). Single ions of Fe, Mg, Zn, Co, and Ni can be

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

sequestered individually in variants of what is known as the corrin or tetrapyrrole ring, itself comprising four C/N rings (Eschenmoser, 1988; Allen, 2004). Pigments developed for photoprotection could then have been adapted as electron transfer agents, as photosynthetic reaction centres and antenna proteins (Mulikidjanian and Junge, 1997; Allen, 2004).

5.1. The first photosynthesisers

The process of photosynthesis was mastered at least by the early Archaean (Westall et al. 2001). The first photosynthesizing bacterium may have been a precursor to the green sulfur bacteria (Baymann et al., 2001). Like some pre-photosynthetic bacteria, these bacteria relied lithotrophically on H₂S as an electron donor. Just as in modern island arcs and accretionary prisms, hydrothermal H₂S of magmatic or metasomatic derivation would have circulated through the sediments in the obducted pile (Fig. 2). In these conditions, a photosynthetic reaction centre (RC1) could have developed that generated elemental sulfur as waste, and gained electrons in the process (Eq. 3).



As we might expect of gradualistic evolution, the green sulfur bacteria continued to rely on iron sulfide clusters as electron transfer agents (Blankenship, 2002).

An evolutionary variant – a photosynthetic precursor of the heliobacteria bacteria – was able to fix CO₂ with electrons supplied indirectly by organic detritus (Vermaas, 1994). This change of electron source echoes the early evolution of biosynthesis, beginning with lithotrophs, followed by rapid and opportunistic adaptation to organotrophy (Sect. 4.2). The heliobacteria substituted a pigment as an electron transfer agent in place of some of the iron-sulfur centres (Allen, 2004). But they retained the use of photosynthetic reaction centre 1 (RC1) (Dismukes et al., 2001; Blankenship, 2002).

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

5.2. Oxygenic photosynthesis

The photosystem (PC2) employed by all cyanobacteria and plants to oxidize water used gene duplication and gene splitting to descend from RC1 (Baymann et al., 2001). These genes probably came from green sulfur bacteria and heliobacteria (Michel and Deisenhofer, 1988; Baymann et al., 2001). PC2 works in conjunction with photosystem 1 (PS1), itself also probably evolved from the first reaction centre (RC1) (Baymann et al., 2001). PS2 is capable of oxidizing two molecules of H₂O during the generation of a single molecule of O₂, gaining incrementally four electrons and four protons for the fixation of carbon from CO₂ or HCO₃⁻ for biosynthesis (Hansson and Wyddrzyński, 1990) (Eqs. 4 and 5).



PS2 oxidizes water using what is known as the oxygen-evolving complex (OEC). Its active centre is a [CaMn₄O₄] cubane containing one Ca atom and three Mn atoms coordinated to a peripheral Mn (Ferreira et al., 2004). To explain such an extraordinary innovation, Russell and Hall (2002) and Russell et al. (2003) suggested that a small cluster, which otherwise would have been interred in the mineral ranciéite [(Ca,Mn²⁺)Mn₄⁴⁺O₉.3H₂O], was co-opted on the outer surface of the membrane of the photosynthetic precursor, and from there sequestered into a protein complex as a 'ready-made' catalytic centre. Ranciéite readily participates in redox reactions and Mn⁴⁺ is reduced by organic molecules (Sunda et al., 1983; Post, 1999). We now imagine the precursors to cyanobacteria embedded at the top of shallow water manganese precipitates with "catalase" activity. Here the precursors exploited the protons and electrons released to them from [CaMn⁴⁺] structures by photons to reduce bicarbonate ions in the pores space (Dismukes et al., 2001). Eventually these [CaMn⁴⁺] molecules with photolytic function were invaginated to become a primitive OEC.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

In ranciéite, Ca^{2+} or a diadochic reduced Mn^{2+} , is coordinated with three oxygens and with the oxygens of three water molecules (cf. Post and Veblen, 1990; Manceau et al., 2002). Calcium and the distal manganese have the same role in the OEC where they ligate two molecules of water prior to their oxidation (Ferreira et al., 2004). However, thus-coordinated, the electrons and protons are stripped from the bonded water in the OEC and transferred separately to take part in biosynthesis, while the two remaining oxide ions bond covalently to form waste O_2 .

5.3. The appearance of oxygenic photosynthesis

We do not know when oxygenic photosynthesis started. Did it appear in the Hadean or at the end of the Archaean, over a billion years later? Geochemical evidence from the Isua Banded Iron Formation (Dymek and Klein 1988), from radio- and stable isotopes in rocks of the same age (Rosing and Frei, 2003), and 16sRNA evolutionary trees (Pace, 2002), suggest that it emerged before 3.75 Ga. Yet soil profiles lacking Fe^{III} and the absence prior to 2.7 Ga of morphological or molecular fossils (the polysaccharide-rich sheaths of cyanobacteria make them particularly prone to fossilization) point to a later age (Westall, 2001, 2004; Blank, 2004).

In the absence of discriminatory evidence, our own preference – based on our plate tectonic scenario, the rapidity with which dynamic structures evolve and emerge in the Universe, the pedigree of PS2 founded in the antecedent RC1, and the likely ubiquity of $[\text{CaMn}^{4+}]$ molecules in shallow water sediments – is for an early onset of oxygenic photosynthesis. The absence of atmospheric oxygen prior to 2.7 Ga is then explained by the buffering effects of reduced iron and sulfide in the ocean and crust, the flooding of the atmosphere with methane from the deep biosphere, the relatively low productivity in the oceans, and by the reduction of O_2 by ambient bacteria in microbial mats (Lécuyer and Ricard, 1999; Farquar et al., 2000; Timmins et al., 2001; Bjerrum and Canfield, 2002; Arnold et al., 2004).

6. Conclusions

1. Geodynamic and metabolic cycles are closely coupled on our planet, a coupling even more direct the first metabolizing systems emerged in moderate-temperature alkaline submarine seepages (Russell and Martin, 2004). Within catalytic iron sulfide cells in the hydrothermal mound, these “metabolists” gained genetic machinery and differentiated into the two prokaryotic domains, the Bacteria and the Archaea (Martin and Russell, 2003). It is likely that life had emerged on the planet at least by 4.2 Ga (Russell and Hall, 1997).
2. Gradual expansion of colonies of prokaryotes from the mound into surrounding sediments on the ocean floor provided a protected environment. From here the colonies were entrained in migrating fluids to depth in the oceanic crust to inaugurate the deep biosphere (Parkes et al., 1990, 1994; Pedersen, 1993; Thorseth et al., 1995). A continual draft of H₂ from the crust and mantle prevented bacterial decay.
3. Because of the relatively low conductivity of mafic rock, the deep biosphere could remain immune from bolide-induced heating events.
4. Obduction of the deep biosphere into the photic zone allowed evolution within shallow-water chemical sediments. Photoprotective molecules first developed from aromatic ring compounds previously employed in group and electron transfer, and from these the photosynthetic reaction centres and antenna proteins evolved (Mulkidjanian et al., 1997; Baymann et al., 2001; Allen, 2004).
5. The first photosynthesists, probable precursors of the green sulfur bacteria, used hydrothermal H₂S as an electron donor and produced S⁰ as waste. The precursors of the heliobacteria then used organic waste as the electron donor (Vermaas, 1994). The biggest evolutionary leap involved the heterodimerization of the reaction centres (RC1) of the green sulfur bacteria and the heliobacteria, and resulted

BGD

1, 591–624, 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

in the combined cyanobacterial PS1 and PS2 (Blankenship, 2002).

6. Both chemosynthesis and oxygenic photosynthesis emerged within mineral constituents (greigite [NiFe₅S₈] and ranciéite [CaMn₄O₉.3H₂O]) with catalytic propensity, moieties of which are employed as reactive centres in protein complexes to this day.

Acknowledgements. This paper was written while MJR was a visiting professor at University Joseph Fourier in Grenoble. The research was supported by grants to NTA from two programs of the Centre National de Recherche Scientifique: the Programme Nationale de Planétologie and the Groupement de Recherche d'Exobiologie. We thank B. Martin, W. Nitschke, and A. Hall for their help, and L. Charlet, F. Westall for reviews of the manuscript.

References

- Allen, D. A. and Seyfried, W. E.: Compositional controls on vent fluids from ultramafic – hosted hydrothermal systems at mid-ocean ridges: An experimental study at 400°C, 500 bars, *Geochimica Cosmochimica Acta*, 67, 1531–1542, 2003.
- Allen, J. F.: Cytochrome *b₆f*: structure for signaling and vectorial metabolism, *Trends in Plant Science* 9, 130–137, 2004.
- Alt, J. C. and Teagle, D. A. H.: The uptake of carbon during alteration of the oceanic crust, *Geochimica et Cosmochimica Acta*, 63, 1527–1535, 1999.
- Amend, J. P. and Shock, E. L.: Energetics of overall metabolic reactions of thermophilic and hyperthermophilic Archaea and Bacteria, *FEMS Microbiological Reviews*, 25, 175–243, 2001.
- Anderson, R. B., Langseth, M. G., and Sclater, J. G.: The mechanisms of heat transfer through the floor of the Indian Ocean, *Journal of Geophysical Research*, 82, 3391–3409, 1977.
- Apps, J. A. and Van der Kamp, P. C.: Energy gases of abiogenic origin in the Earth's crust. The future of energy gases, US Geological Survey, Professional Paper 1570, 81–132, 1993.
- Armstrong, R. L.: Radiogenic isotopes: the case for crustal recycling on a near-steady-state no-continental-growth Earth, *Philosophical Transactions of the Royal Society of London (Ser. A)*, 301, 443–472, 1981.
- Armstrong, R. L.: The persistent myth of crustal growth, *Australian Journal of Earth Sciences*, 38, 613–630, 1991.

BGD

1, 591–624, 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

- Arnold, G. L., Anbar, A. D., Barling, J., and Lyons, T. W.: Molybdenum isotope evidence for widespread anoxia in Mid-Proterozoic oceans, *Science express*, 5 March, 2004.
- Arndt, N. T.: Why was flood volcanism on submerged continental platforms so common in the Precambrian?, *Precambrian Research*, 97, 155–164, 1999.
- 5 Bahcall, J. N., Pinsonneault, M. H., and Basu, S.: Solar models: Current epoch and time dependences, neutrinos and helioseismological properties, *Astrophysical Journal*, 555, 990–1012, 2001.
- Baltscheffsky, H.: Energy conversion leading to the origin and early evolution of life: Did inorganic pyrophosphate precede adenosine triphosphate? In *Origin and Evolution of Biological Energy Conversion*, edited by Baltscheffsky, H., VCH Publishers, Cambridge, pp. 1–9, 1996.
- 10 Baymann, F., Brugna, M., Mühlenhoff, U., and Nitschke, W.: Daddy, where did (PS)I come from? *Biochimica Cosmochimica Acta*, 1507, 291–310, 2001.
- Baymann, F., Lebrun, E., Brugna, M., Schoepp-Cothenet, B., Giudici-Ortoni, M. T., and Nitschke, W.: The redox protein construction kit: pre-last universal common ancestor evolution of energy-conserving enzymes, *Philosophical Transactions of the Royal Society of London*, 358B, 267–274, 2003.
- 15 Bischoff, J. L. and Rosenbauer, R. J.: The critical point and two-phase boundary of seawater, 200–500°C, *Earth and Planetary Science Letters*, 68, 172–180, 1984.
- Bjerrum, C. J. and Canfield, D. E.: Ocean productivity before about 1.9 Gyr ago limited by phosphorus adsorption onto iron oxides, *Nature*, 417, 159–162, 2002.
- 20 Blank, C. E.: Evolutionary timing of the origins of mesophilic sulphate reduction and oxygenic photosynthesis: a phylogenomic dating approach, *Geobiology*, 2, 1–20, 2004.
- Blankenship, R. E.: *Molecular Mechanisms of Photosynthesis*, Blackwell Science, Oxford, 2002.
- 25 Bonatti, E., Simmons, E. C., Breger, D., Hamlyn, P. R., and Lawrence, J.: Ultramafic rock/seawater interaction in the oceanic crust: Mg-silicate (sepiolite) deposit from the Indian Ocean floor, *Earth and Planetary Science Letters*, 62, 229–238, 1983.
- Bonomi, F., Werth, M. T., and Kurtz, D. M.: Assembly of $\text{Fe}_n\text{S}_n(\text{SR})^{2-}$ ($n=2,4$) in aqueous media from iron salts, thiols and sulfur, sulfide, thiosulfide plus rhodanase: *Inorganic Chemistry*, 24, 4331–4335, 1985.
- 30 Bounama, C., Franck, S., and von Bloh, W.: The fate of the Earth's ocean, *Hydrology and Earth System Sciences*, 5, 569–575, 2001.
- Bowring, S. A. and Williams, I. S.: Priscoan (4.00–4.03 Ga) orthogneisses from northwest

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

Canada, Contributions Mineralogy Petrology, 134, 3–16, 1999.

Braterman, P. S., Cairns-Smith, A. G., and Sloper, R. A.: Photo-oxidation of hydrated Fe^{2+} – significance for banded iron formations, *Nature*, 303, 163–164, 1983.

Brochier, C. and Philippe, H.: A non-hyperthermophilic ancestor for bacteria, *Nature*, 417, 244, 2002.

Cairns-Smith, A. G., Hall, A. J., and Russell, M. J.: Mineral theories of the origin of life and an iron sulphide example, *Origins of life and evolution of the Biosphere*, 22, 161–180, 1992.

Campbell, I. H., Griffiths, R. W., and Hill, R. I.: Melting in an Archaean mantle plume: heads it's basalts, tails it's komatiites, *Nature*, 339, 697–699, 1989.

Canuto, V. M., Levine, J. S., Augustsson, T. R., and Imhoff, C. L.: UV radiation from the young Sun and oxygen and ozone levels in the prebiological palaeoatmosphere, *Nature*, 296, 816–820, 1982.

Cathles, L. M.: Scales and effects of fluid flow in the upper crust, *Science*, 248, 323–329, 1990.

Cockell, C. S. and Knowland, J.: UV radiation screening compounds, *Biological Reviews*, 74, 311–345, 1999.

Compston, W. and Pidgeon, R. T.: Jack Hills, evidence of more very old detrital zircons in Western Australia, *Nature*, 321, 766–769, 1986.

Darnault, C., Volbeda, A., Kim, E. J., Legrand, P., Vernède, X., Lindahl, P. A., and Fontecilla-Camps, J. C.: Ni-Zn- $[\text{Fe}_4\text{-S}_4]$ and Ni-Ni- $[\text{Fe}_4\text{-S}_4]$ clusters in closed and open α subunits of acetyl-CoA synthase/carbon monoxide dehydrogenase, *Nature Structural Biology*, 10, 271–279, 2003.

Davies, G. F.: On the emergence of plate tectonics, *Geology*, 20, 963–966, 1992.

Davis, E. E. and Becker, K.: Tidal pumping of fluids from the oceanic crust: New observations and opportunities for sampling the crustal hydrosphere, *Earth and Planetary Science Letters*, 172, 141–149, 1999.

Dismukes, G. C., Klimov, V. V., Baranov, S. V., Kozlov, Yu. N., DasGupta, J., and Tyryshkin, A.: The origin of atmospheric oxygen on Earth: The innovation of oxygenic photosynthesis, *Proceedings of the National Academy of Science, USA*, 99, 2170–2175, 2001.

Dobbeck, H., Svetlitchnyi, V., Gremer, L., Huber, R., and Meyer, O.: Crystal structure of a carbon monoxide dehydrogenase reveals a $[\text{Ni-4Fe-5S}]$ cluster, *Science*, 293, 1281–1285, 2001.

Douville, E., Charlou, J. L., Oelkers, E. H., Bienvvenu, P., Colon, C. F. J., Donval, J. P., Fouquet, Y., Prieur, D., and Appriou, P.: The rainbow vent fluids ($36^\circ 14' \text{N}$, MAR): the influence of ultra-

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

mafic rocks and phase separation on trace metal content in Mid-Atlantic Ridge hydrothermal fluids, *Chemical Geology*, 184, 37–48, 2002.

Drennan, C. L., Heo, J., Sintchak, M. D., Schreiter, E., and Ludden, P. W.: Life on carbon monoxide: X-ray structure of *Rhodospirillum rubrum* Ni-Fe-S carbon monoxide dehydrogenase, *Proceedings of the National Academy of Science, USA*, 98, 11 973–11 978, 2001.

Dymek, R. F. and Klein, C.: Chemistry, petrology and origin of banded iron-formation lithologies from the 3800 Ma Isua Supracrustal Belt, West Greenland, *Precambrian Research*, 39, 247–302, 1988.

Eck, R. V. and Dayhoff, M. O.: Evolution of the structure of ferredoxin based on living relics of primitive amino acid sequences, *Science*, 152, 363–366, 1966.

Eschenmoser, A.: Vitamin B12: experiments concerning the origin of its molecular structure, *Angewandte Chemie (International edition in English)*, 27, 5–39, 1988.

Faggerbakke, K. M., Heldal, M., and Norland, S.: Content of carbon, nitrogen, oxygen, sulfur and phosphorous in native aquatic and cultured bacteria, *Aquatic Microbial Ecology*, 10, 15–27, 1996.

Farquhar, J., Bao, H., and Thiemens, M. H.: Atmospheric influence of Earth's earliest sulfur cycle, *Science*, 289, 756–758, 2000.

Ferreira, K. N., Iverson, T. M., Maghlaoui, K., Barber, J., and Iwata, S.: Architecture of the photosynthetic oxygen-evolving center, *Science*, 303, 1831–1838, 2004.

Ferris, J. P., Hill, A. R. Liu, R., and Orgel, L. E.: Synthesis of long prebiotic oligomers on mineral surfaces, *Nature*, 381, 59–61, 1996.

Filtness, M. J., Butler, I. B., and Rickard, D.: The origin of life: the properties of iron sulphide membranes, *Applied Earth Science (Trans. Inst. Min. Metall.)*, 112B, 171–172, 2003.

Foley, S. F., Buhre, S., and Jacob, D. E.: Evolution of the Archaean crust by delamination and shallow subduction, *Nature*, 421, 249–252, 2003.

Forterre, P.: A hot topic: the origin of hyperthermophiles, *Cell*, 85, 789–792, 1996.

Francis, D., Luddon, J., Johnstone, R., and Davis, W.: Picrite evidence for more Fe in Archean mantle reservoirs, *Earth and Planetary Science Letters*, 167, 197–213, 1999.

Froude, D. O., Ireland, T. R., Kinny, P. O., Williams, I. S., and Compston, W.: Ion microprobe identification of 4100–4200 Ma-old terrestrial zircons, *Nature*, 304, 616–618, 1983.

Furness, H., Banerjee, N. R., Muehlenbachs, K., Staudigel, H., and de Wit, M.: Early life recorded in Archean pillow lavas, *Science*, 304, 578–581, 2004.

Gaffey, M. J.: The early solar system. *Origins of Life and Evolution of the Biosphere*, 27, 185–

203, 1997.

Gaucher, E. A., Thomson, J. M., Burgan, M., and Benner, S. A.: Inferring the palaeoenvironment of ancient bacteria on the basis of resurrected proteins, *Nature*, 425, 285–288, 2003.

Geptner, A., Kristmannsdóttir, H., Kristjánsson, J. K., and Marteinson, V. Th.: Biogenic saponite from an active submarine hot spring, Iceland, *Clays and Clay Minerals*, 50, 174–185, 2002.

Haeckel, E.: *The History of Creation*, Translated by Lankester, E. R., Appleton, London, 1892 (1876).

Hall, D. O., Cammack, R., and Rao, K. K.: Role for ferredoxins in the origin of life and biological evolution, *Nature*, 233, 136–138, 1971.

Hansson, Ö and Wydrzynski, T.: Current perceptions of Photosystem II., *Photosynthesis Research*, 23, 131–162, 1990.

Heinen, W. and Lauwers, A. M.: Organic sulfur compounds resulting from the interaction of iron sulfide, hydrogen sulfide and carbon dioxide in an anaerobic aqueous environment, *Origins of Life and Evolution of the Biosphere*, 26, 131–150, 1996.

Hennet, R. J.-C., Holm, N. G., and Engel, M. H.: Abiotic synthesis of amino acids under hydrothermal conditions and the origin of life: A perpetual phenomenon?, *Naturwissenschaften*, 79, 361–365, 1992.

Holmes, A.: Radioactivity and Earth movements, *Transactions of the Geological Society of Glasgow*, 18, 559–606, 1931.

Huber, C. and Wächtershäuser, G.: Activated acetic acid by carbon fixation on (Fe,Ni)S under primordial conditions, *Science*, 276, 245–247, 1997.

Janecky, D. R. and Seyfried, W. E.: The solubility of magnesium-hydroxide-sulfate-hydrate in seawater at elevated temperatures and pressures, *American Journal of Science*, 283, 831–860, 1983.

Takegawa, T., Noda, M., and Nannri, H.: Geochemical cycles of bio-essential elements on the early Earth and their relationships to the origin of life, *Resource Geology*, 52, 83–89, 2002.

Karsten, J. L., Klein, E. M., and Sherman, S. B.: Subduction zone geochemical characteristics in ocean ridge basalts from the southern Chile ridge: implications of modern subduction systems for the Archean, *Lithos*, 37, 143–161, 1996.

Kasting, J. F.: Earth's early atmosphere, *Science*, 259, 920–926, 1993.

Kasting, J. F. and Ackerman, T. P.: Climatic consequences of very high carbon dioxide levels in the earth's early atmosphere, *Science*, 234, 1383–1385, 1986.

BGD

1, 591–624, 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

- Kasting, J. F. and Brown, L. L.: The early atmosphere as a source of biogenic compounds, In A. Brack, editor, *The Molecular Origins of Life*, Cambridge University Press, 35–56, 1998.
- Kelley, D. S., Karson, J. A., Blackman, D. K., Früh-Green, G. L., Butterfield, D. A., Lilley, M. D., Olson, E. J., Schrenk, M. O., Roe, K. K., Lebon, G. T., and Rivizzigno, P.: AT3-60 Shipboard Party, An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30° N, *Nature*, 12, 127–128, 2001.
- Koga, Y., Kyuragi, T., Nishihara, M., and Sone, N.: Did archaeal and bacterial cells arise independently from noncellular precursors? A hypothesis stating that the advent of membrane phospholipid with enantiomeric glycerophosphate backbones caused the separation of the two lines of descent, *Journal of Molecular Evolution*, 46, 54–63, 1998.
- Kotelnikova, S. and Pedersen, K.: Evidence for methanogenic *Archaea* and homoacetogenic *Bacteria* in deep granitic rock aquifers, *FEMS Microbiology Reviews* 20, 339–349, 1997.
- Kramers, J. D.: Volatile element abundance patterns and early liquid water ocean on Earth, *Precambrian Research*, 126, 379–394, 2003.
- Lécuyer, C. and Ricard, Y.: Long-term fluxes and budget of ferric iron for the redox states of the Earth's mantle and atmosphere, *Earth and Planetary Science Letters*, 165, 197–211, 1999.
- Leduc, S.: *The Mechanism of Life*, Rebman Ltd., London, 1911.
- Liu, S. V., Zhou, J., Zhang, C., Cole, D. R., Gajdarziska-Josifovska, M., and Phelps, T. J.: Thermophilic Fe(III)-reducing bacteria from the deep subsurface: the evolutionary implications, *Science*, 277, 1106–1109, 1997.
- Luther, G. W., Theberge, S. M., and Rickard, D. T.: Evidence for aqueous clusters as intermediates during zinc sulfide formation, *Geochimica Cosmochimica Acta*, 63, 3159–3169, 1999.
- Macalady, J. and Banfield, J. F.: Molecular geomicrobiology: genes and geochemical cycling, *Earth and Planetary Science Letters*, 209, 1–17, 2003.
- Macleod, G., McKeown, C., Hall, A. J., and Russell, M. J.: Hydrothermal and oceanic pH conditions of possible relevance to the origin of life, *Origins of Life and Evolution of the Biosphere*, 24, 19–41, 1994.
- Madigan, M. T., Matinko, J. M., and Parker, J.: *Brock: Biology of Microorganisms*, New Jersey, Prentice Hall, 2000.
- Maisonneuve, J.: The composition of the Precambrian ocean waters, *Sedimentary Geology*, 31, 1–11, 1982.
- Manceau, A., Lanson, B., and Drits, V. A.: Structure of heavy metal sorbed birnesite. Part III:

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

- Results from powder and polarized extended X-ray absorption fine structure spectroscopy, *Geochimica Cosmochimica Acta*, 66, 2639–2663, 2002.
- Maruyama, S.: Pacific-type orogeny revisited: Miyashiro-type orogeny proposed, *The Island Arc*, 6, 91–120, 1997.
- 5 Marteinson, V. Th., Kristjánsson, J. K., Kristmannsdóttir, H., Samundsson, K., Hannington, M., Petursdottir, S. K., Geptner, A., and Stoffers, P.: Discovery and description of giant submarine smectite cones on the seafloor in Eyjafjordur, Northern Iceland, and a novel thermal microbial habitat, *Applied and Environmental Microbiology*, 67, 827–833, 2001.
- Martin, W. and Russell, M. J.: On the origin of cells: An hypothesis for the evolutionary transi-
10 tions from abiotic geochemistry to chemoautotrophic prokaryotes and from prokaryotes to nucleated cells, *Philosophical Transactions of the Royal Society of London*, 358B, 27–85, 2003.
- McFadden, B. A. and Shively, J. M.: Bacterial assimilation of carbon dioxide by the Calvin cycle, In *Variation in Autotrophic Life*, edited by Shively, J. M. and Barton, L. L., Academic Press, 15 25–50, 1991.
- Menon, S. and Ragsdale, S. W.: Unleashing hydrogenase activity in carbon monoxide dehydrogenase/acetyl-CoA synthase and pyruvate:ferredoxin oxidoreductase, *Science*, 287, 1245–1247, 2000.
- Michel, H. and Deisenhofer, J.: Relevance of the photosynthetic reaction center from purple
20 bacteria to the structure of photosystem II, *Biochemistry*, 27, 1–7, 1988.
- Milner-White, E. J. and Russell, M. J.: Sites for phosphates and iron-sulfur thiolates in the first membranes: 3 to 6 residue anion-binding motifs (nests), *Origins of Life and Evolution of the Biosphere*, 34, in press, 2004.
- Morita, R. Y.: Is H₂ the universal energy source for long-term survival?, *Microbial Ecology*, 38,
25 307–320, 2000.
- Morel, F. M. M. and Hudson, R. J. M.: The geobiological cycle of trace elements in aquatic systems: Redfield revisited. In *Chemical Processes in Lakes*, edited by W. Stumm, Wiley-Interscience, New York, 251–281, 1985.
- Moulton, V., Gardner, P. P., Pointon, R. F., Creamer, L. K., Jameson, G. B., and Penny, D.: RNA
30 folding argues against a hot origin of life, *Journal Molecular Evolution*, 51, 416–421, 2000.
- Mulkidjanian, A. Y. and Junge, W.: On the origin of photosynthesis as inferred from sequence analysis – a primordial UV-protector as common ancestor of reaction centers and antenna proteins, *Photosynthesis Research* 51, 27–42, 1997.

- Nisbet, E. G. and Sleep, N. H.: The habitat and nature of early life, *Nature*, 409, 1083–1091, 2001.
- Orr, W.: Sulfur: In *Handbook of Geochemistry*, Vol. II/2, edited by Wedepohl, K. H., Berlin, Springer-Verlag, 16-L-5, 1978.
- 5 Pace, N. R.: A molecular view of microbial diversity and the biosphere, *Science*, 276, 734–740, 1997.
- Pace, N. R.: The large scale topology of the tree of life, *Abstract, Astrobiology*, 2, 484, 2002.
- Parkes, R. J., Cragg, B. A., Fry, J. C., Herbert, R. A., and Wimpenny, J. W. T.: Bacterial biomass and activity in deep sediment layers from the Peru margin: *Philosophical Transactions of the Royal Society of London*, 331A, 139–153, 1990.
- 10 Parkes, R. J., Cragg, B. A., Bale, S. J., Getliff, J. M., Goodman, K., Rochelle, P. A., Fry, J. C., Weightman, A. J., and Harvey, S. M.: Deep bacterial biosphere in Pacific Ocean sediments, *Nature*, 371, 410–413, 1994.
- Pavlov, A. A. and Kasting, J. F.: Mass-independent fractionation of sulfur isotopes in Archean sediments: Strong evidence for an anoxic Archean atmosphere, *Astrobiology*, 2, 27–41, 2002.
- 15 Pederson, K.: The deep subterranean biosphere, *Earth Science Reviews* 34, 243–260, 1993.
- Peretó, J. G., Velasco, A. M., Becerra, A., and Lazcano, A.: Comparative biochemistry of CO₂ fixation and the evolution of autotrophy, *International Microbiology*, 2, 3–10, 1999.
- 20 Post, J. E. and Veblen, D. R.: Crystal structure determinations of synthetic sodium, magnesium and potassium birnessite using TEM and the Rietveld method, *American Mineralogist*, 75, 477–489, 1990.
- Pratt, J. M.: Nature's design and use of catalysts based on Co and the macrocyclic corrin ligand: 4 × 10⁹ years of coordination chemistry, *Pure and Applied Chemistry*, 65, 1513–1520, 1993.
- 25 Rahman, L.: The geochemical modelling of emergent life from submarine hydrothermal environments, unpublished PhD thesis, University of Glasgow, 2002.
- Redfield, A. C., Ketchum, B. H., and Richards, F. A.: The influence of organisms on the composition of seawater: In *The Sea*, edited by Hill, M. N., 2, Wiley-Interscience, New York, 26–77, 1963.
- 30 Reysenbach, A. L. and Lovley, D. R. *Geoglobus ahangari*, gen. nov., sp., nov., a novel hyperthermophile capable of oxidizing organic acids and growing autotrophically on hydrogen with Fe (III) serving as the sole electron acceptor, *International Journal Systematic Evolutionary*

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

Microbiology, 52, 719–728, 2002.

Rickard, D., Butler, I. B., and Olroyd, A.: A novel iron sulphide switch and its implications for earth and planetary science, *Earth and Planetary Science Letters*, 189, 85–91, 2001.

Rosing, M. T. and Frei, R.: U-rich Archaean sea-floor sediments from Greenland – indications of >3700 Ma oxygenic photosynthesis, *Earth and Planetary Science Letters*, 217, 237–244, 2003.

Russell, M. J., Hall, A. J., Cairns-Smith, A. G., and Braterman, P. S.: Submarine hot springs and the origin of life, -correspondence-, *Nature*, 336, 117, 1988.

Russell, M. J., Daniel, R. M., Hall, A. J., and Sherringham, J.: A hydrothermally precipitated catalytic iron sulphide membrane as a first step toward life, *Journal of Molecular Evolution*, 39, 231–243, 1994.

Russell, M. J. and Hall, A. J.: The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front, *Journal of the Geological Society of London*, 154, 377–402, 1997.

Russell, M. J., Daia, D. E., and Hall, A. J.: The emergence of life from FeS bubbles at alkaline hot springs in an acid ocean. In *Thermophiles: The Keys to Molecular Evolution and the Origin of Life*, edited by Wiegel, J. and Adams, M. W. W., Taylor and Francis, Washington, 77–126, 1998.

Russell, M. J. and Hall, A. J.: From geochemistry to biochemistry: chemiosmotic coupling and transition element clusters in the onset of life and photosynthesis, *The Geochemical News*, no. 113/October, 6–12, 2002.

Russell, M. J.: On the importance of being alkaline, *Science*, 302, 580–581, 2003.

Russell, M. J., Hall, A. J., and Mellersh, A. R.: On the dissipation of thermal and chemical energies on the early Earth: The onsets of hydrothermal convection, chemiosmosis, genetically regulated metabolism and oxygenic photosynthesis, In *Natural and Laboratory-Simulated Thermal Geochemical Processes*, edited by R. Ikan, Dordrecht, Kluwer Academic Publishers, 325–388, 2003.

Russell, M. J. and Martin, W.: The rocky roots of the acetyl-CoA pathway, *Trends in Biochemical Sciences*, 29, 358–363, 2004.

Sandiford, M. and McLaren, S.: Thermo-mechanical controls on heat production distributions and the long-term evolution of the continents, In *Evolution and Differentiation of Continental Crust*, edited by Brown, M. and Rushmer, T., Cambridge University Press, 2004.

Schulte, M. D. and Rogers, K. L.: Thiols in hydrothermal solution: Standard partial molar prop-

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

- erties and their role in the organic geochemistry of hydrothermal environments, *Geochimica et Cosmochimica Acta*, 68, 1087–1097, 2004.
- Schwartzman, D. W. and Lineweaver, C. H.: The hyperthermophilic origin of life revisited, *Biochemical Society Transaction*, 32, 168–171, 2004.
- 5 Sedwick, P. N., McMurtry, G. M., Hilton, D. R. and Goff, F.: Carbon dioxide and helium in hydrothermal fluids from Lothi Seamount, Hawaii, USA, *Temporal variability and implications for the release of mantle volatiles*, *Geochimica Cosmochimica Acta*, 58, 1219–1227, 1994.
- Shock, E. L.: Chemical environments of submarine hydrothermal systems, *Origins of Life and Evolution of the Biosphere*, 22, 67–107, 1992.
- 10 Shock, E. L., McCollom, T., and Schulte, M. D.: The emergence of metabolism from within hydrothermal systems. In *Thermophiles: The Keys to Molecular Evolution and the Origin of Life*, edited by Wiegel, J. ad Adams, M. W. W., Taylor and Francis, Washington, 59–76, 1998.
- Sleep, N. H. and Windley, B. F.: Archean plate tectonics: constraints and influences, *Journal Geology*, 90, 363–379, 1982.
- 15 Stevens, W. C. and Kurtz, D. M.: Assembly of $[\text{Fe}_n\text{S}_n(\text{SPh})_4]^{2-}$ ($n = 2,4$) and their iron-thiolate precursors in aqueous media, *American Chemical Society*, 24, 3444–3449, 1985.
- Stevenson, R. K., David, J., and Parent, M.: Isotopic evolution of the Minto Block, Northeastern Superior Province, Quebec, *GAC-MAC, Vancouver*, Abstract 342, 2003.
- Sunda, W. G., Huntsman, S. A., and Harvey, G. R.: Photoreduction of manganese oxides in seawater and its geochemical and biological implications, *Nature*, 301, 234–236, 1983.
- 20 Thorseth, I. H., Torsvik, T., Furness, H., and Muehlenbachs, K.: Microbes play an important role in the alteration of oceanic crust, *Chemical Geology*, 126, 137–146, 1995.
- Timmins, G. S., Jackson, S. K., and Swartz, H. M.: The evolution of bioluminescent oxygen consumption as an ancient oxygen detoxification mechanism, *Journal of Molecular Evolution*,
- 25 52, 321–332, 2001.
- Towe, K. M.: Environmental oxygen conditions during the origin and evolution of life, *Advanced Space Research*, 18, 7–15, 1996.
- Turcotte D. L.: On the thermal evolution of the Earth, *Earth and Planetary Science Letters*, 48, 53–58, 1980.
- 30 Van Hunen, J., van den Berg, A. P., and Vlaar, N. J.: On the role of subducting oceanic plateaus in the development of shallow flat subduction, *Tectonophysics*, 352, 317–334, 2002.
- Vargas, M., Kashefi, K., Blunt-Harris, E. L., and Lovley, D. R.: Microbial evidence for Fe(III) reduction on early Earth, *Nature*, 395, 65–67, 1988.

**Hadean geodynamic
and metabolic cycles**

M. J. Russell and N. T.
Arndt

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2004

- Vaughan, D. J. and Craig, J. R.: Mineral Chemistry of Natural Sulfides, Cambridge University Press, 1978.
- Vermaas, W. F. J.: Evolution of heliobacteria: implications for photosynthetic reaction center complexes, *Photosynthesis Research*, 41, 285–294, 1994.
- 5 Vermaas, W. F. J.: Photosynthetic reaction centers, antenna complexes, chlorophyll-binding proteins, gene duplication and divergence, sequence alignment, *Encyclopedia of Life Sciences*, Nature Publishing Co., <http://eee.els.net>, 2003.
- Von Damm, K. L.: Sea floor hydrothermal activity: Black smoker chemistry and chimneys, *Annual Review of Earth and Planetary Sciences*, 18, 173–204, 1990.
- 10 Von Damm, K. L.: Chemistry of hydrothermal vent fluids from 9°–10° N, East Pacific Rise: “Time zero”, the immediate post eruptive period, *Journal of Geophysical Research*, 105, B5, 11 203–11 222, 2000.
- Walker, J. C. G. and Brimblecombe, P.: Iron and sulfur in the pre-biological ocean, *Precambrian Research*, 28, 205–222, 1985.
- 15 Westall, F., De Wit, M. J., Dann, J., Van Der Gaast., S., De Ronde., C., and Gerneke., D.: Early Archean Fossil Bacteria and Biofilms in Hydrothermally Influenced Sediments from the Barberton Greenstone Belt, South Africa, *Precambrian Research*, 106, 93–116, 2001.
- Westall, F.: The geological context for the origin of life and the mineral signatures of fossil life, In *The Early Earth and the Origin of Life*, edited by Barbier et al., Springer, 2004.
- 20 Wellsbury, P., Goodman, K., Barth, T., Cragg, B. A., Barnes, S. P., and Parkes, R. J.: Deep marine biosphere fuelled by increasing organic matter availability during burial and heating, *Nature*, 388, 573–576, 1997.
- Wheat, C. G., Mottl, M. M., and Rudnicki, M.: Trace element and REE composition of a low-temperature ridge-flank hydrothermal spring, *Geochimica Cosmochimica Acta*, 66, 3693–3705, 2002.
- 25 Whitman, W. B., Coleman, D. C., and Wiebe, W. J.: Prokaryotes: The unseen majority, *Proceedings of the National Academy of Science, USA*, 95, 6578–6583, 1998.
- Wicken, J. S.: *Evolution, Information and Thermodynamics: Extending the Darwinian Program*, Oxford University Press, New York, 1987.
- 30 Wilde, S. A., Valley, J. W., Peck, W. H., and Graham, C. M.: Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago, *Nature*, 409, 175–178, 2001.
- Woese, C. R., Kandler, O., and Wheelis, M. L.: Towards a natural system of organisms: pro-

posal for the domains Archaea, Bacteria and Eucarya, Proceedings of the National Academy of Science, USA, 87, 4576–4579, 1990.

Wolin, M. J.: Hydrogen transfer in microbial communities: In Microbial Interactions and Communities, edited by Bull, A. T. and Slater, J. H., Academic Press, London, 323–356, 1982.

- 5 Wolthers, M., Van der Gaast, S. J., and Rickard, D.: The structure of disordered mackinawite, American Mineralogist, 88, 2007–2015, 2003.

BGD

1, 591–624, 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2004

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

Table 1. Comparison between types of modern high submarine springs.

Parameter	J da Fuca ¹	Rainbow ²	Lost City ³	Eyjafjordur ⁴
T°C	224°	365°	40°–75°	71.4°
pH	3.2	2.8	≤9.8	10.03 (24°C)
age yr	na	na	na	11 000
H ₂	na	13	0.43	na
H ₂ S	3.5	1.0	0.064	0.01
SO ₄	0	(0)	5.9–12.9	0.2
Fe	18.74	24	na	0.00014
Mn	3.58	2.25	na	0.0000018
Mg	0	0	9–19	0.01
Ca	96.4	67	22	0.061
Na	796	553	482	3.4
K	51.6	20	na	4.2
SiO ₂	23.3	6.9	na	1.6
CO ₂	≤4.46	na	na	0.57
Cl	1087	380	548	1.26
Co	na	0.013	na	na
Ni	na	0.003	na	na
Zn	0.9	0.16	na	na
Mo	na	0.000002	na	na

Data for columns ¹ to ⁴ from Von Damm (1990), Douville et al. (2002), Kelley et al. (2001) and Marteinsson et al. (2001). Elemental and molecular concentrations are in millimoles. Temperatures at the base of the convection cells developed at oceanic spreading centres and the off-ridge systems are presumed to be ~400°C and ~100°C, respectively.

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

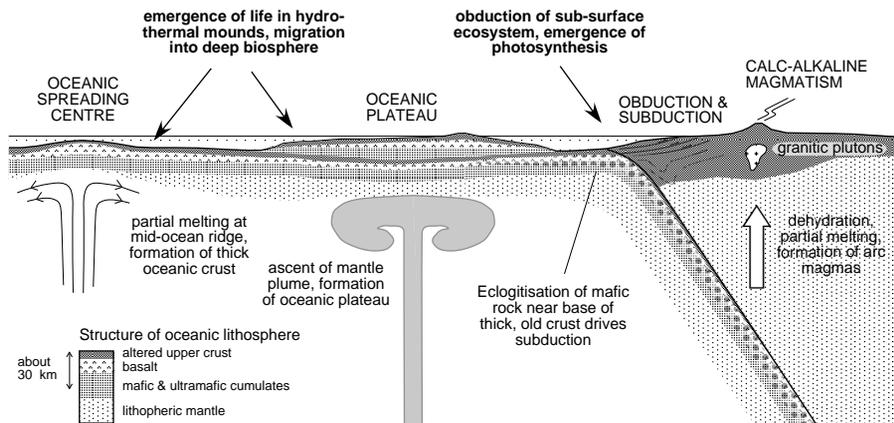


Fig. 1. Cross-section of mantle convection cell for the Earth at the Hadean/Archaean boundary (Campbell et al., 1989; Davies, 1992; Foley et al., 2003). Life is held to have emerged at an alkaline seepage site. An early batch of prokaryotic colonies comprising the “deep biosphere” were conveyed toward a plate margin where they were obducted into the photic zone, facilitating the onset of photosynthesis. (At times and in places plume-type convective mass transfer may have involved the whole mantle.)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

Hadean geodynamic and metabolic cycles

M. J. Russell and N. T. Arndt

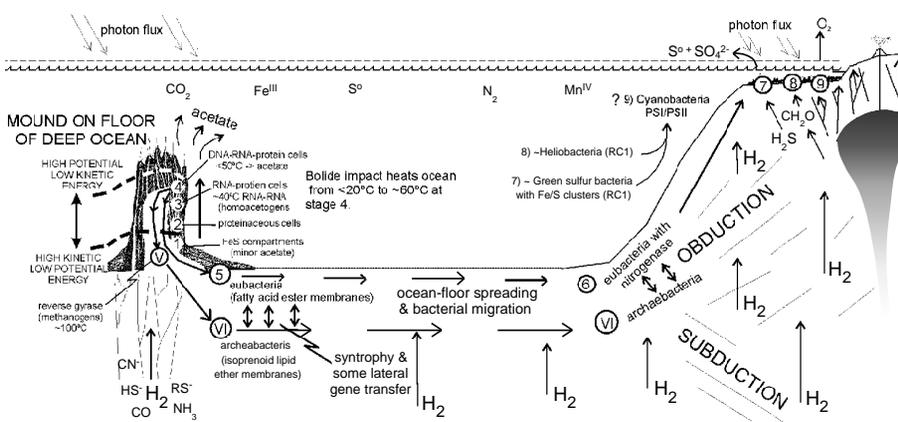


Fig. 2. Chemosynthetic life emerges at a warm alkaline seepage, differentiates into the precursors of the bacteria and archaea, and expands into the surrounding sediments and crust (Martin and Russell, 2003; Russell and Martin, 2004). From here a proportion is conveyed by ocean floor spreading toward a constructive margin produced largely by obduction. Once at the margin some of the cells happen to invade sediments in the photic zone where, at a sulfurous spring, some evolve to exploit solar photons. Numbers 1–3 relate to life’s emergence, 4 marks the point of differentiation of the Archaea from the Bacteria. Roman numerals V–VII mark evolutionary stages of the Archaea, and 5 and 6 show stages of evolution of the bacteria in the deep biosphere. Photon energy was first mastered by the green sulfur bacteria (7), followed by the heliobacteria (8). These photosynthesizing bacteria had probable appeared by the early Archaean (Westall et al., 2001). Oxygenic photosynthesis (9) is a further evolutionary development, though the age of its emergence is controversial. Photosynthetic bacteria embedded within calcium manganate hydrates, precursors to the cyanobacteria, found that the electrons and protons released from the hydrate, driven by photons, could contribute to biosynthesis. Oxygen was released as a waste gas. (Not to scale).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Print Version	
Interactive Discussion	