ESF ArchEnviron Programme workshop

Meeting No. **1524**.

Archean Oceans: the first habitat of life on Earth

April 12-14, Rio Tinto, Spain

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Summary (1 p.)

The workshop “Archean ocean: the first habitat of life on Earth” was a discussion meeting with the goal to define what we know about the oceans in the Archean, and to discuss the most fruitful avenues of research to better understand the conditions of early life in the oceanic environment.

Oceans were most likely the habitat of first life on Earth. Although we know from the geological record that water was abundant on the surface of the Earth in the Archean, we are only starting to unravel the physical and chemical conditions of oceans in the Archean.

This workshop brought together scientists from diverse fields to integrate the available information on Archean oceans, the theoretical constraints from modeling work on the physical and chemical conditions of Archean oceans, and implications for primitive life.

The workshop included an excursion to the Rio Tinto area, which is currently regarded as one of the potential analogues for life on early Earth and Mars.

After initial presentations by keynote speakers and participants and the excursion (see program), a list was made of the most important questions regarding Archean oceans. These question were discussed in smaller teams, and subsequently presented and discussed in the final plenary session.

Workshop content and discussion

The workshop was organized in such a way that almost all participants gave a presentation. Longer overview presentations were given by the keynote speakers/session organizers (see program below). In all sessions there was ample time for discussion.
A wide range of topics have been discussed, of which a summary is given below.

Global context, plate tectonics, outgassing

It is not clear if plate tectonics as we know it nowadays operated all the way back into the early Archean. There are good indications for subduction processes at around 3.0-3.3 Ga, but further back the record becomes difficult to decipher and definitive evidence for plate tectonics, including subduction processes are lacking. There is evidence for mid-ocean ridge processes as far back as 3.8 Ga from Greenland.
The way that the geodynamic processes on Earth operated, has important implications on the outgassing/regassing (back into the mantle) budgets of water and other volatiles.
Currently, the oceans are shrinking: there is a net water budget back into the mantle. In the Archean, the oceanic volume may have been several times the current water volume at the surface of the Earth.
For CO_2 there is a missing reservoir, or a large part of the original CO_2 (90%) was lost to space from Earth.
Geodynamic processes and associated budgets of outgassing and regassing may have been episodic rather than stable over billion years evolution.

The rock record for the Archean is patchy, and sample bias is likely in many respects. Nonetheless there is an interesting sequence of first occurrence of various sediments in the rock record:
Oldest sequences consist of basaltic volcanic sequences, with interbedded fine cherts, assumed to represent chemical deposits from seawater.
Apart from minor volcanoclastic sediments, no large volume clastic sedimentary units occur until 3.3. 3.2 Ga (Fig Tree-Moodies Group, BGB).
Oldest large scale carbonate reefs occur at 2.9 Ga, although rare dolomite units (several meters thickness) occur as early as 3.45 Ga (Pilbara).
All Archean volcanic sequences have experienced early pervasive CO_2 alteration.

Clastic sediments from the Barberton Greenstone Belt show strong indications for tidal effects (herringbone cross bedding, tidal bedding). These sediments also preserve evidence for microbial colonization.

Atmospheric evolution

Prior to 3 Ga, the air was CO_2 rich (many times present day levels) and anoxic. There is good evidence for anoxic conditions from the rock record (detrital siderite). The most conclusive indications come from Mass Independent Fractionation (MIF) of S isotopes pre-2.45 Ga.

The solar flux at 3.5 Ga was only ~70% of its current flux. To keep atmospheric conditions in a range under which water was liquid, a greenhouse gas is required in the atmosphere. CH_4 is a likely candidate, which would have been produced by methanogenic micro-organisms. Before CH_4 production started, Earth may have been too cold for liquid water at the near surface (Archean snowball Earth).

In fact, MIF in the Archean (pre 2.45 Ga) may mark the collapse of CH_4, not the rise of O_2. CH_4 and O_2 are mutually exclusive in large quantities in the atmosphere, because in the presence of O_2, CH_4 is consumed by anaerobic oxidation (AOM).

The temperature of the atmosphere would have partly followed the methane decrease at 2.45 Ga, resulting in a temperature low at 2.45 Ga. High levels of CO_2 (10 times present), and considerable CH_4 levels could have resulted in a high (~70 ˚C) surface temperature on Earth in the early/mid Archean.

To acquire the MIF signal SO_2 must have been in the atmosphere with sufficient residence times to acquire the MIF signal in the high levels of the atmosphere.

Composition, pH, temperature, redox potential of seawater

The properties of seawater in the Archean can be derived from chemical sediments deposited directly from seawater. In many cases it is difficult to distinguish between chert, BIF, or carbonates deposited directly from seawater, from hydrothermal precipitates and alteration products. Si isotopes may be used to find cherts which are deposited from seawater.

Silica concentrations in seawater are currently kept low by silica secreting organisms. In the Archean silica concentrations in seawater were higher. High CO_2 concentrations in the atmosphere (needed to maintain moderate temperatures) would have resulted in more acidic conditions in ocean water. REE pattern of Archean chemical sediments confirm that the pH was lower or similar to present day (8.2).

Oxygen isotopic composition, in combination with Si isotopic composition of cherts indicate that the temperature of Archean oceans at 3.5 Ga was higher, ~70˚ C.

Ce is a proxy for the redox potential in seawater. Archean oceans probably had a lower redox potential than present day oceans.

Fluid inclusion data indicate a 10x present day salinity in Archean sea water.

Archean oceans may have been stably stratified, in contrast to current day oceanic overturn as a result of polar ice caps.

Life

A complex interrelation exists between the abiogenic planetary environment and biological processes. The chemical cycles associated with life lead to a shift in the geochemical sources and sinks, and subsequently to traceable signs of life and its products in the preserved record of sedimentary (cherts, carbonates, barites, sulphates) and volcanic deposits.

The fossil record of life has been extensively studied in the Barberton and Pilbara greenstone belts. Both microscopic and isotopic evidence point to the presence of life at 3.5 Ga. Morphological evidence for life at that time suggests various settings, including hydrothermal systems, in subsurface rock units, and shallow water environments. Life at 3.5 Ga may have been relatively evolved, including chemolithotrophs, heterotrophs, and aerobic photosynthesis.

The fossil record prior to 3.5 Ga (Isua, Greenland) is unreliable, because these terrains have been intensely affected by more recent deformation and metamorphism.

The microbiological metabolic pathways are not yet well understood, but the protein Rubisco is likely to have played an important role in the evolution from a pre-photosynthetic world, to an anaerobic photosynthetic world, to aerobic photosynthesis. Before oxygen was present in the atmosphere, to be used for redox reactions, sulphate reduction was a likely source of energy.

Under a CH_4 atmosphere, metabolic pathways would have been stable, but relatively slow. The use, and production of oxygen in metabolic pathways would have sharply increased biological productivity. However, the resulting decrease of CH_4 (O_2 in the atmosphere leads to CH_4 instability) in the atmosphere may have led to global glaciations.

Fe must have been essential in the early evolution of life, since it is currently at the core of many biological processes. Although Fe is one of the most abundant elements on Earth and terrestrial planets, its availability under neutral pH conditions is very limited. This may point to acidic conditions during early evolution of life. The Rio Tinto subsurface microbiological environment may be a good analogue for early evolution of life on both Earth and Mars.

Result and impact to the field

The combination of detailed studies of the rock record and geological context in combination with a mix of analytical techniques such as stable isotopes (in particular S, Mo, Ca), REE and visual microscopic techniques is providing key data points for the reconstruction of the Archean oceanic environment.

There is agreement on:

1) First indications for large scale continents above sea level (clastic sedimentary deposits) are from 3.3 Ga. Prior to that, emerging landmasses were associated with volcanic edifices.
2) Life can be traced back to 3.5 Ga (Pilbara and Barberton greenstone belts). The older sequences from Greenland are too heavily disturbed by later events to reliably confirm the presence of life before 3.5 Ga.
3) The Archean atmosphere was lacking in free oxygen before 2.45 Ga. Methane was probably present since 3.5 Ga, providing greenhouse conditions suitable for liquid water.
4) There are good indications that oceanic water temperature was higher in the Archean (70˚ C)
5) The role of Fe must have been essential in early life.

Further avenues of research

1) What was the hypsometric curve like for the early Earth ? Was continental crust higher or lower than oceanic crust ?
2) The microbiological metabolic pathways for early life need to be studied within the environmental context (atmosphere, ocean composition, temperature, pH, etc)
3) Precision of stable isotope measurements of S and other elements (Si, Mo, Ca) continue to be improved. This is leading to important advances in understanding the early eEarth environments and the role of life.
4) Detailed geochemical/isotopic/morphological studies have so far been focused on cherts and volcano-clastic sediments. There is scope to extend these studies to other rocktypes in the Archean record (barite, dolomite, basalt, shale, paleohydrothermal systems). Systematic and combined studies of fresh (unweathered) sequences would be very useful. Drill core from Barberton 3.5-3.0 Ga sequences would be a prime target.
5) Global glaciation events may have occurred in the Archean, which have not yet been detected.
6) It is important to compare Earth's early evolution with the evolution of other planets. Mars is a prime candidate for such comparisons.
7) Is the higher ocean water temperature in the Archean an indication for a higher surface atmospheric temperature ?
8) Was sulphate reduction a dominant biological process in the early Archean ?
9) What causes the 80%/20% anorganic/organic carbonate split as evidenced by the consistent carbon isotopic signature of 30 ‰ ?

10) Study barite deposits. These could a baseline for sulphur isotopes.
11) How did the weathering cycle work in the Archean ?

The workshop was considered a great success by all participants. Its interdisciplinary nature led to many fruitful discussions and we expect that a large number of joint research projects will result from these discussions.
It was decided to write a joint review paper for Precambrian Research based on the presentations and discussion at the workshop on the topic of Archean oceans as a habitat for early life on Earth.

Thursday April 12th

9:00-9:10 Introduction by organizers

Overview from different perspectives (***Keynotes*** 30'presentation, 10' discussion)

Chair H. Strausss

9:10 - 9:50 ***J. van Hunen***- Archean oceans and geodynamics

9:50 – 10:30 ***M. Bau*** **–** The Archean ocean: the trace element perspective

11:00 – 11:40 ***K. Eriksson*** – Physical Processes on the early earth: evidence from the Barberton Greenstone Belt

11:40 – 12:20 ***E. Nisbet*** **–** The evolution of the oxygen-rich atmosphere

12:20 – 13:00 **ALL** – discussion on first order questions/topics

14:30 – 15:30 ***R. Amils*** - Introduction to Rio Tinto area

15:30 – 20:00 **EXCURSION to Rio Tinto area**

Friday April 13th

Chair : F. Robert

9:00 – 9:40 ***F. Westall*** **–** Traces of life in the Early Archaean

9:40 – 10:20 ***H. Strauss*** **–** Multiple sulphur isotopes:clues for sulphur biogeochemistry and the evolution of the atmosphere-ocean-system

10:20 – 10:45 10-15' presentations

D. Fernandez-Remolar - Differential evolution of Early Mars and Early Earth from similar surface conditions before 3.8 Ga)?

N.V. Grassineau - Evolution of Archaean life in time and space: a perspective from the stable isotopes.

Chair: K. Eriksson

11:15 – 11:55 ***F. Robert*** **–** Constraints from silicon and oxygen isotopic compositions of cherts on the temperature of Precambrian seawater

11:55 – 12:30 10-15' presentations

M. Sanchez Roman – Microbial and Geochemical Signals in Dolomite: a Potential Tool to Understand Early Ocean Chemistry

M.C. Stam - Sulfur isotopes: interpretation of signatures for biogenic activity in the Archaean

12:30 – 13:10 ***E. Javaux*** – Microfossils in siliciclastics: a window into Proterozoic and Archean life

Chair E. Nisbet, J. van Hunen

14:30 – 17:00 5' to 15' presentations

D. C. Catling – Marine microbes and Earth's Archaean atmosphere

L. Charlet – Reactivity of two major components of Archean ocean floor: Surface Fe(II) and FeS clusters

T. W. Dahl - Molybdenum Isotope Proxy

S.H.J. van den Boorn – How well do cherts reflect properties of Archaean seawater ?

C. Vasconcelos - Formation of lamination in modern stromatolites from Lagoa Vermelha, Brazil: An example for Precambrian relics?

R. Warthmann **–** Purple sulfur bacteria inducing lithification in modern- and possibly Archean stromatolites

T Weber – Basic building blocks of life

W. Altermann - The Sedimentary Rocks of the BGB: Petrography, Diagenesis & Potential Fossil Preservation

E. Stueeken – Ca-Isotopes in Archean Carbonates

17:30 – 18:00 ALL – Key topics for split topical discussion

18:00 – 20:00 Topical sessions (3-6 topics)

Saturday April 14th

Chair: E. Javaux, F.Westall

9:00 – 10:15 Reports from Topical sessions

10:30 – 12:00 Discussion and wrap-up