Geobiology 2013 Lecture 11

Oxygenation of Earth's Atmosphere

Need to know

- How C and S- isotopic data in rocks are informative about the advent and antiquity of biogeochemical cycles
- Geologic indicators of changes in atmospheric pO_2
- A general overview of the course of oxygenation of the atm-ocean system

- Reading: Anbar & Knoll, 2002. Science 297, 1137.

Biogeochemical Redox Couples

$CO_2 + H_2O \rightarrow CH_2O + O_2$ oxygenic photosynthesis

↕ Interdependency?

$CH_2O + O_2 \rightarrow CO_2 + H_2O$ aerobic respiration

$CO_2 + 2H_2 \rightarrow CH_4 + 2H_2O$ methanogenesis

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ oxidative methanotrophy

$CO_2 + HS^- + H_2O \rightarrow \text{biomass} + SO4^{2-}$ anoxygenic photosynthesis

Biogeochemical Redox Couples

aerobic respiration

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

1 mole glucose $\xrightarrow{O_2}$ 32 mole ATP

1 mole glucose $\xrightarrow{\text{fermentation}}$ 2-4 mole ATP

Biosynthesis requires approx. 1mole ATP per 4g of cell carbon

Biogeochemical Redox Couples

oxygenic photosynthesis

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

Biogeochemical Redox Couples

oxygenic photosynthesis

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

Biogeochemical Redox Couples

anoxygenic photosynthesis

$$11H_2O + CO_2 + 4Fe^{2+} \rightarrow CH_2O + 8H^+ + 4Fe(OH)_3$$


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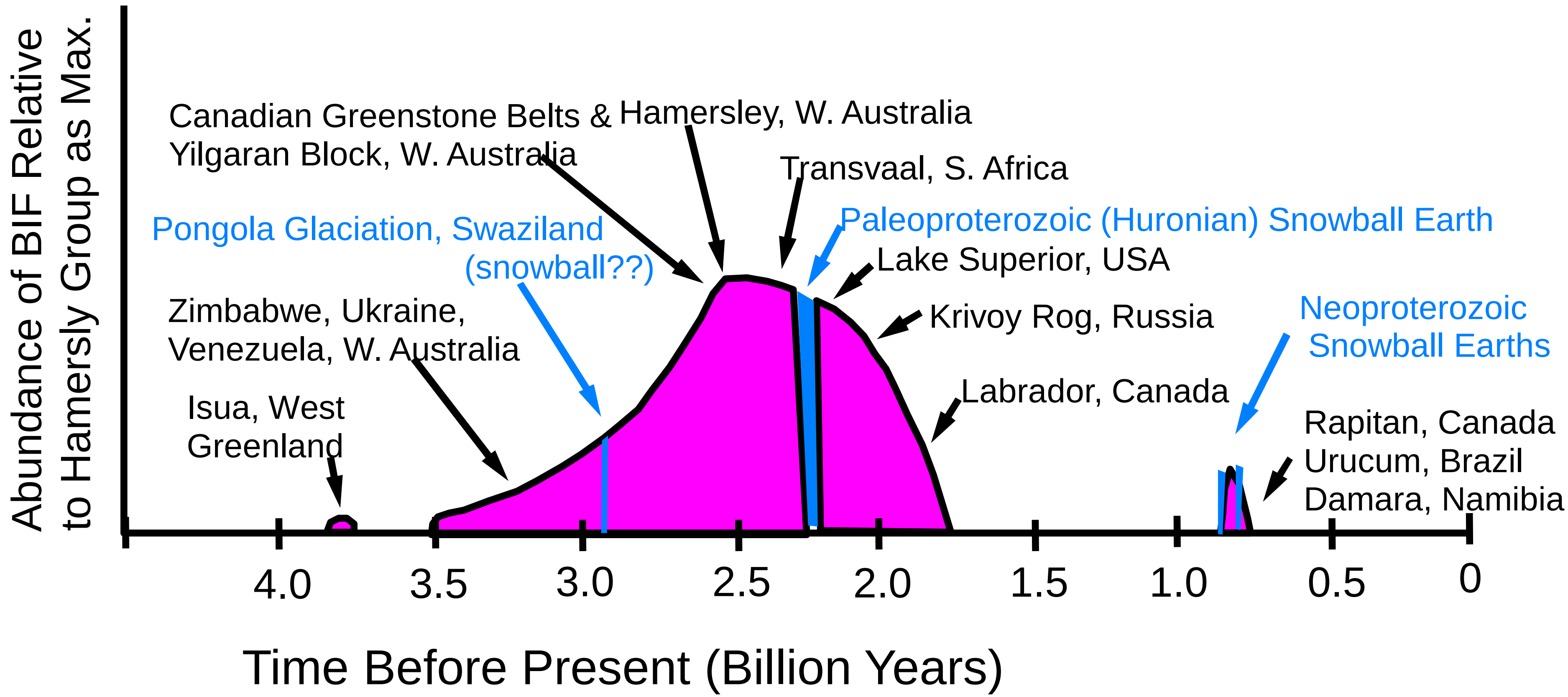
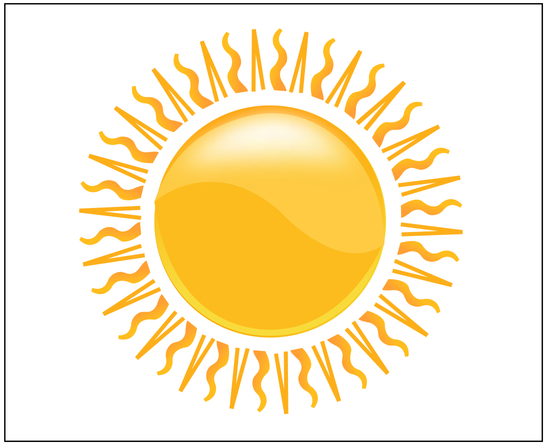
Precambrian Banded Iron Formations (BIFs)

(Adapted from Klein & Beukes, 1992)



Courtesy Joe Kirschvink, CalTech



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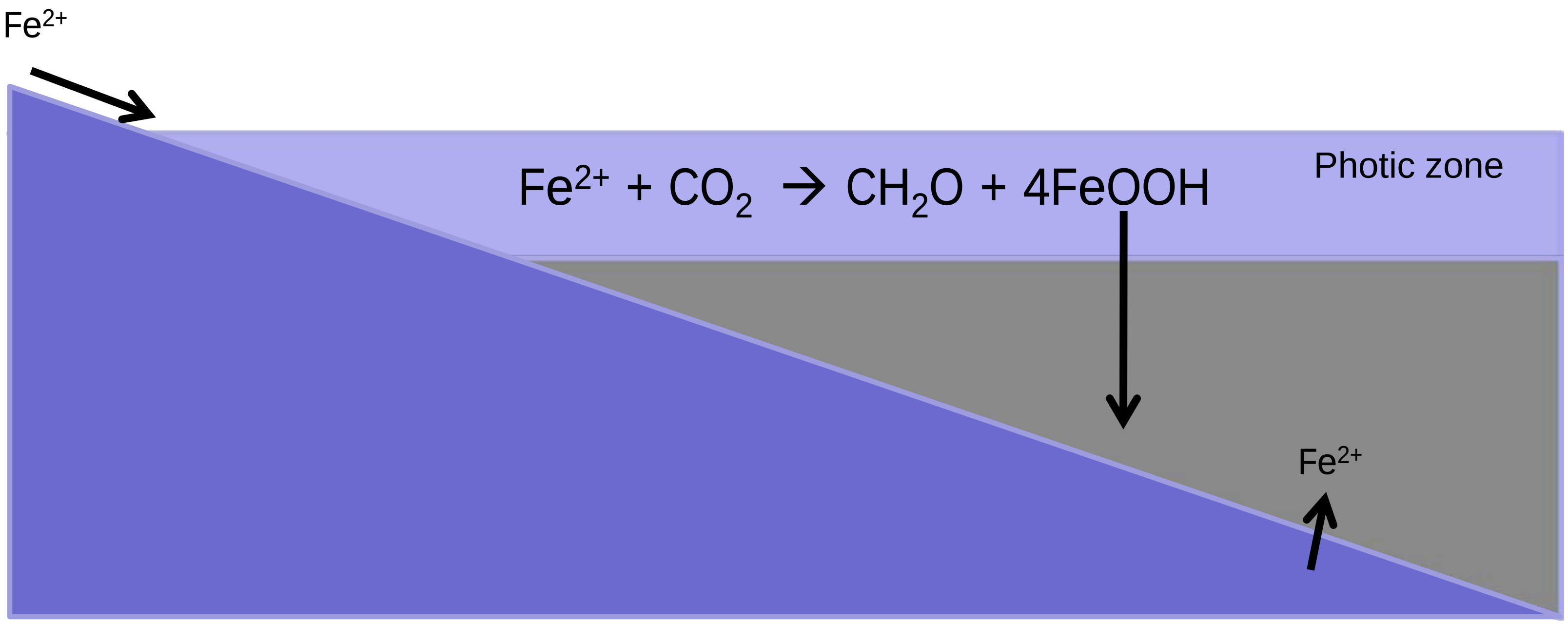
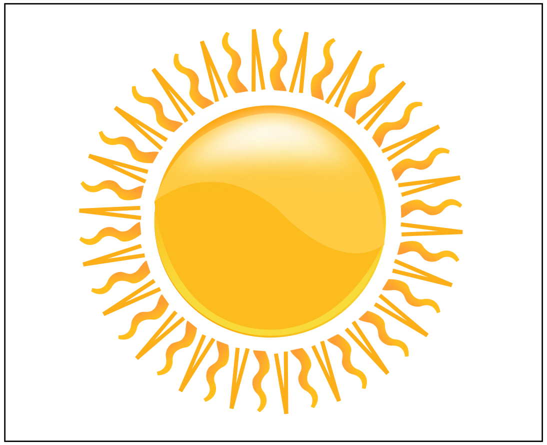


(Canfield et al. 2006, Kharecha et al. 2005, Kappler et al. 2005)



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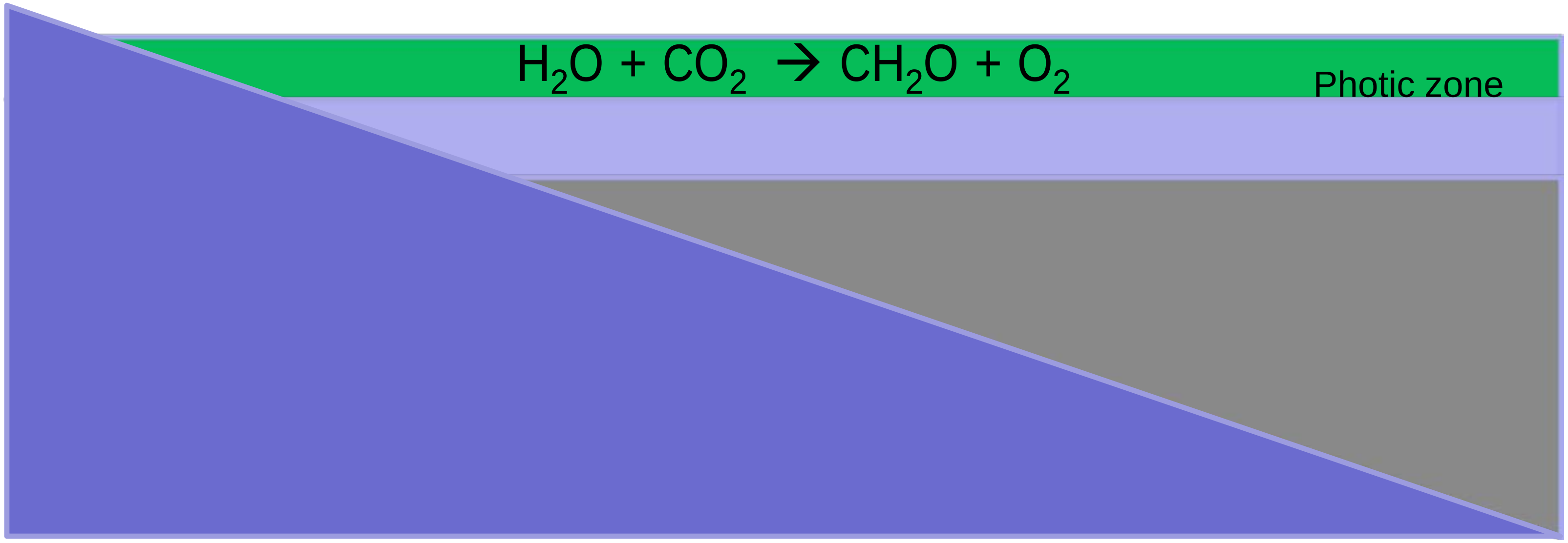

STROMATOLITE RECORD OF MICROBIAL INTERACTIONS WITH SEDIMENTS

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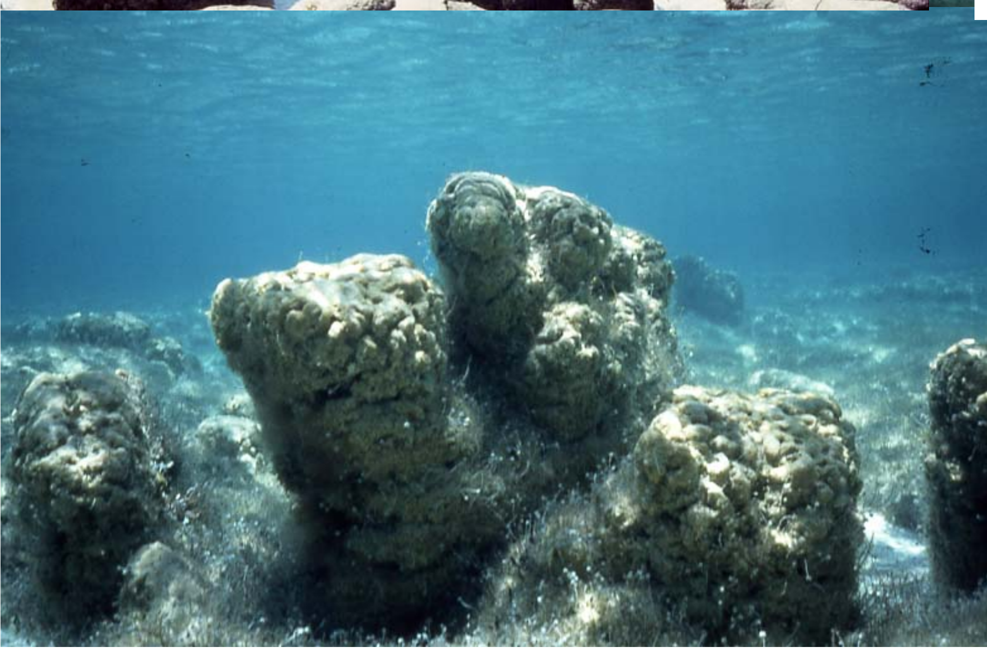
Bosak et al., 2013

‘Classic’ picture of stromatolites, Telegraph Station, Hamelin Pool WA. These are effectively stranded above high water and ‘dead’.

Small (0.5) club-shaped subtidal stromatolites, Telegraph Station



1m domal subtidal stromatolites, Carbla Point, Hamelin Pool

‘Reef’ of 1m stromatolites, Carbla Point

STROMATOLITES AS INDICATORS OF MICROBIAL PROCESSES

3.4 Ga

Allwood et al. 2007

?
=

1.2 Ga

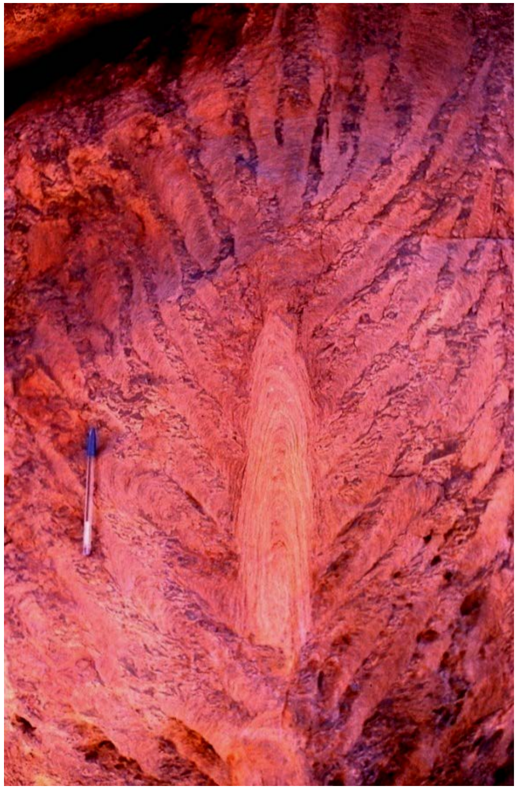
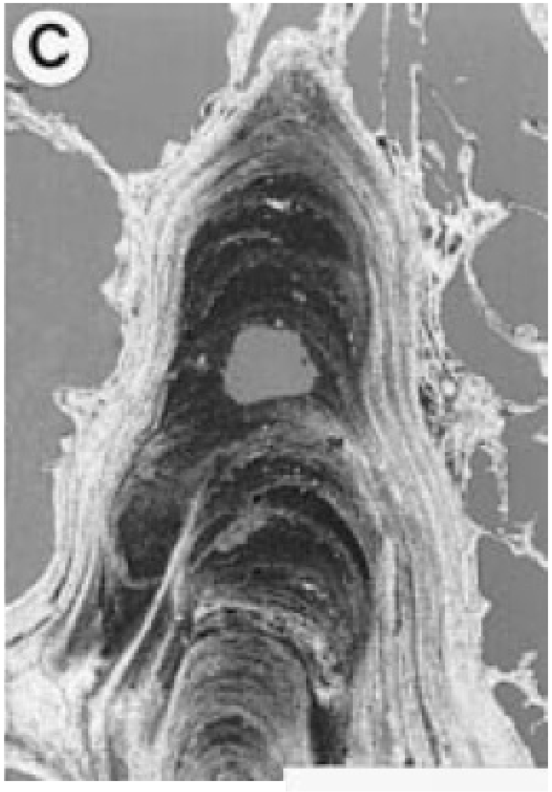


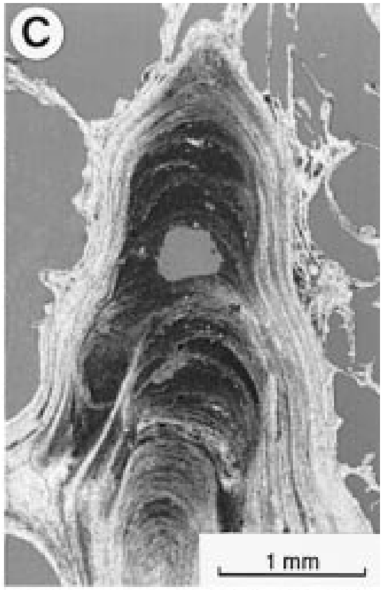
Photo: P. Hoffman

?
=

modern



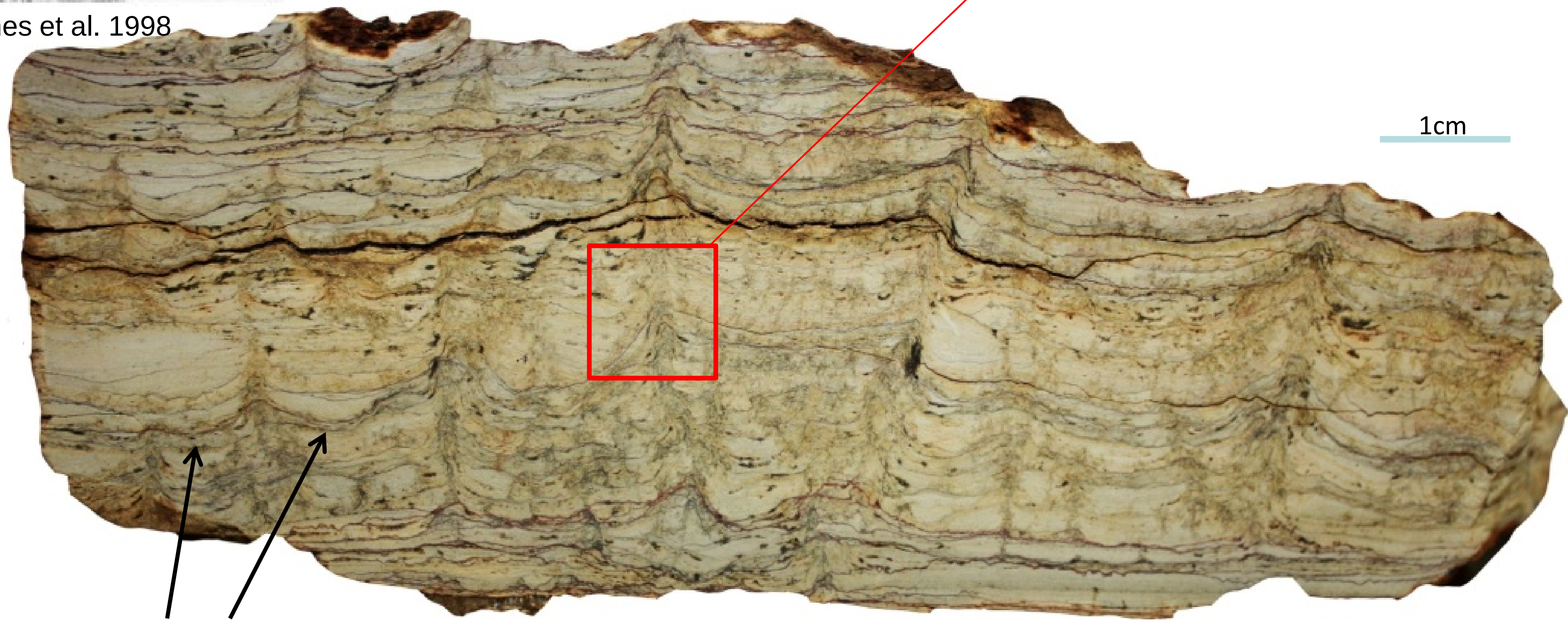
Jones et al. 1998 1 mm



Jones et al. 1998

modern

ancient
(2.7Ga)



1cm

regularly occurring inter-column laminae

Flannery et al., 2012

STROMATOLITE MORPHOLOGY AND OXYGENIC PHOTOSYNTHESIS AT 2.7 GA?

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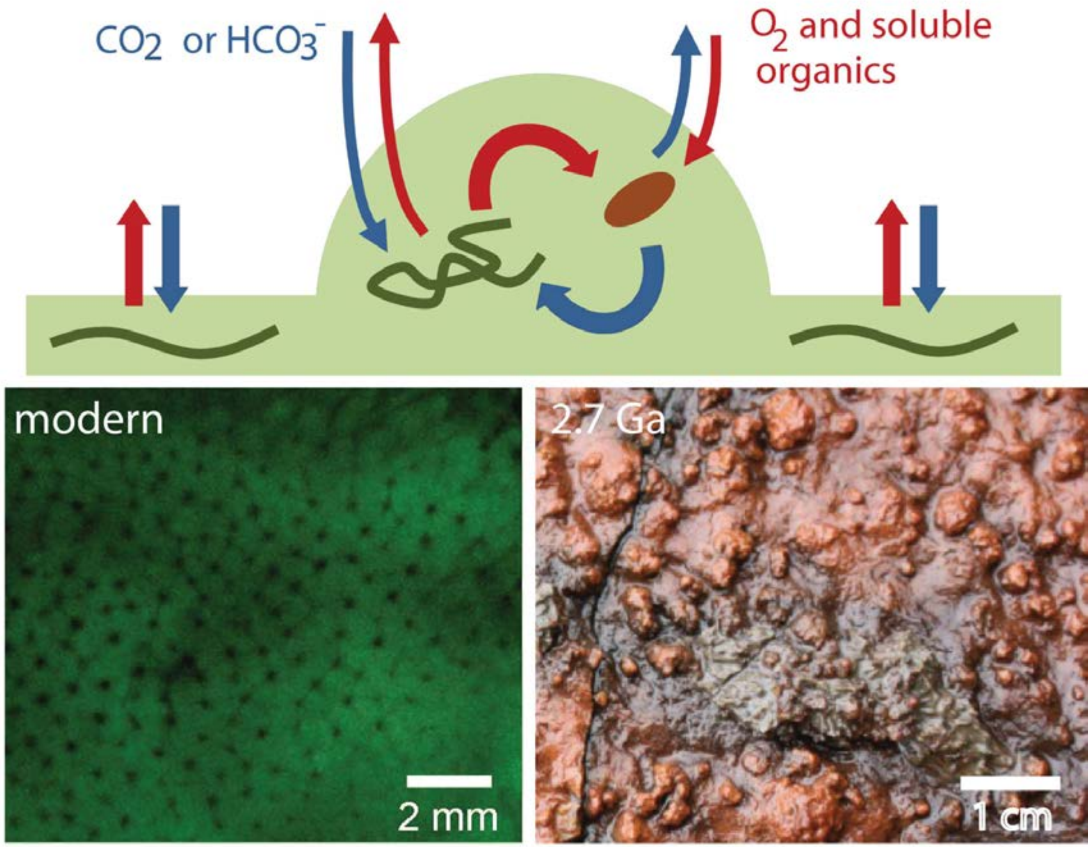
Sim et al. 2012

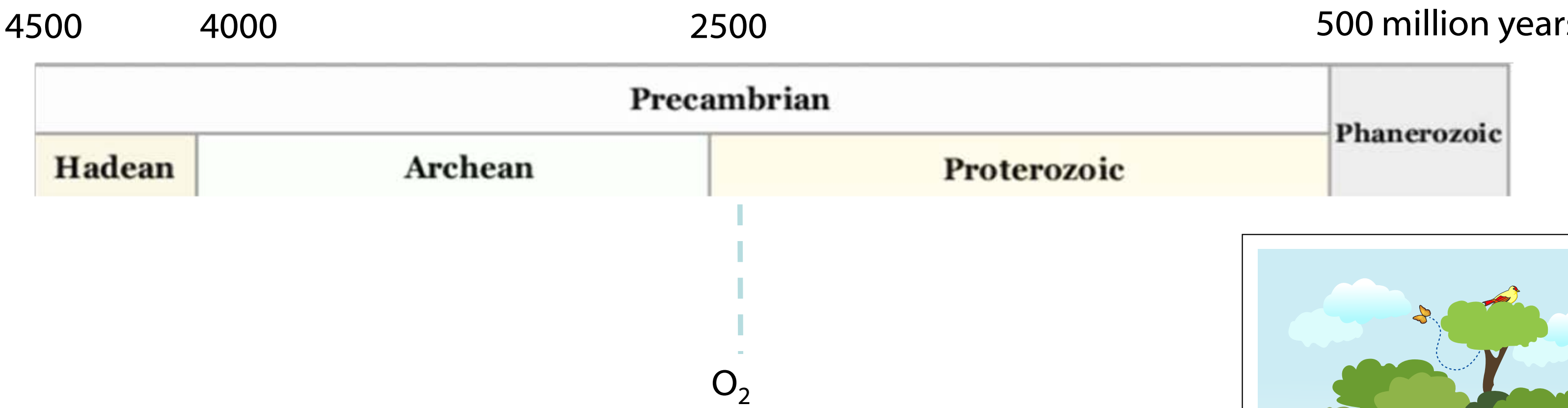
STROMATOLITE MORPHOLOGY AND OXYGENIC PHOTOSYNTHESIS AT 2.7 GA?

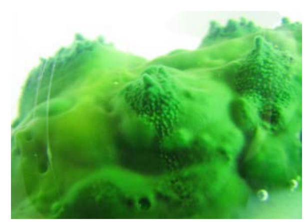


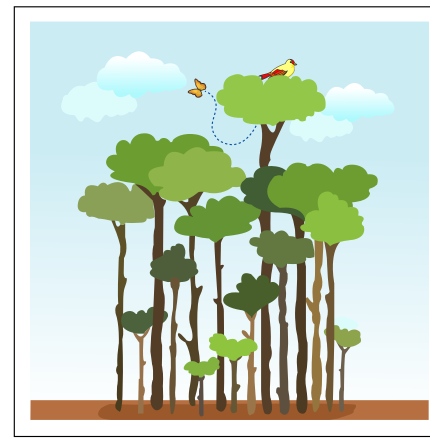
Sim et al. 2012

STROMATOLITE MORPHOLOGY AND OXYGENIC PHOTOSYNTHESIS AT 2.7 GA?

Bosak et al. 2013







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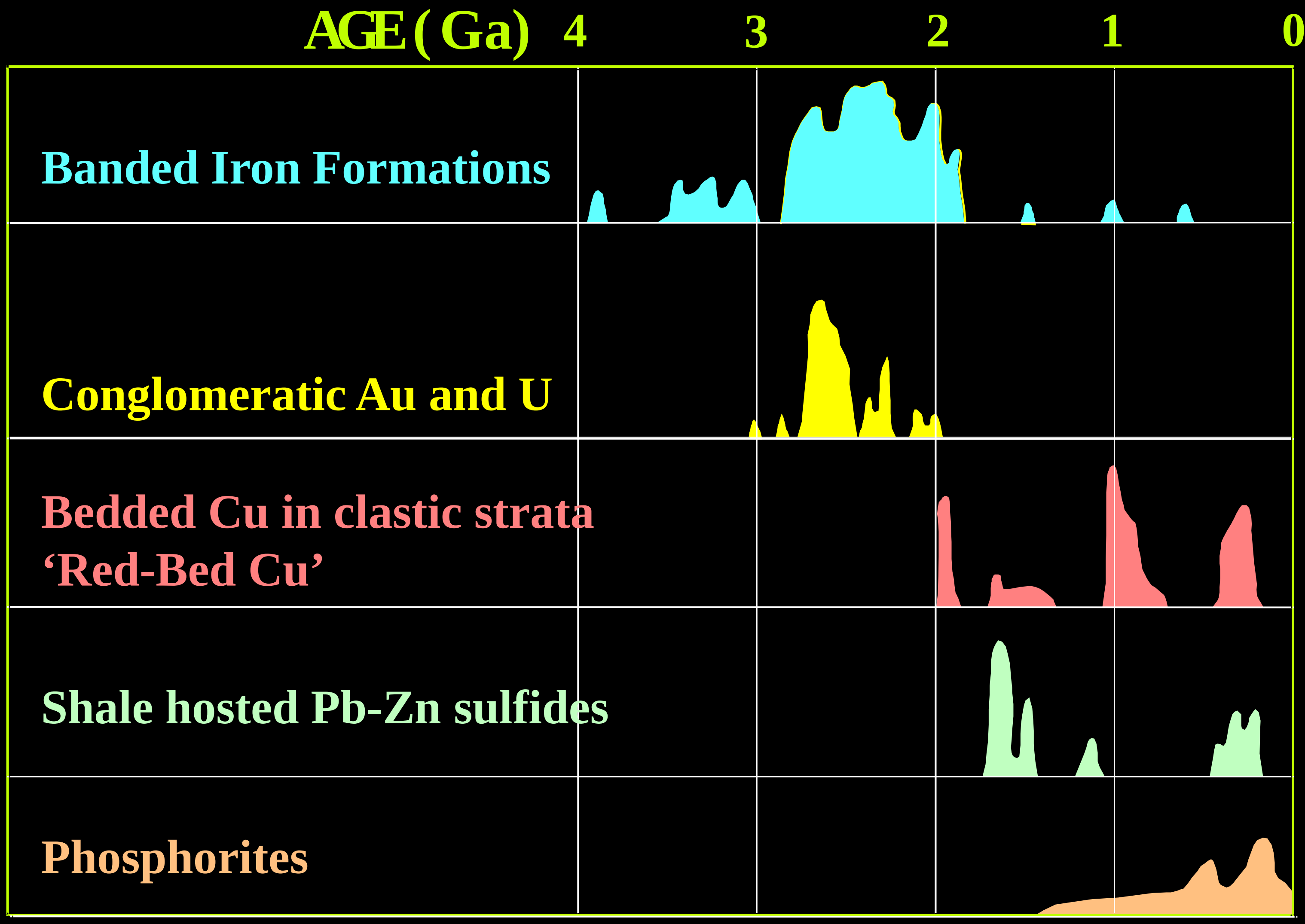
MINERALIZATION THROUGH GEOLOGIC TIME

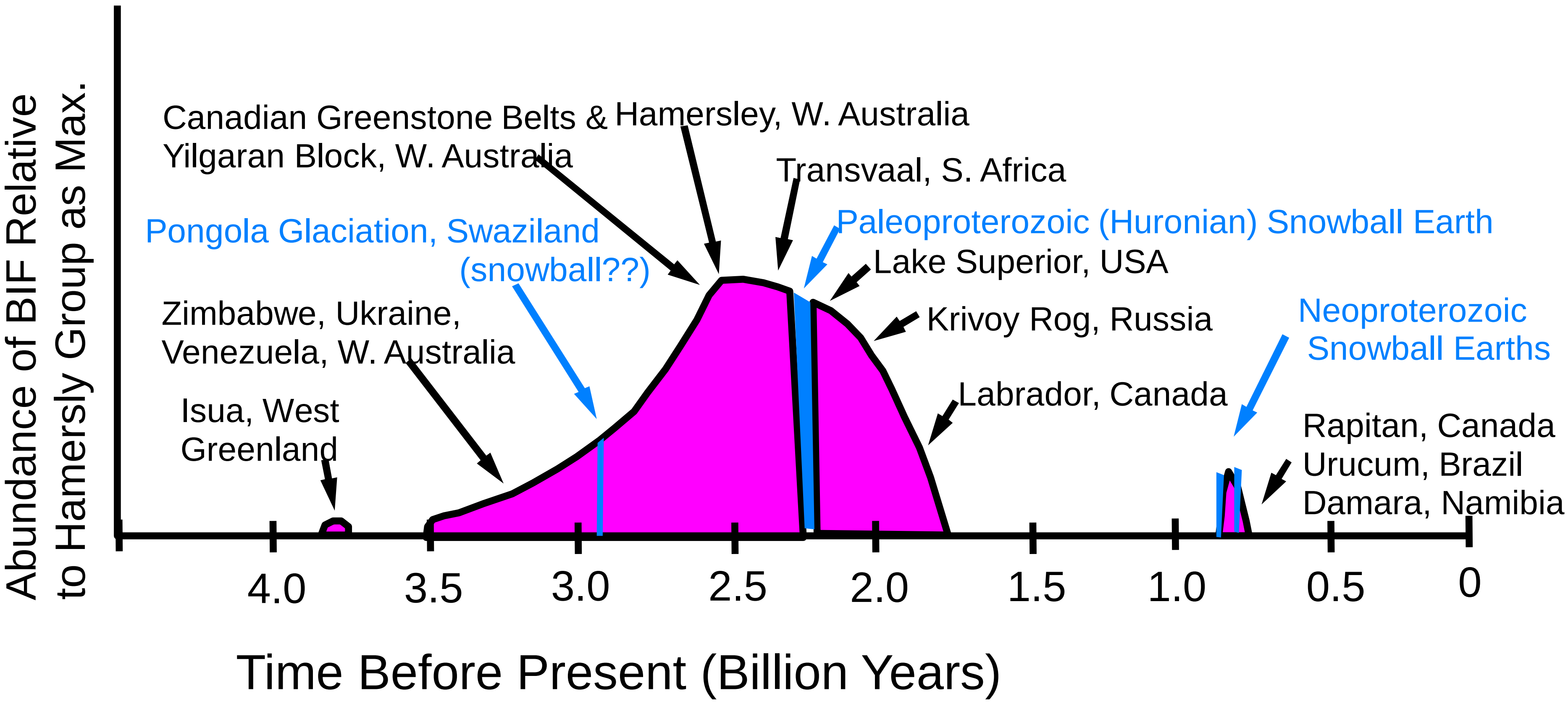


(adapted from Lambert & Groves,1981)

An Atypical Banded Iron Stone (BIF)

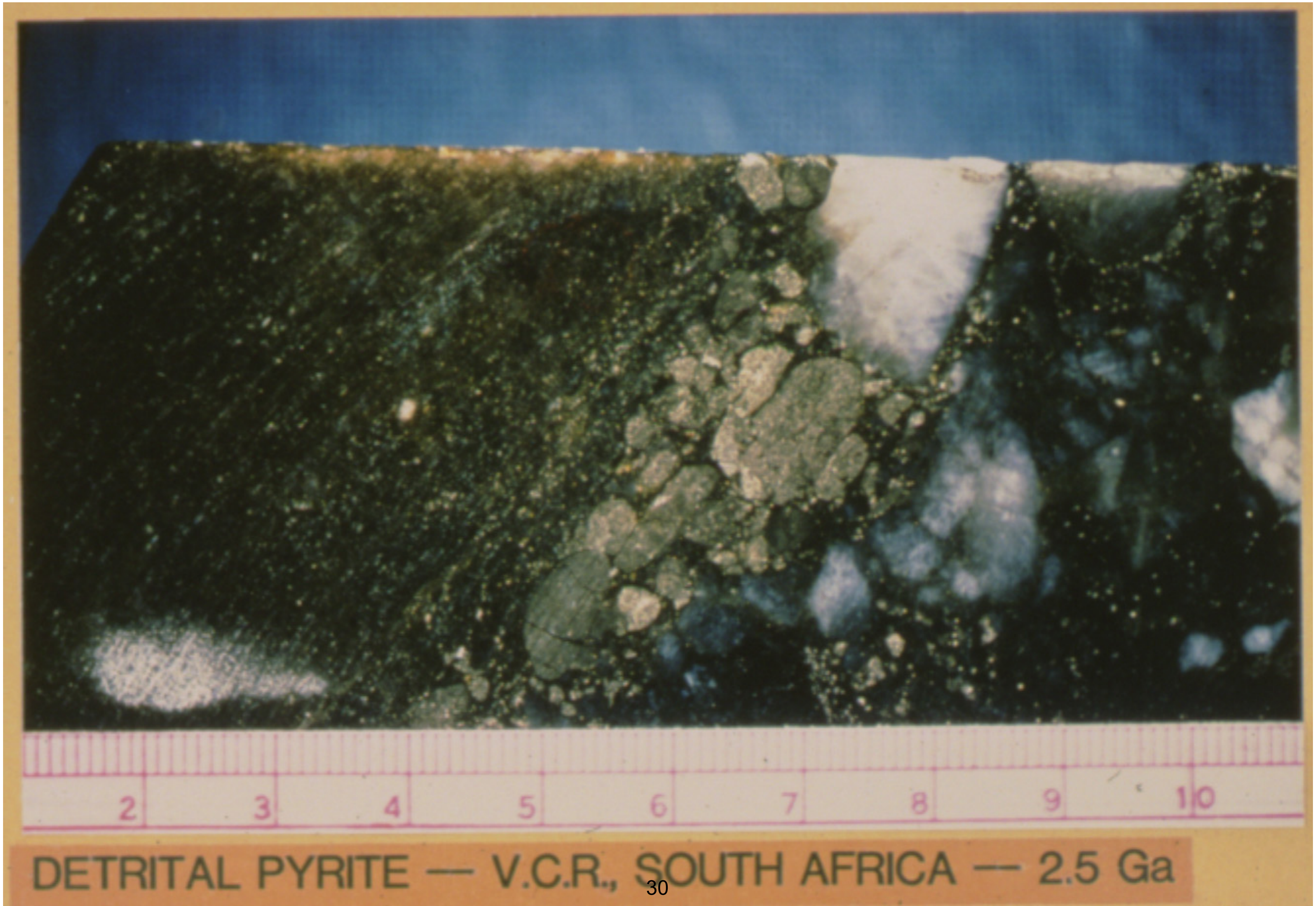
BIF — NEGAUNEE IRON FORMATION, MICHIGAN — 2.2 Ga

Precambrian Banded Iron Formations (BIFs) (Adapted from Klein & Beukes, 1992)

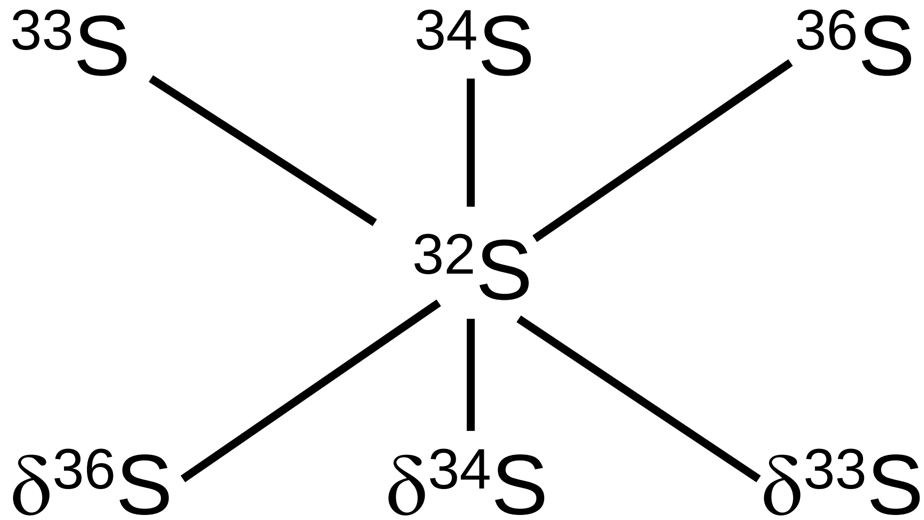


Courtesy Joe Kirschvink, CalTech

Pyrite (FeS_2) is Unstable in O_2-Rich Environments



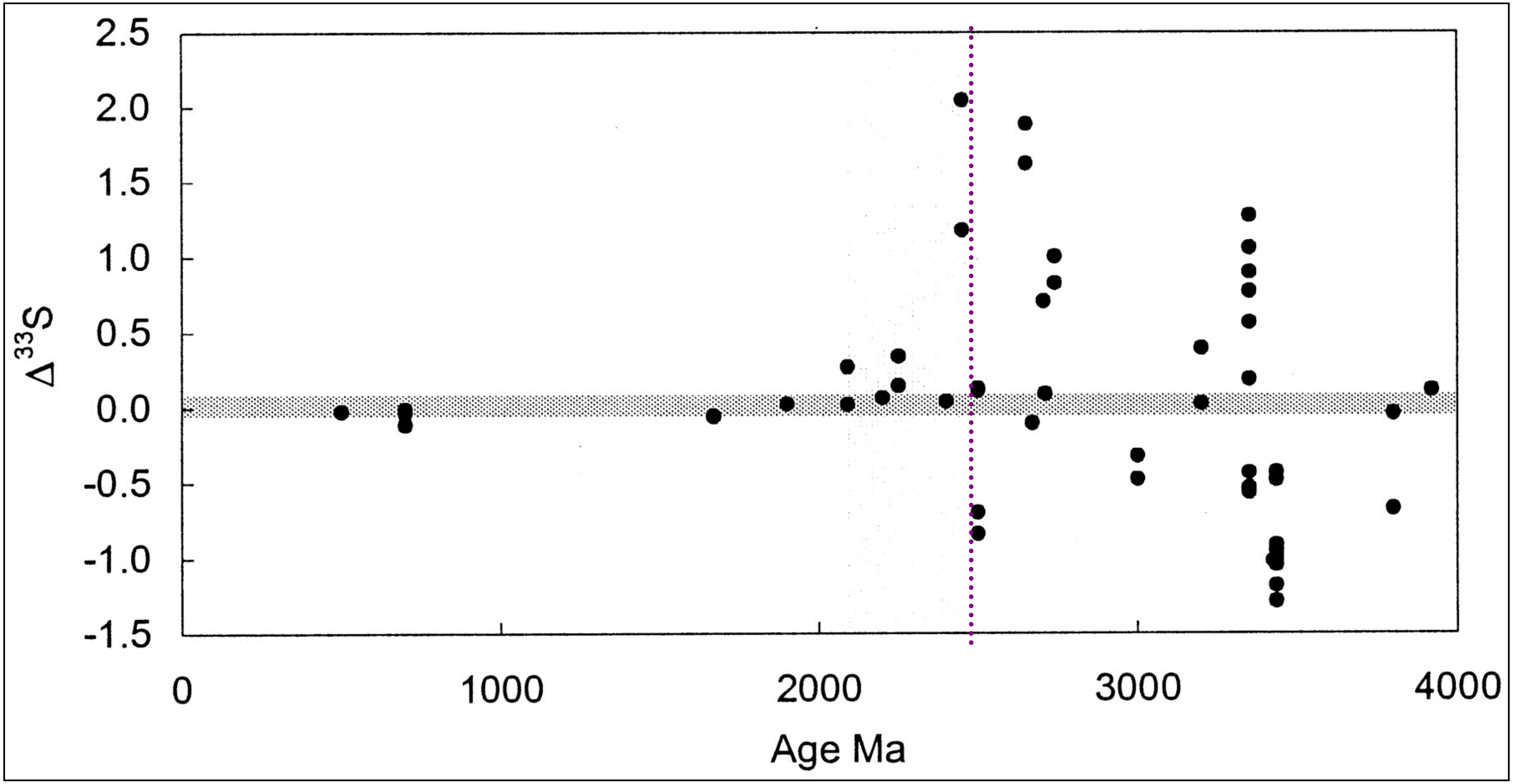
Multiple sulfur isotopes



Mass-dependent Fractionation:

$\delta^{33}S = 0.515\delta^{34}S$, $\delta^{36}S = 1.91\delta^{34}S$

A quantitative O_2 barometer??
Sulfur Isotopic Evidence for $pO_2 > 10^{-5}$ PAL



J. Farquhar, H. Bao, M. Thiemens (2000) *Science* **289**:756-758.

Conundrum: If oxygen-producing photosynthesis was occurring by 3.5-2.7 Ga, why doesn't free O_2 appear until 2.3 Ga, a 1200-400 Myr delay?

The BIG question in geobiology today!!

Conundrum: If oxygen-producing photosynthesis was occurring by 3.5-2.7 Ga, why doesn't free O2 appear until 2.3 Ga, a 1200-400 Myr delay?

Sources

•Photosynthesis

•Hydrogen escape

Vs.

Sinks

•Respiration

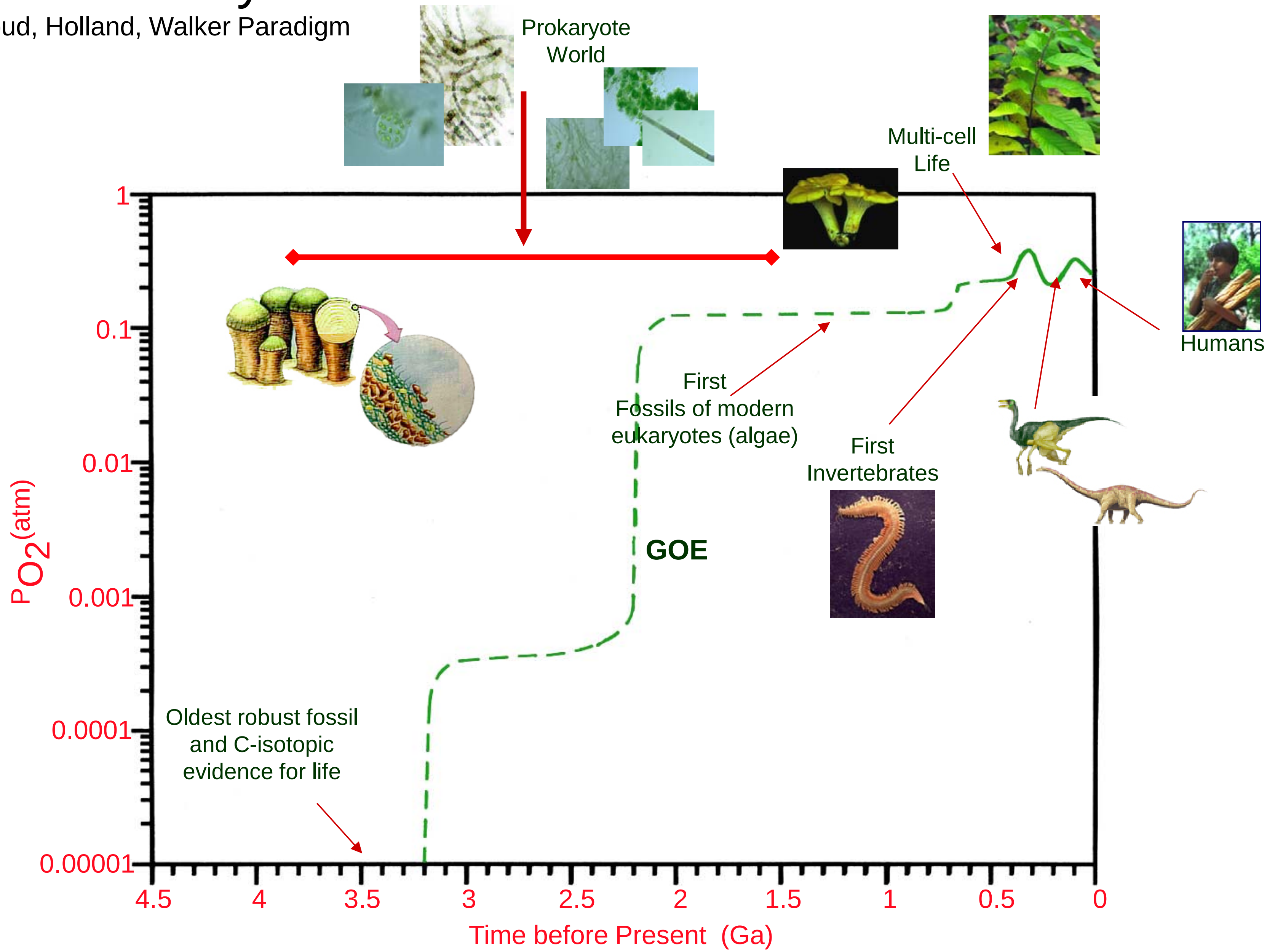
•Reduced minerals in rocks

•Reduced volcanic gases

•Reduced hydrothermal vent fluids

Life's History on Earth

Cloud, Holland, Walker Paradigm



Anbar & Knoll: Fig. 1. Biological and geochemical changes during the Proterozoic Eon.

Color gradations denote postulated changes in deep sea redox. (**A)** Periods of deposition of banded iron formations. (**B) Range of values of** 34S, the difference in 34S between coeval marine sulfides and sulfates. Dashed line: 34S 20‰, the maximum Archean value. Dotted line: 34S 45‰, the maximum fractionation associated with single-step BSR. Asterisk: 34S determined from a single sample, and thus not well constrained. (**C) Range of values of 13Ccarb (after a compilation by A. J.** Kaufman). The frequency and magnitude of variations in the Paleoproterozoic are somewhat uncertain. (**D) Eukaryotic evolution, as indicated** by the first appearances of body fossils (solid lines) and molecular biomarkers (dotted lines), including chlorophytes (1), ciliates (2), dinoflagellates (3), rhodophytes (4), eukaryotes of unknown affinities, possibly stem groups (5), stramenopiles (6), and testate amoebae (7). See text for geochemical references. Fossil distributions from (*147).*

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Fig. 2. Schematic depiction of effects of changing ocean redox conditions on the depth distributions of Mo (dashed lines) and Fe (solid lines). Influences of nutrient-type depletion and aeolian inputs on surface seawater concentrations are omitted for simplicity. Color gradations are the same as in Fig. 1. During the Archean, oceans are anoxic but not sulfidic. Significant O_2 is only associated with cyanobacterial "blooms." Mo is scarce because it is not readily mobilized from crustal rocks during weathering under low *P_{O2}. Fe is abundant in the absence of O_2 and H_2S.* From 1850 to 1250 Ma, moderate *P_{O2} oxygenates surface waters but sulfidic deep waters* develop. Mo is scarce because of rapid removal in sulfidic waters. Mo is somewhat elevated at the surface because of upper ocean oxygenation and enhanced oxidative weathering. Fe, as in the modern Black Sea, is depleted in sulfidic deep waters, severely depleted in oxic surface waters, and enriched near the redoxcline where both O_2 and H_2S are scarce. During the Phanerozoic, O_2 penetrates to the sediment-water interface. Mo and Fe distributions are similar to today's. See text for details and references.

Evidence for O2 pulses during the Phanerozoic

Pulse of atmospheric oxygen during the late Cambrian

Matthew R. Saltzman, Seth A. Young, Lee R. Kump, Benjamin C. Gilld, Timothy W. Lyons, and Bruce Runnegar

PNAS 108, 3876–3881

Abstract
A rise in atmospheric O2 has been linked to the Cambrian explosion of life. For the plankton and animal radiation that began some 40 million yr later and continued through much of the Ordovician (Great Ordovician Biodiversification Event), the search for an environmental trigger(s) has remained elusive. Here we present a carbon and sulfur isotope mass balance model for the latest Cambrian time interval spanning the globally recognized Steptoean Positive Carbon Isotope Excursion (SPICE) that indicates a major increase in atmospheric O2. We estimate that this organic carbon and pyrite burial event added approximately 19 × 1018 moles of O2 to the atmosphere (i.e., equal to change from an initial starting point for O2 between 10–18% to a peak of 20–28% O2) beginning at approximately 500 million years. We further report on new paired carbon isotope results from carbonate and organic matter through the SPICE in North America, Australia, and China that reveal an approximately 2‰ increase in biological fractionation, also consistent with a major increase in atmospheric O2. The SPICE is followed by an increase in plankton diversity that may relate to changes in macro- and micronutrient abundances in increasingly oxic marine environments, representing a critical initial step in the trophic chain. Ecologically diverse plankton groups could provide new food sources for an animal biota expanding into progressively more ventilated marine habitats during the Ordovician, ultimately establishing complex ecosystems that are a hallmark of the Great Ordovician Biodiversification Event.

Plot of (14) and (17) data from Mt. Whelan core in Australia that were used in the isotope mass balance model (see Table S1) to calculate changes in atmospheric O2.

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Arial D. Anbar, Yun Duan, et al.

High-resolution chemostratigraphy reveals an episode of enrichment of the redox-sensitive transition metals molybdenum and rhenium in the late Archean Mount McRae Shale in Western Australia. Correlations with organic carbon indicate that these metals were derived from contemporaneous seawater. Rhenium/osmium geochronology demonstrates that the enrichment is a primary sedimentary feature dating to 2501 ± 8 million years ago (Ma). Molybdenum and rhenium were probably supplied to Archean oceans by oxidative weathering of crustal sulfide minerals. These findings point to the presence of small amounts of O_2 in the environment more than 50 million years before the start of the Great Oxidation Events.

http://www.sciencemag.org/content/317/5846/1903.full

Geochemical data from Mt McRae Shale ABDP-9

12.007 Geobiology
Spring 2013