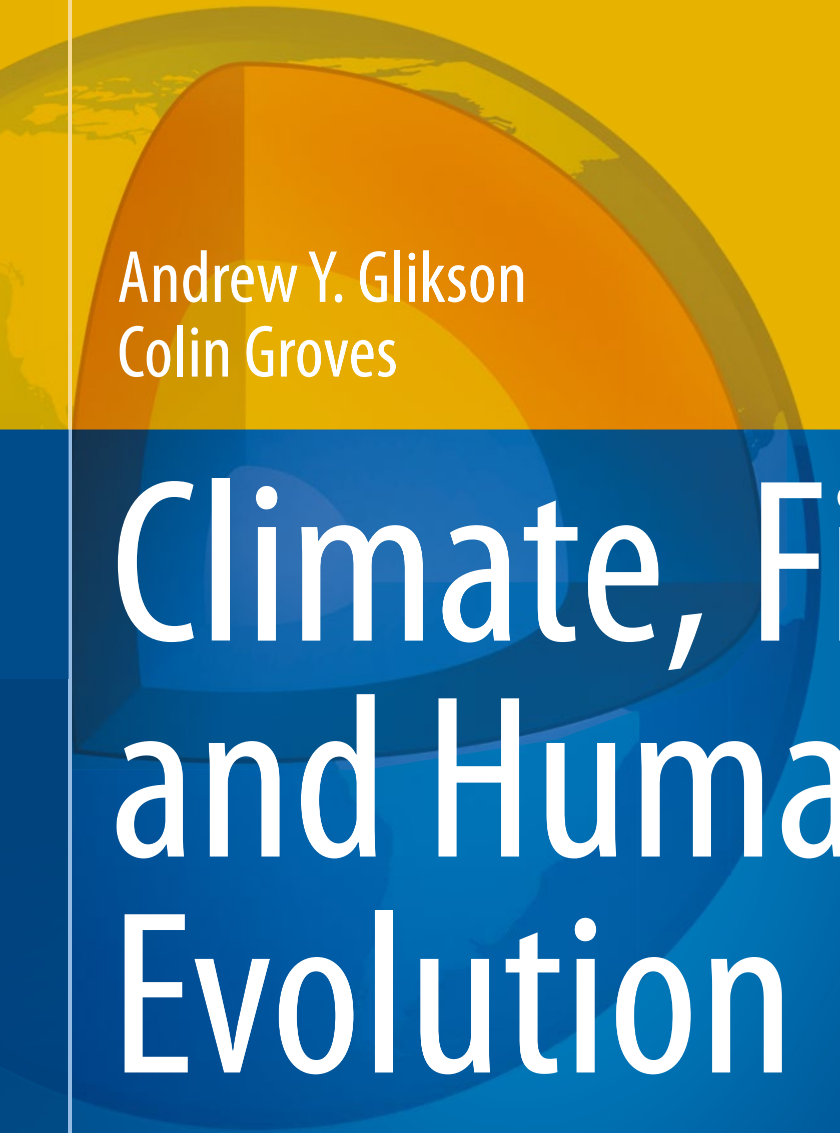
Modern Approaches in Solid Earth Sciences

Andrew Y. Glikson
Colin Groves



Climate, Fire and Human Evolution

The Deep Time Dimensions of the Anthropocene

Springer

Modern Approaches in Solid Earth Sciences

Volume 10

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This book represents an expansion of the book by Andrew Y. Glikson, *Evolution of the Atmosphere, Fire and the Anthropocene Climate Event Horizon* (Springer, 2014).

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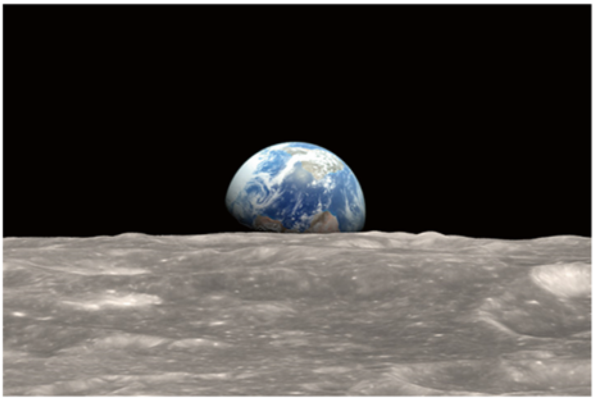


Earthrise (NASA) (http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4129)

Bushfire smoke covering the sun in Tasmania's Southern Midlands, looking west towards Lake Repulse, Friday, Jan. 4, 2013 (Kim Foale; AAP Image, by permission)

In honor of Sir David Attenborough

Foreword

Andrew Y. Glikson and Colin Groves' new book *Climate, Fire, and Human Evolution* traces the fascinating and complex history of the Earth over the past 4 billion years. It explores the fundamental context of the Earth's climate system; the cycles of carbon, oxygen and nitrogen and the crucial role of fire, to provide the critical baseline for our understanding of how a single species, *Homo sapiens*, has changed the atmosphere, oceans and biosphere.

The fate of our species, and all the others with which we share this planet, is now in peril from the unintended consequences of our development, and especially our use of energy. I commend this scholarly yet readable work as a vital reference for understanding our past and present, and hopefully for saving our future.

North Ryde, Sydney, NSW, Australia Lesley Hughes

Prologue

On Earth – a unique habitable planet in the solar system and possibly beyond – the evolution of the atmosphere, oceans and life are intimately intertwined, where life depends critically on the presence of liquid water allowed by the Earth's unique orbital position around the sun and evolving atmosphere–ocean processes which regulate surface temperatures in the range of ~ –90° to +58 °C (Fig. 1). The carbon

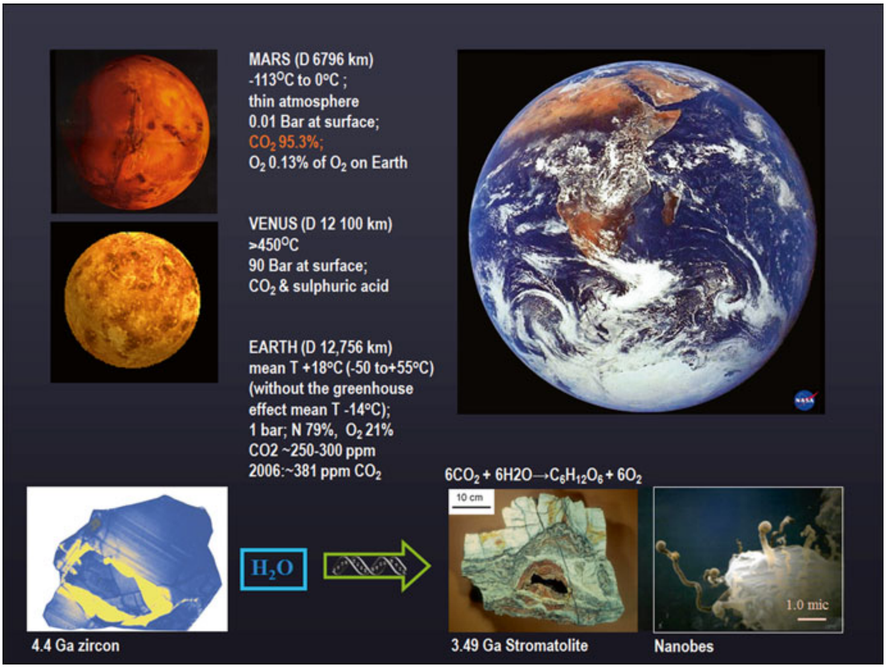


Fig. 1 Earth, Mars and Venus comparison and the terrestrial evolutionary chain, showing a ~4.4 Ga zircon crystal (Peck et al. 2001; Elsevier, by permission); water, DNA-RNA chains; Pilbara stromatolite (courtesy J.W. Schopf) and Nanobe organisms (Uwins et al. 1998) (courtesy P. Uwins)

cycle is intrinsically linked to Earth's mantle and tectonic activity, releasing carbon through volcanic eruptions and returning it to the mantle via tectonic subduction. The atmosphere, mediating the carbon, oxygen and nitrogen cycles, acts as lungs of the biosphere, allowing the existence of an aqueous medium where metabolic microbiological processes are performed in aqueous, land, air and extreme environments, including by chemo-bacteria around volcanic fumaroles, microbes and algae within and below ice and nanobes in deep crustal fractures and near-surface phototrophs. In this book, we trace milestones in the evolution of the atmosphere, oceans and biosphere through natural evolution and cataclysms from about ~3.8 billion years ago [Ga] all the way to the Anthropocene – an era triggered by a genus which uniquely mastered fire, a source of energy allowing it to release energy orders of magnitude higher than its own physiological capacity, facilitating its domination over the composition of the terrestrial atmosphere and large part of the biosphere.

Based on evidence from 4.4 billion–year-old zircons, hydrous activity has already been in existence at the earliest stages of the development of the Earth crust, in spite of solar luminosity being some 28 % lower than at present (Sagan and Mullen 1972), consistent with concepts regarding homeostasis in the Earth's atmosphere–ocean–biosphere system (Lovelock and Margulis 1974). According to this hypothesis, life acquired a homeostatic influence over the planetary environment where the physical and chemical conditions of most of the planetary surface adjusted to conditions mostly favourable for life through maintenance of liquid water with pH not far from neutral, despite major changes including increase in insolation, escape of hydrogen to space and enrichment of the atmosphere in oxygen. Maintenance of liquid water occurred through variations in the greenhouse gas levels of the atmosphere and distribution of infrared-absorbing oceans. From an initial Venus-like atmosphere dominated by CO, CH_4, CO_2, SO_2, N_2O, H_2 and H_2S, the sequestration of CO_2 and build-up of nitrogen – a stable non-reactive gas – has led to intermittent ice ages from at least as early as ~3.0 Ga, succeeded by multi-stage variations in the level of atmospheric photosynthetic oxygen produced by phytoplankton and from the Silurian ~420 Ma ago by land plants. The advent of land plants under an oxygen-rich atmosphere resulted in a flammable carbon-rich biosphere. Shifts in state of the climate caused by re-arrangement of continent–ocean patterns through plate tectonics and changes in atmospheric composition associated with erosion and weathering processes led to changes in the carbon cycle. Abrupt events such as volcanism, asteroid impacts, possible supernovae and episodic release of methane and hydrogen sulphide were superposed on longer-term trends, triggering amplifying feedback processes. Changes in atmospheric chemistry resulted in variations in alkalinity, acidity (pH) and oxidation/reduction state (Eh) of the hydrosphere and thereby of the marine food chain.

Born on a combustible Earth surface under increasingly unstable climates shifting from the relatively warm Pliocene (5.2–2.6 Ma) to the deep ice ages of the Pleistocene, the arrival of humans depended on both biological adaptations and cultural evolution. The mastering of fire as a necessity allowed the genus *Homo* to increase entropy in nature by orders of magnitude. Gathered around campfires during long nights for hundreds of thousands of years, captivated by the flickering lifelike dance of the flames, humans developed insights, imagination, cravings, hope, premonitions of death and aspiration for immortality, omniscience, omnipotence and concepts of spirits and gods. Inherent in pantheism is the reverence of Earth, its rocks and its living creatures, contrasted by the subsequent rise of monotheistic sky-god creeds, many of which regard Earth as but a corridor to heaven. Once the climate stabilized in the early Holocene, from about 7000 years ago production of excess grain and animal husbandry by Neolithic civilizations, in particular along the great river valleys, allowed human imagination and dreams to express themselves through the construction of monuments to immortality and through genocidal tribal and national wars in the name of gods and of ideologies. Further to burning large parts of the forests, the discovery of combustion and exhumation of carbon deposits derived from the Earth's ~420 million–year-old fossil biospheres set the stage for an anthropogenic oxidation event, leading to an abrupt shift in state of the atmosphere–ocean–cryosphere system. The consequent progressive mass extinction of species is tracking towards levels commensurate with those of the past five great mass extinctions of species, constituting a geological event horizon in the history of planet Earth.

Acknowledgements

This book represents an expansion of *Evolution of the Atmosphere, Fire and the Anthropocene Climate Event Horizon* (Glikson 2014), in connection with which we wish to thank the following people: Brenda McAvoy kindly helped with proof corrections. Helpful comments were obtained from Wallace Ambrose, Barrie Pittock, Hugh Davies, Leona Ellis, Miryam Glikson-Simpson, Victor Gostin, Clive Hamilton, Edward Linacre, Tony McMichael, Reg Morrison, Bruce Radke and Colin Soskolne. I thank Petra Van Steenbergen and Corina Van der Giessen for editorial help. I am grateful to Reg Morrison for contributing special figures and photographs, Jim Gehler for Ediacara photos, Mary White and John Laurie for fossil plant photos and Gerta Keller for reproduction of figures. The following people gave permission to reproduce figures in the book: John Adamek, Anita Andrew, Annemarie Abbondanzo, Robert Berner, Tom Boden, David Bowman, Karl Braganza, Pep Canadell, Randall Carlson, Giuseppe Cortese, Peter deMenocal, Gifty Dzah, Alexey Fedorov, Jim Gehling, Kath Grey, Jeanette Hammann, James Hansen, Paul Hoffman, John Johnson, Jean Jouzel, Barry Lomax, Petra Löw, Cesca McInerney, Michele McLeod, Yvonne Mondragon, Jennifer Phillips, Miha Razinger, Dana Royer, Elizabeth Sandler, Bill Schopf, Appy Sluijs, Phillipa Uwins, John Valley, Simon Wilde and James Zachos.

Contents

Chapter 1
Early Earth Systems

Ancient Water

No one
Was there to hear
The muffled roar of an earthquake
Nor anyone who froze with fear
Of rising cliffs, eclipsed deep lakes
And sparkling comet-lit horizons
Brighter than one thousand suns
That blinded no one's vision
No one
Stood there in awe
Of an angry black coned volcano
Nor any pair of eyes that saw
Red streams eject from inferno
Plumes spewing out of Earth
And yellow sulphur clouds
Choking no one's breath
No one
Was numbed by thunder
As jet black storms gathered
Nor anyone was struck asunder
By lightning, when rocks shuttered
Engulfed by gushing torrents
That drowned the smouldering ashes
Which no one was to lament
In time
Once again an orange star rose
Above a sleeping archipelago
Sun rays breaking into blue depth ooze
Waves rippling sand's ebb and flow
Receding to submerged twilight worlds
Where budding algal mats
Declare life
On the young Earth

(By Andrew Glikson)

A.Y. Glikson, C. Groves, *Climate, Fire and Human Evolution*, Modern Approaches in Solid Earth Sciences 10, DOI 10.1007/978-3-319-22512-8_1

Abstract The development of isotopic age determination methods and stable isotopic tracers to paleo-climate investigations, including oxygen ($\delta^{18}O$), sulphur ($\delta^{33}S$) and carbon ($\delta^{13}C$), integrated with Sedimentological records and organic and biological proxies studies, allows vital insights into the composition of early atmosphere–ocean-biosphere system, suggesting low atmospheric oxygen, high levels of greenhouse gases (CO_2, CO, CH_4 and likely H_2S), oceanic anoxia and high acidity, limiting habitats to single-cell methanogenic and photosynthesizing autotrophs. Increases in atmospheric oxygen have been related to proliferation of phytoplankton in the oceans, likely about ~2.4 Ga (billion years-ago) and 0.7–0.6 Ga. The oldest recorded indirect traces of biogenic activity are provided by dolomite and banded iron formation (BIF) from ~3.85 Ga-old Akilia and 3.71–3.70 Ga Isua greenstone belt, southwest Greenland, where metamorphosed banded ironstones and dolomite seawater-like REE and Y signatures (Bolhar et al. Earth Planet Sci Lett 222:43–60, 2004; Friend et al. Contrib Miner Petrol 183(4):725–737, 2007) were shown to be consistent with those of sea water (Nutman et al. Precamb Res 183:725–737, 2010). Oldest possible micro-fossils occur in ~3.49 Ga black chert in the central Pilbara Craton (Glikson. Aust J of Earth Sci 55:125–139, 2008; Glikson. Icarus 207:39–44, 2010; Duck et al. Geochim Cosmochim Acta 70:1457–1470, 2008; Golding et al. Earliest seafloor hydrothermal systems on earth: comparison with modern analogues. In: Golding S, Glikson MV (eds) Earliest life on earth: habitats, environments and methods of detection. Springer, Dordrecht, pp 1–15, 2010) and in 3.465 Ga brecciated chert (Schopf et al. Precamb Res 158:141–155, 2007). Possible stromatolites occur in ~3.49 and ~3.42 carbonates. The evidence suggests life may have developed around fumaroles in the ancient oceans as soon as they formed. The evidence indicates extended atmospheric greenhouse periods interrupted by glacial periods which led to an increase in oxygen solubility in water, with implications for enhanced life. Intermittent volcanic eruptions and asteroid and comet impacts, representing continuation of the Late Heavy Bombardment as recorded on the Moon, resulted in major crises in biological evolution.

1.1 Archaean and Proterozoic Atmospheres

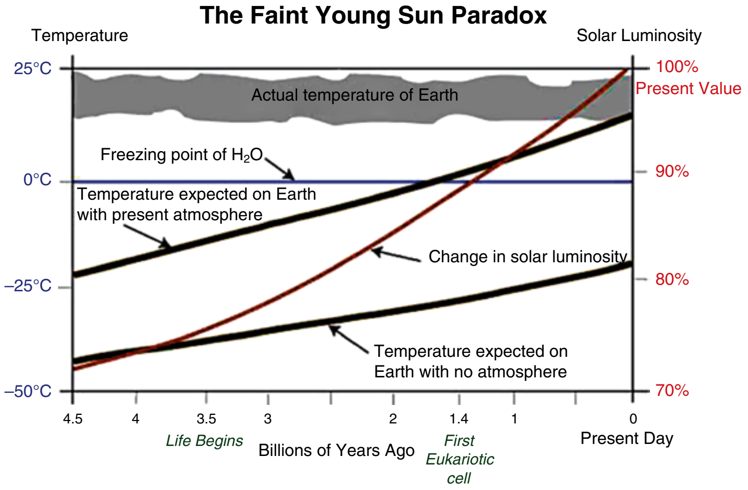
Terrestrial climates are driven through the exposure of the Earth surface to solar insolation cycles (Solanki 2002; Bard and Frank 2006), variations in the gaseous and aerosol composition of the atmosphere, the effects of photosynthesis on CO_2 and O_2 cycles, microbial effects on methane levels, volcanic eruptions, asteroid and comet impacts and other factors. By contrast to the thick CO_2 and SO_2 blankets on Venus, which exert an extreme pressure of 93 bar at the surface, and unlike the thin 0.006 bar atmosphere of Mars, the presence in the Earth's atmosphere of trace concentrations of well-mixed greenhouse gases (GHG) (CO_2, CH_4, N_2O, O_3) modulates surface temperatures, allowing the presence of liquid water (Fig. 1.1) and thereby

Fig. 1.1 Natural mortar and pestle – Komati River, Barberton Mountain Land, Swaziland (Photograph by Andrew Glikson)

life. During the Holocene surface temperatures ranged between −89 °C and +58 °C, with a mean of about +14 °C.

During early stages of terrestrial evolution low solar luminosity *(The Faint Young Sun)* lower luminosity than at present representing early stages in the fusion of hydrogen to helium (Sagan and Mullen 1972), is thought to have been compensated by high greenhouse gas (GHG) levels (Fig. 1.2), allowing surface temperature to remain above freezing (Kasting 1993). This author suggested that to warm the oceans above freezing point the atmosphere would have needed CO_2 levels some 100–1000 times the present atmospheric level. Alternative hypotheses were proposed by Longdoz and Francois (1997) in terms of albedo and seasonal variations on the early Earth. Rosing et al. (2010) pointed out a high ocean to continent surface area ratio in the Archaean would have led to a lower albedo and due to absorption of infrared radiation by open water. Temporal fluctuations in atmospheric GHG levels constituted a major driver of alternating glacial and greenhouse states (Kasting and Ono 2006). Rosing et al. 2010 suggested the Archaean atmosphere was less clouded and more transparent than later atmospheres due to a paucity of condensation nuclei such as occur above land, including dust particles, soot and sulphuric acid released by plant photosynthesis (Kreidenweis and Seinfeld 1988). The relations between GHG, clouds and surface albedo during the Archaean remains a subject of continuing debate (Goldblatt and Zahnle 2011).

Planetary evolution transpires through gradual changes as well as major upheavals. The former include plate tectonics, crustal accretion, crustal subduction, rise and erosion of mountain belts. The latter include abrupt magmatic and tectonic events and extra-terrestrial impact-triggered cratering. Geochronological age sequences, geochemistry and isotopic indices point to secular evolution from a



Even though the Sun was about 30% dimmer than it is now,
the temperature on Earth has been more or less stable.

Fig. 1.2 The faint young sun paradox according to Sagan and Mullen (1972), suggesting compensation of the lower solar luminosity by high atmospheric greenhouse gas levels at early stages of terrestrial evolution. (From the *Habitable Planet*: A system approach to environmental science, produced by the Harvard-Smithsonian Center for Astrophysics, Science Media Group and used with permission by the Annenberg Learner (Courtesy Michele McLeod) www.learner.org; http://www.learner.org/courses/envsci/unit/text.php?unit=1&secNum=4)

mainly basaltic crust (SIMA: Silica-Magnesium-iron-dominated crust) to granite-dominated crustal nuclei (SIAL: Silica-Alumina-dominated crust) (Glikson 1972, 1980, 1984; McCulloch and Bennett 1994).

Atmospheric CO_2 levels are buffered by the oceans (at present ~37,000 GtC) which contain about 48 times the atmospheric CO_2 inventory (currently ~800 GtC). The solubility of CO_2 in water decreases with higher temperature and salinity and the transformation of the $CO_3^{[-2]}$ ion to carbonic acid ($HCO_3^{[-1]}$) retards the growth of calcifying organisms, including corals and plankton. Plants and animals work in opposite directions of the entropy scale, where plants synthesize complex organic compounds from CO_2 and water, producing oxygen, whereas animals burn oxygen and expel CO_2. Disturbances in the carbon and oxygen balance occur when changes occur in the extent of photosynthetic processes, CO_2 solubility in the oceans, burial of carbon in carbonate and from remains of plants and oxidation of carbon through fire and combustion.

Forming a thin breathable veneer only slightly more than one thousandth the Earth's diameter, evolving both gradually as well as through major perturbations, the atmosphere acts as lungs of the biosphere, facilitating an exchange of carbon and oxygen with plants and animals (Royer et al. 2004, 2007; Siegenthaler et al. 2005; Berner 2006; Berner et al. 2007; Beerling and Royer 2011). In turn biological activity continuously modifies the atmosphere, for example through production of methane in anoxic environments, release of photosynthetic oxygen from plants and of dimethyl sulphide from marine phytoplankton. Long term chemical changes in the air-ocean system are affected by changes in plate tectonic-driven geomorphic changes including subduction of oceanic and continental plates (Ruddiman 1997, 2003, 2008), weathering, volcanic and methane eruptions, and variations in marine and terrestrial photosynthetic activity (Broecker 2000; Zachos et al. 2001; Hansen et al. 2007; Glikson 2008). The range of paleo-climate proxies used in these studies are reviewed in detail by Royer et al. (2001).

Early terrestrial beginnings are interpreted in terms of a cosmic collision ~4.5 billion years-ago between an embryonic semi-molten Earth and a Mars-scale body – *Theia* – determined from Pb isotopes (Stevenson 1987). The consequent formation of a metallic core, inducing a magnetic field which protects the Earth from cosmic radiation, and a strong gravity field which to a large extent prevents atmospheric gases from escaping into space, resulted in a haven for life at the Earth surface (Gould 1990). Relict ~4.4 Ga and younger zircons, representing the *Hadean* era, a term coined by Preston Cloud in 1972, signify vestiges of granitic and felsic volcanic crustal nuclei, implying the presence of a water component in the melt and low-temperature surface conditions (Wilde et al. 2001; Mojzsis et al. 2001; Knauth 2005, Valley et al. 2002) (Figs. 1.3 and 1.4). However, Pidgeon et al. (2013) and Pidgeon (2014) attributed the $\delta^{18}O$ values of zircon to secondary radiation damage and associated with hydrous alteration. Precambrian terrains contain relict ~4.1–3.8 Ga-old rocks, including volcanic and sedimentary components, exposed in Greenland, Labrador, Slave Province, Minnesota, Siberia, northeast China, southern Africa, India, Western Australia and Antarctica (Van Kranendonk 2007). These formations, formed parallel to the Late Heavy Bombardment (LHB) on the Moon (~3.95–3.85 Ga) (Ryder 1991), are metamorphosed to an extent complicating recognition of primary impact shock features, which to date precluded an identification of signatures of the LHB on Earth.

Knauth and Lowe (2003) and Knauth (2005) measured low $\delta^{18}O$ values in ~3.5–3.2 Ga cherts of the Onverwacht Group, Barberton Greenstone Belt (BGB), Kaapvaal Craton, suggesting extremely high ocean temperatures in the range of 55–85 °C (Figs. 1.3, and 1.4). The maximum $\delta^{18}O$ value in Barberton chert (+22‰) is lower than the minimum values (+23‰) in Phanerozoic sedimentary cherts, precluding late diagenesis as the explanation of the overall low $\delta^{18}O$ values. Regional metamorphic, hydrothermal, or long-term resetting of original $\delta^{18}O$ values is also precluded by preservation of $\delta^{18}O$ across different metamorphic grades. According to Knauth (2005) high-temperature conditions extended beyond submarine fumaroles and the Archaean oceans were characterized by high salinities 1.5–2.0 times the modern level. In this interpretation ensuing evaporite deposits were removed by subduction, allowing lower salinities. However, well preserved Archaean sedimentary sequences contain little evidence of evaporite deposits. The low-oxygen levels of the Archaean atmosphere and hydrosphere limited marine life to extremophile cyanobacteria. Microbial methanogenesis involves reactions of CO_2 with H_2 or acetate (CH_3CO_2—) produced from fermenta-

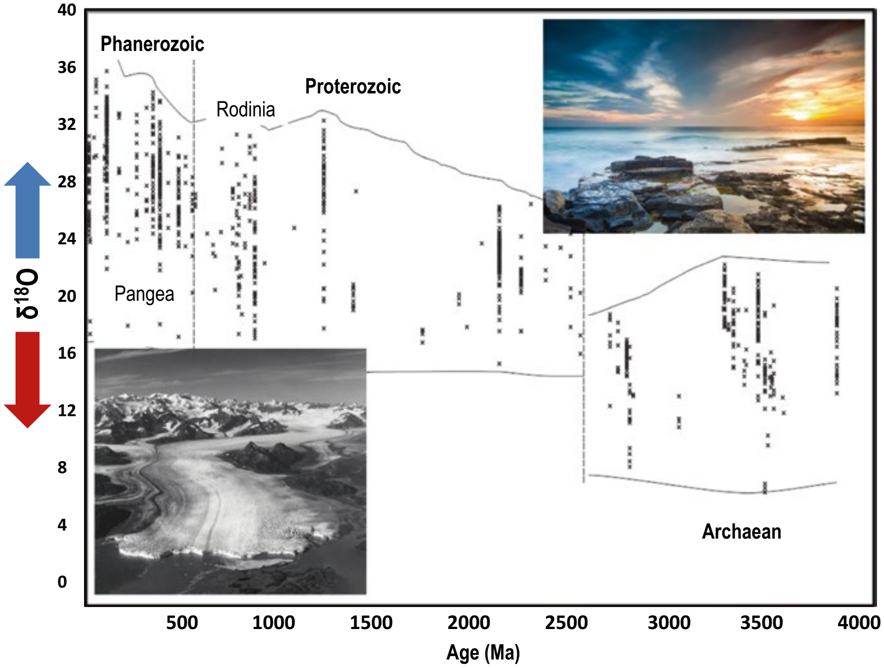


Fig. 1.3 A compilation of oxygen isotope data for cherts. The overall increase in $\delta^{18}O$ with time is interpreted as global cooling over the past 3500 Ma. The variation in $\delta^{18}O$ for cherts at any given time is caused by the presence of low $\delta^{18}O$ meteoric waters during burial at elevated temperatures (Knauth 2005; Elsevier, by permission). Insets: (1) Columbia Glacier (NASA). (http://www.google.com.au/search?q=nasa+glacier&hl=en&tbm=isch&tbo=u&source=univ&sa=X&ei=hkmEUbCDBonGkgXDg4C4CQ&sqi=2&ved=0CEYQsAQ&biw=1360&bih=878); (2) http://www.flickr.com/photos/anieto2k/8636213185/sizes/l/in/photostream/ (anieto2k's photo stream)

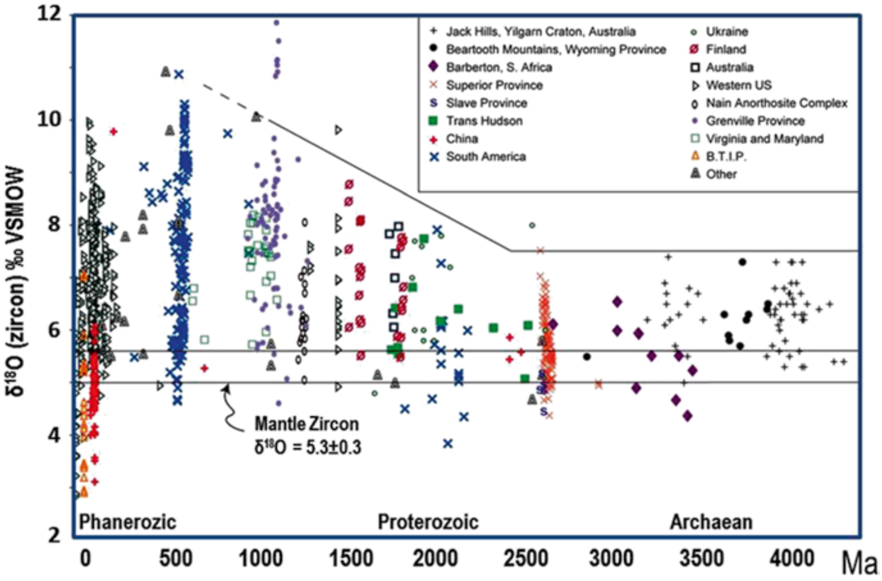


Fig. 1.4 $\delta^{18}O$ ratio of igneous zircons from 4.4 Ga to recent, displaying an increase in abundance of low-temperature effects with time from approximately ~2.3 Ga (Courtesy J.W. Valley)