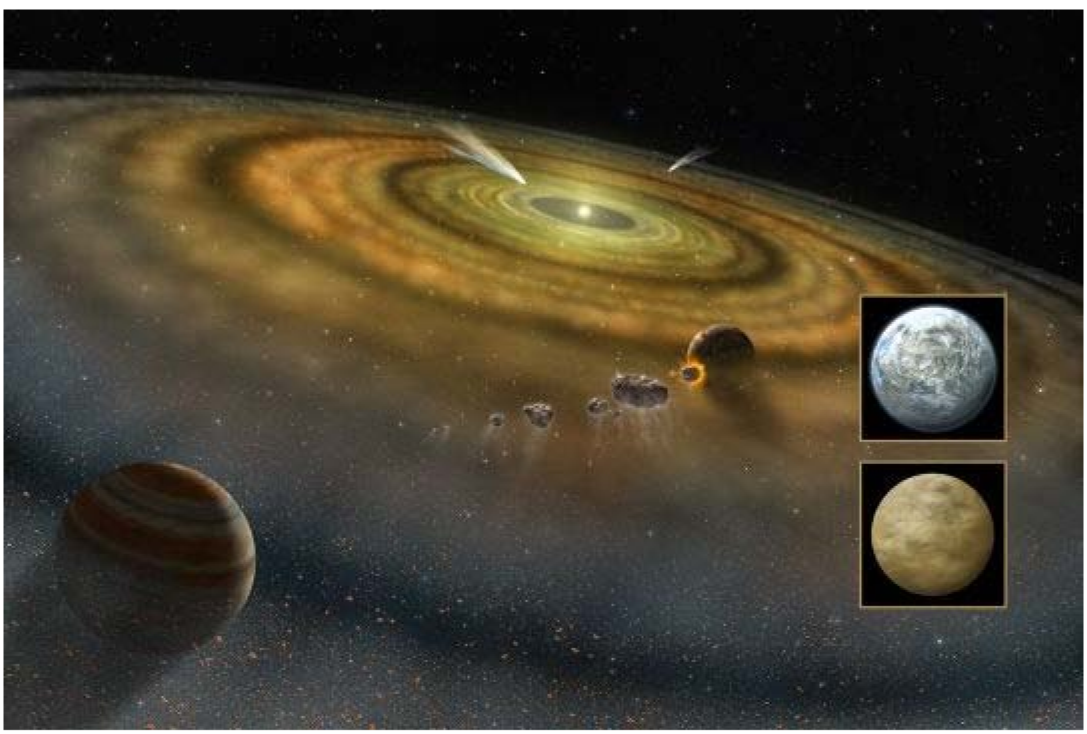
The Chaotian Eon

Formation of the Solar System



Planetary formation, courtesy of NASA

This very brief unit is concerned with the formation of the

Solar System, up to the formation of the Earth, it represents a convergence and overlap of cosmology with geology (timescale), as shown by the dual menu hierarchies above. Our inspiration here is an intriguing suggestion by Goldblatt et al. 2010, to extend the geological timescale further back so that a new eon, called the Chaotian now precedes the Hadean (see diagram at right). Although this is getting into pretty speculative territory, it looks like fun, so why not? MAK110725

Eon	Era	Period	Age (Ga)
			?3.9
Hadean	Neohadean	Promethean	4.0
		Acastan	4.1
	Mesohadean	Procrustean	4.2
		Canadian	4.3
	Palaeohadean	Jacobian	4.4
		Hephaestean	~4.5
Chaotian	Neochaotian	Titanomachean	
		Hyperitian	
	Eochaotian	Erebrean	
		Nephelean	

Proposed time scale for the Solar System formation and the early Earth, from Goldblatt et al. 2010 p.2; Creative Commons attribution license.

Links: See Solar System Formation for more on events during Chaotian time; Comets in the solar system's formation and evolution - chart (in French) showing the "phylogeny" so to speak of Solar System; Origin and Evolution of Solar System, diagram from free pdf ebook ***Exploring the Trans-Neptunian Solar System*** (1998); The Earth as a Planet - good page on the early Earth, includes material relevant to both the Chaotian (formation of the Solar System and the Earth) and the Hadean.

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The Chaotian Eon

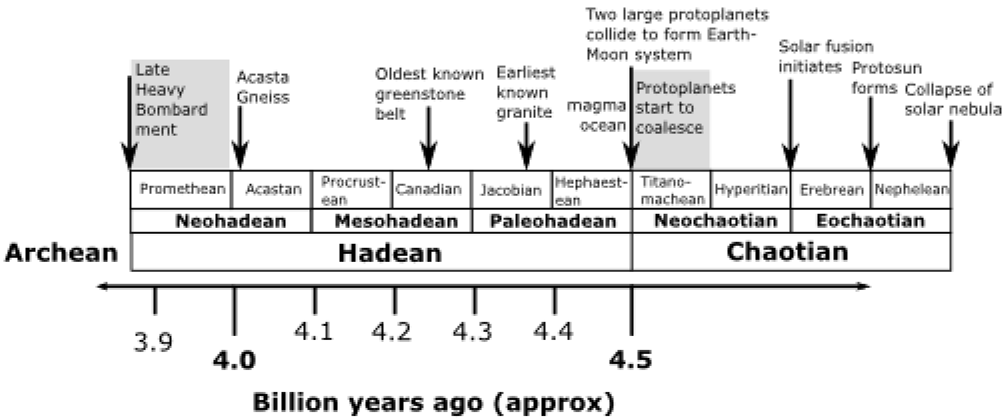
Earth's forgotten youth, and beyond

Posted on March 16, 2010 by Chris Rowan at All Geo - Highly Allochthonous)

The further back in time we go, the more and more fragmented the Earth's geological record becomes. Whilst not exactly common, rocks with ages up to about 3.5 billion years old are found at multiple points on the Earth's surface. However, rocks older than this are much less common. Extensive outcrops older than about 3.8 billion years are exceptionally rare, possibly because a series of very large meteorite impacts prior to this time – the Late Heavy Bombardment – largely destroyed any older bits of crust. The Acasta Gneiss in northern Canada, dated at around 4.03 billion (4030 million) years, is generally regarded as the oldest known outcrop of crust, although a recent study has claimed that the Nuvvuagittuq greenstone belt, also in northern Canada, may be as old as 4280 million years. The only known bits of the Earth that are older are 4.2-4.4 billion year-old zircon crystals found in the Jack Hills Conglomerate in Australia; the conglomerate itself was deposited about 3 billion years ago, but it contains debris eroded from much older, and now long-vanished, bits of crust.

Two or three data points is not a hell of a lot to go on when trying to reconstruct the evolution of the early Earth, especially when the material involved is far from pristine (the Acasta Gneiss, being a gneiss. has been partially remelted, for example). It is therefore no surprise that the geological timescale for the period between the Earth's formation, about 4.56 billion years ago, and the start of the Archean Eon, usually pegged at about 3.8 billion years ago, is rather lacking in detail. This period is usually referred to as the 'Hadean', which is more of a reference to the presumed conditions on the Earth's surface than a subtle pointer to the fact that we don't know what the hell was really going on.

However, this has not stopped Colin Goldblatt and his co-authors having a go at adding a bit more structure to the Earth's earliest days – and beyond. The 'Chaotian' eon at the start of their proposed new timescale is a common framework for the entire solar system, beginning with the gravitational collapse of the gas cloud that it would eventually form from. Key events – such as the initiation of solar fusion, or the first interactions between sizeable protoplanets that condensed from the protoplanetary disk – mark the boundaries between different eras and periods within the Chaotian. The start of the Hadean is marked by the collision of the proto-Earth, which the authors call ***Tellus***, with another Mars-sized protoplanet, forming the Earth-Moon system.



Proposed new timescale for the formation of the solar system (Chaotian) and the evolution of the early Earth (Hadean). Click for a larger image

Thus, the Chaotian marks the time when solar system first became a distinct entity from the galactic neighbourhood; the beginning of the Hadean is when the Earth's geological history begins to be shaped as much by internal processes, such as mantle convection, as by external events such as collisions with other protoplanets, Similarly, from beginning of the Archean, at the end of the Late Heavy Bombardment, internal processes start to completely dominate the Earth's geological evolution; extraterrestrial collisions can still have significant geochemical and biological impacts, but they no longer melt the entire crust. Conceptually, I find this quite a nice way of looking at it.

The authors also attempt to subdivide the Hadean, but because we still don't understand the key events in the Earth's geological development over this period, it's not quite as successful. The Hephaestean period probably covers the recovery from the Moon-forming impact. The Jacobian, Canadian and Acastan periods refer to the Jack Hills zircons, Nuvvuagittuq greenstone belt and Acasta Gneiss, respectively, but although these outcrops can give us clues about what the Earth was like when they first formed, it is a bit risky to try to characterise an entire planetary system from one sampling point. For example, the Jack Hills zircons tell us that granite – in other words, continental crust – was forming 4.4 billion years ago, but this is only a minimum age; we have no evidence that it wasn't forming before that. Also, for all we know greenstone belts were also forming at exactly the same time, and have just not been preserved. The small amount of data we have available means that a single new outcrop might force the entire timescale to be redrafted.

It's difficult to know if we're ever going to be able to construct a truly robust, process based timescale for the first 700 million years of Earth's history, because it's unclear how much we'll ever truly know about the Hadean. Still, this is an interesting attempt to set the story of our planet's birth into a slightly more structured framework.

Reference: Goldblatt, C., Zahnle, K. J., Sleep, N. H., and Nisbet, E. G.: The Eons of Chaos and Hades, ***Solid Earth***, 1, 1-3, doi:10.5194/se-1-1-2010, 2010 abstract pdf

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The Eochaotian Era

The Solar nebula

Shock waves through icy parts of the solar nebula may be the mechanism that enriched ancient meteorites (called chondrites) with water -- water that some believe provided an otherwise dry Earth with oceans. Source - NASA, artwork © W.K. Hartmann

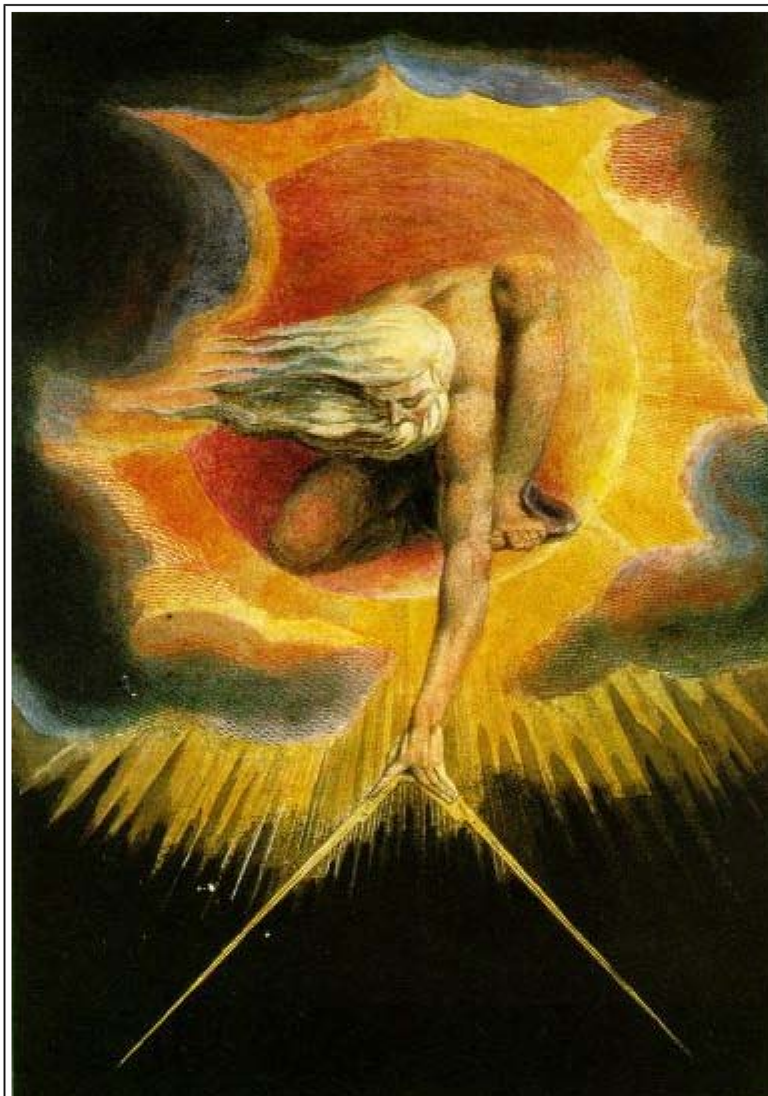
Introduction - The Chaotian Eon

We begin at the beginning... (well, not exactly, there's still 8 billion years of cosmic evolution)

In our review of the earliest periods of geological and solar system time, we have adopted the terminology proposed by Goldblatt et al. 2010, who refer to two eons (Chaotian and Hadean), five eras, and ten periods. The authors explain:

> "We suggest two Chaotian eras, each era with two periods. The Eochaotian begins when the Solar Nebula became a closed system with respect to the rest of the giant molecular cloud and encompasses the agglomeration of the Solar System constituents from the nebula. It includes the Nephelean Period, for the cloud that is the nebula, and the Erebrean Period (Erebus, darkness) for the proto-Sun, yet to be luminous. The Neochaotian Era begins with the first light from the Sun...Events and material from before the nebula are Prenephelean. We recommend that this term replace "presolar" for meteorite grains that formed before the nebula (Nittler, 2003), in contrast to within the nebula but before the Sun."

-- Goldblatt et al. 2010 p.2



The Ancient of Days by William Blake. 1794; Relief etching with watercolor, 23.3 x 16.8 cm; British Museum, London. Although Ancient of Days is one of the names of God in Aramaic, Greek, and Laton, the former (***Atik Yomin***) and occurring in Jewish mysticism as the highest emanation of the Godhead, Blake's relief etching represents a more complex and nuanced archetype, which he calls Urizen, the embodiment of conventional reason and law. Blake's visionary artwork, as with Milton's ***Paradise Lost*** and more recently Philip Pullman's ***His Dark Materials*** (influenced by both Blake and Milton) reinterpreted and subverted traditional religious themes (note that "The Golden Compass" of Pullman's first novel was not, as portrayed in the film, a navigation instrument but a compass or drawing instrument as per Blake's illustration above). MAK110904

With the usual geographic and stratigraphic regions being rather thing on the ground, Inspiration for these names is derived from mythology, specifically the works of Hesiod and Milton. Hesiod describes creation (***Theogony*** 116-):

> "Verily at the first Chaos came to be, but next
> wide-bosomed Gaea [Earth]. From Chaos came
> forth Erebus [darkness] and black Nyx [Night]; but
> of Nyx were born Aether [the bright upper atmosphere]
> and Hermera [Day]. . . "

From Milton (***Paradise Lost*** II, 907-):

> ". . . ***Chaos*** Umpire sits,
> And by decision more imbroiles the fray
> By which he Reigns; next him high Arbiter
> ***Chance*** governs all. Into this wilde Abyss,
> The Womb of nature and perhaps her Grave. . .
> Unless th' Almighty Maker them ordain

His dark materials to create more Worlds"

The Pre-solar nebula

Editor's note: I'm just copying this basic intro from Wikipedia; essentially, this is just a basic place holder page, to serve as a lead in to the Hadean. In the future a proper account could be added here, if someone wants to contribute. But the Wikipedia entry is quite well referenced and should serve well enough MAK110904

The formation and evolution of the Solar System is estimated to have begun 4.568 billion years ago with the gravitational collapse of a small part of a giant molecular cloud. Most of the collapsing mass collected in the centre, forming the Sun, while the rest flattened into a protoplanetary disk out of which the planets, moons, asteroids, and other small Solar System bodies formed (link, link). This widely accepted model, known as the nebular hypothesis, was first developed in the 18th century by Emanuel Swedenborg, Immanuel Kant, and Pierre-Simon Laplace. Its subsequent development has interwoven a variety of scientific disciplines including astronomy, physics, geology, and planetary science. Since the dawn of the space age in the 1950s and the discovery of extrasolar planets in the 1990s, the models have been both challenged and refined to account for new observations.

The nebular hypothesis maintains that the Solar System formed from the gravitational collapse of a fragment of a giant molecular cloud. (Montmerle et al 2006) The cloud itself had a size of about 20 pc, (Montmerle et al 2006) while the fragments were roughly 1 pc (three and a quarter light-years) across. (Zabludoff 2003) The further collapse of the fragments led to the formation of dense cores 0.01-0.1 pc (2,000-20,000 AU) in size. (Montmerle et al 2006) (Rawal 1986). One of these collapsing fragments (known as the pre-solar nebula) would form what became the Solar System. (Irvine 1983). The composition of this region with a mass just over that of the Sun was about the same as that of the Sun today, with hydrogen, along with helium and trace amounts of lithium produced by Big Bang nucleosynthesis, forming about 98% of its mass. The remaining 2% of the mass consisted of heavier elements that were created by nucleosynthesis in earlier generations of stars. (Zeilik & Gregory 1998 p. 207) Late in the life of these stars, they ejected heavier elements into the interstellar medium. (Lineweaver 2001)

Studies of ancient meteorites reveal traces of stable daughter nuclei of short-lived isotopes, such as iron-60, that only form in exploding, short-lived stars. This indicates that one or more supernovae occurred near the Sun while it was forming. A shock wave from a supernova may have triggered the formation of the Sun by creating regions of over-density within the cloud, causing these regions to collapse. (Williams 2010). Because only massive, short-lived stars produce supernovae, the Sun must have formed in a large star-forming region that produced massive stars, possibly similar to the Orion Nebula (Hester et al 2004; Bizzarro et al 2007). Studies of the structure of

Hubble Space Telescope image of probable protoplanetary discs in the Orion Nebula, a light-years-wide "stellar nursery" probably very similar to the primordial nebula from which our Sun formed . This view of a small portion of the Orion Nebula, captured by the Wide Field and Planetary Camera 2, reveals five young stars. Four of the stars are surrounded by gas and dust trapped as the stars formed, but were left in orbit about the star. They seem to be protoplanetary disks, or proplyds, that might evolve on to agglomerate planets. The proplyds which are closest to the hottest stars of the parent star cluster are seen as bright objects, while the object farthest from the hottest stars is seen as a dark object. The field of view is only 0.14 light-years across. The Orion Nebula star-birth region is 1500 light-years away, in the direction of the constellation Orion. Image and caption from Wikipedia - image by NASA, public domain

the Kuiper belt and of anomalous materials within it suggest that the Sun formed within a cluster of stars with a diameter of between 6.5 and 19.5 light-years and a collective mass equivalent to 3,000 Suns. (Portegies Zwart 2009) Several simulations of our young Sun interacting with close-passing stars over the first 100 million years of its life produce anomalous orbits observed in the outer Solar System, such as detached objects. (Kaib & Quinn 2008)

Because of the conservation of angular momentum, the nebula spun faster as it collapsed. As the material within the nebula condensed, the atoms within it began to collide with increasing frequency, converting their kinetic energy into heat. The centre, where most of the mass collected, became increasingly hotter than the surrounding disc. (Zabludoff 2003) Over about 100,000 years, (Montmerle et al 2006) the competing forces of gravity, gas pressure, magnetic fields, and rotation caused the contracting nebula to flatten into a spinning protoplanetary disc with a diameter of ~200 AU (Zabludoff 2003) and form a hot, dense protostar (a star in which hydrogen fusion has not yet begun) at the centre. (Greaves 2005)

At this point in its evolution, the Sun is believed to have been a T Tauri star. (Caffe et al 1987). Studies of T Tauri stars show that they are often accompanied by discs of pre-planetary matter with masses of 0.001-0.1 solar masses. (Momose et al 2003) These discs extend to several hundred AU—the Hubble Space Telescope has observed protoplanetary discs of up to 1000 AU in diameter in star-forming regions such as the Orion Nebula (Padgett et al 1999) and are rather cool, reaching only a thousand kelvins at their hottest. (Küker et al 2003). Within 50 million years, the temperature and pressure at the core of the Sun became so great that its hydrogen began to fuse, creating an internal source of energy that countered gravitational contraction until hydrostatic equilibrium was achieved (Yi et al 2001)This marked the Sun's entry into the prime phase of its life, known as the main sequence. Main sequence stars derive energy from the fusion of hydrogen into helium in their cores. The Sun remains a main sequence star today. (Zeilik & Gregory 1998 p. 320)

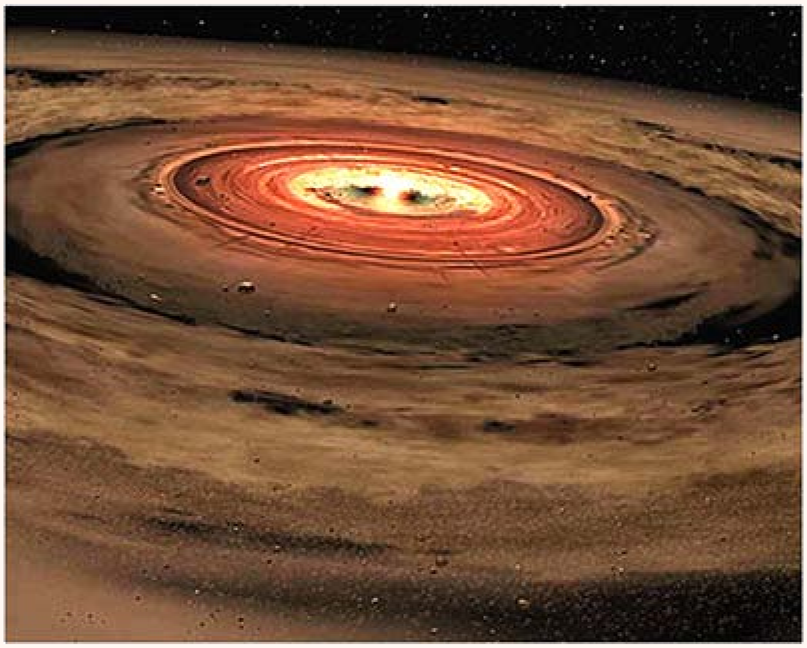
- Wikipedia

Links: Formation of the Solar System; A Possible Sequence of Events for the Formation of the Solar System - astronomyonline.org; Astro 1: `Slides' for Class 43 - The Formation of the Sun and Planets page by Niel Brandt

Page by MAK110904, edited RFVS111024; incorporated content by Wikipedia, NASA, and Goldblatt et al. 2010, and other sources.

The Neochaotian Era

Formation of the Solar System



Artist's Impression of Accretion Disc - NASA, via Essay Web

Introduction

This page was originally the Cryptic Era of the Hadean page. With the new timescale proposed by Goldblatt et al. 2010 it becomes the the ***Titanomachean Period***. The reason for these mythological names are explained in the previous page. As defined by Goldblatt et al. 2010:

> "The Neochaotian Era begins with the first light from the Sun. Its periods are the ***Hyperitian*** (the Titan Sun god Hyperion) for the time when gravitational collapse made the Sun's first light brighter than its subsequent main sequence (Sackmann et al., 1993), followed by the ***Titanomachean*** (the war of Titans), to encompass the collision of proto-planets to form our present set of planets."

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Neochaotian events

1. &gtn; 4567 Ma Supernova "Germinator" exploded causing a gravito-thermal collapse in the Sun Nebula (Eochaotian era)

2. ???? Ma The planetesimal system formed, soon giving rise to

a. a number of protoplanets in the inner solar system, out to and including the current asteroid belt distance from Sun,
b. the jovians Jupiter, Saturn, Neptune and Uranus, and
c. the outer solar system icy planets (like Pluto).

in this era there were some 10-20 heavy FUor eruptions from Sun in its T Tauri stage, rising temperatures by 700? Kelvin; (Hyperitian period)

3. 4560 Ma For 10-30 Ma the inner solar system was characterized by protoplanet collisions and terrestrial planet formation: Mercury, Venus, Protogaia (protoearth), Theia and Mars. I've read one dating of Protogaia's formation to be 4557 Ma, which might be after Sun's T Tauri eruptions - this would then be one possible starting point of Hadean; most certainly Protogaia evolved some atmosphere soon after its creation. (Early Titanomachean)

4. 4533 Ma For a time after formation Protogaia was moonless, until Theia had grown to the size of current Mars. It is believed Theia was in Lagrange 4 coorbit (preceeding Trojan = same orbit but 30° forth) with Protogaia, but that position became unstable as Theia grew. Then Theia collided with Protogaia, and the major part became Earth, while some debris came in orbit around earth and assembled to Moon in some 10 years. It's very unclear whether this collision removed the atmosphere or not, some simulation numbers indicate a 50:50 probability whether removed or not removed. In either case the impact created a silicate atmosphere that is supposed to have cooled very fast (decades) (Later Titanomachean

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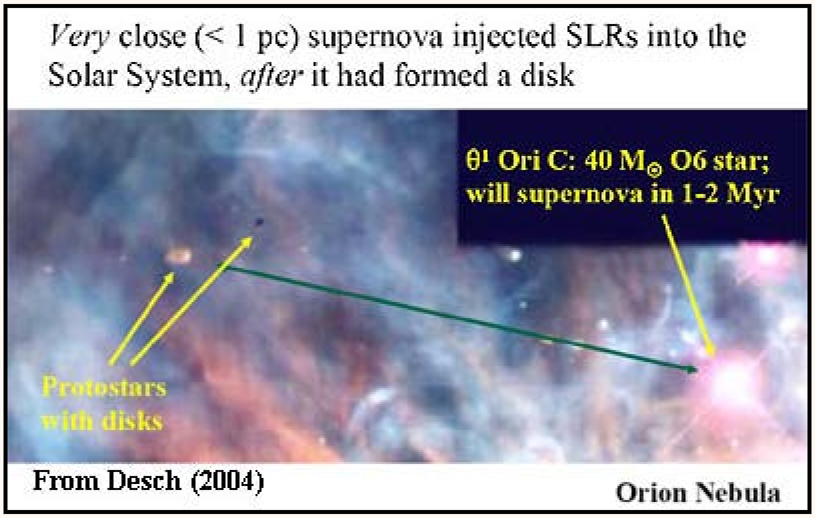
The Neochaotian Era

The Neochaotian (formerly Cryptic) Era encompasses the time during which the first 99% of the Earth's mass accreted from the solar disk. This interval began at 4567 Mya, the age of the oldest chondritic meteorites (essentially undifferentiated stardust). It ended when the Earth swallowed the hypothetical planetoid Theia (~4515 Mya), plus an allowance of 15 My for the Moon to form from all of the resulting debris which was not reabsorbed by the Earth. This brings us to the nice, round, even number of 4500 Mya, so that mathematical convenience and geological protocol are equally served.

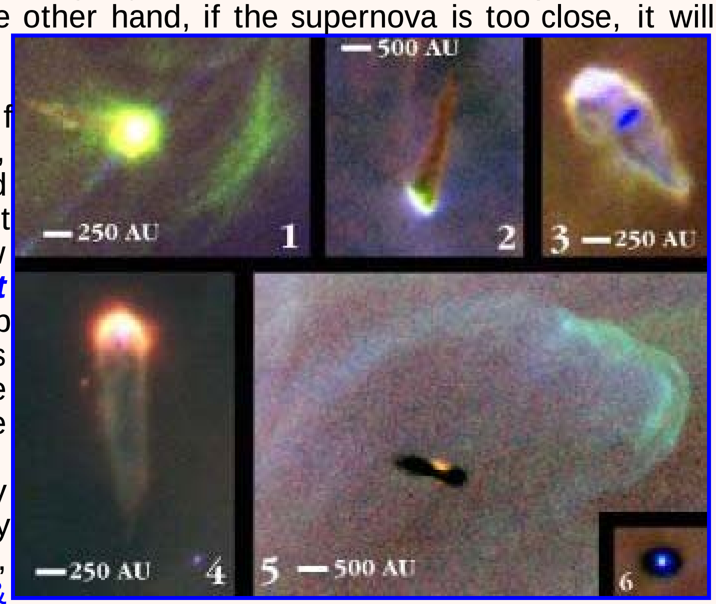
The beginning of the solar system is one of the most accurately measured dates in astronomy. It is based on isotope ratios in the oldest meteorites which can confidently be ascribed to our own solar system. Those dates converge on 4560-4570 Mya with remarkable consistency. The meteorites are dated with the usual long-lived heavy-metal isotope ratios. We know that they date from near the beginning of the solar system because of the presence of other isotopes trapped by inclusions (individual grains) within the rock. These isotopes can ***only*** be produced from the decay of relatively short-lived radioactive materials (e.g. . Thus, the meteorite cannot be much younger than the solar system.

The Problem of SLRs



Sounds good, but how did the short-lived radionuclides ("SLR"s) get there in the first place? There are several theories. The most popular seems to be that a supernova happened to explode in the galactic neighborhood at about the time the sun was turning on its fusion reactor. Supernovas produce most of the required SLRs, and the explosion inserted them into the protoplanetary disk. Other theories, relating to bursts of star formation within nebulae, explain why the presence of nearby supernova is not as coincidental as it might seem. Yet other ideas are put forward to explain why some ancient meteorites lack certain specific SLRs, how these materials were trapped in the disk, etc.

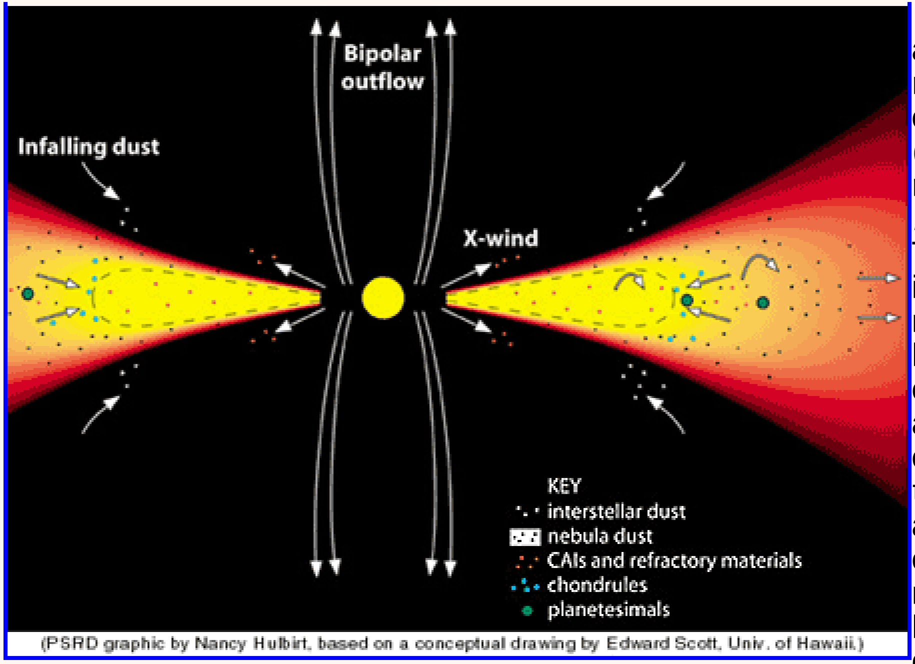
In a very useful unpublished review, Desch (2004) notes that no single explanation accounts for all of the known SLRs in the early solar system. While Desch favors a close supernova (which reasonably explains the SLR types) he admits that the probability of a supernova just happening to be within ~3 light years of the system at just the right time is low. He asserts that this objection may be overcome if supernova events are also the ***cause*** of solar system formation, i.e. the supernova's shockwave induced collapse of the protoplanetary disk.. However, as Desch states, no detailed models yet support the relationship between the death of one star with the birth of planets around another. In this connection it is important to remember that the supernova has to be within a few light-years, or all of the SLRs it produces will decay before they reach the protoplanetary disk. On the other hand, if the supernova is too close, it will destroy the disk.



There are problems with the supernova hypothesis. If the supernova has to be the catalyst for condensation, then we'd expect that condensation of chondrites would occur at the same time as injection of SLRs. It turns out that most chondrite formation may have occurred a few My ***after*** SLRs were incorporated into solids. Wadhwa ***et al***. (2007); Wadhwa & Russell (2000). Wadhwa's group (which includes Desch) sees all this as a process beginning with the supernova, but it complicates the relationship yet further. In addition, SLR relative abundances are not easily explained by a supernova. Gounelle ***et al***. (2005). Even in the sort of nebulary scenario postulated by Desch and others, the probability of significant SLR accumulation from a supernova, without destroying the disk, is less than 1%. Williams & Gaidos (2007).

If we sound unconvinced about the supernova, it's only because we're unconvinced. It seems to involve quite a bit of special pleading. We therefore advance our own unconvincing idea. From a quick race through the literature, at least one factor may not have been taken into account. What happens when a star first ignites its fusion motor? Presumably, things go "boom" and the immediate neighborhood is cleared by a flood of photons. After this (a) the shock wave of photons ignites other regions, (b) the original area is quickly refilled as gravity reasserts itself, with the incoming particles creating a new and bigger "boom," or (c) some combination of the two.

This sort of thing surely isn't like flipping on



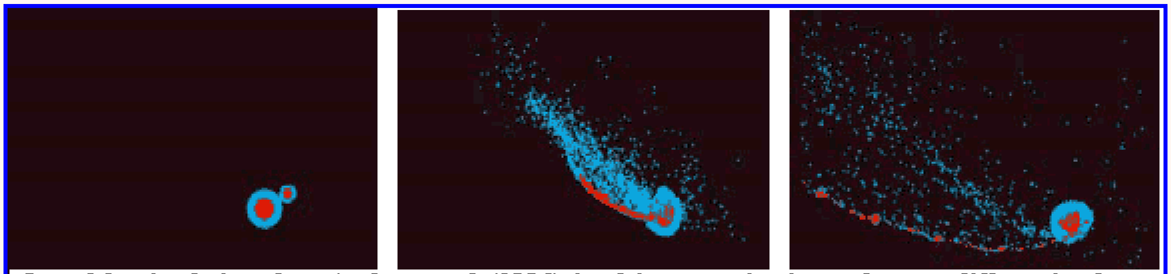
a light switch. Instead, the process seems rife with possibilities for locally non-linear effects, huge, fluctuating magnetic fields (Gounelle et al., 2005), and some briefly relativistic heavy ions. Take a look at the ***real*** protoplanetary clouds in the image. They are grossly asymmetric, inhomogeneous, and are associated with multiple, visible wave fronts, which are likewise lop-sided. Consider the magnitude of the forces necessary to generate this asymmetry against the homogenizing effects of gravity. In a few million years, these bodies will presumably settle down and raise their little solar systems like everyone else. But, during their fifteen minutes of flame, they clearly display -- locally and very briefly -- the ability to generate some remarkable pyrotechnics. In other words, for a short time, parts of the protosun might behave as a sort of amateur supernova.

The recent literature contains some thought in this direction, ***e.g.***, Gounelle ***et al***. (2005) ("X-wind" model). Unfortunately, this model does not account for the presence of ^{60}Fe, for which the authors concede a supernova origin. Desch (2004) argues that these kinds of forces would also exhaust themselves quickly ionizing gas, rather than causing nuclear reactions. But this effect might also raise the possibility of wakefield acceleration, which would produce a proportion of even higher energy particles.

Other Image Credits: Protosuns from the Physics 108 website of **Prof. Joseph Howard**, Salisbury Univ. (MD, USA). X-wind graphic from **Planetary Science Research Discoveries**.

Accretion of the Earth

The bulk of the sun's protoplanetary disk condensed from gas and dust into rock in only 2-3 My. Bizzarro et al. (2004). The inner planets are thought to have accreted in about 30 My, and perhaps much less. Krot ***et al***. (2005). Baker ***et al***. (2005) report absolute dates from basaltic meteorites within 1-2 My of the formation of the solar system, i.e. 4566.2 ± 0.1 My. Note that this is basalt, not some undifferentiated chondrite. It necessarily came from a sizeable body which had generated large internal pressures and was beginning to separate into different rock layers.



One of the simulations from Asphaug et al. (2006), involving a grazing impact between differentiated planetoids of 0.1 and 0.01 Earth masses at a few km/sec. Note the formation of a string of iron-rich (red) fragments from the core of the smaller body.

After that, things were kept lively for another 30 My or so by impacts between the inner planets and a few remaining planetoids, such as the Earth-Theia collision. For the most part, these late encounters added no net mass to the inner planets. The bodies involved were probably still molten. Greenwood ***et al***. (2005). The relatively large tidal forces exerted by the existing planets simply ripped the impactors apart and threw the remains out of the inner solar system. Massed gained from the planetoids was offset by mass lost to space from the force of the impact. The formation of our own moon was a relatively unusual event. Simulations show that impacts (or near misses) in this era had about an even chance of ***reducing*** planetary masses by shaving off pieces of the planet during glancing collisions. Asphaug et al. (2006).

The fact that these large Late Titanomachean collisions were both random and rare does have significant implications for properties other than mass. Large collisions would strip off the earliest atmospheres, might change the composition of the crust, alter the crust:core ratio, and change the spin rate and axis of the planet, all depending on the properties of the impacting planetoids. Halliday (2004); Koeberl (2006). The net result of is that the inner planets show considerably more random variability than one might expect. Canup & Agnor (2000). ATW070724

The Chaotian Eon

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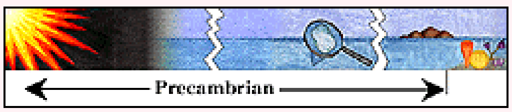
The Precambrian

The Precambrian - literally "before the Cambrian" - includes most of the history of life on Earth (albeit very simple life for almost the whole eon). The term is rarely uised now, since modern geology has a more precise undferstanding (down to the geon scale at least, and even life did develop, from prokaryotes during the Archean to eukaryotes during the proterozoic. We have retained the term here in the interest of deep time exponential and logarithmic timescales. So the Precambrian + Phanerozoic is almost ten times longer than the Phanerozoic alone, the Phanerozoic almost ten times longer than the Cenozoic alone, and so on. This unit is also a conventient place to put planetary timescales, since in the case of the moon and Mars all the action was happebning during the early to mid Precambrian, by the late Precambrian these were dead worlds. Only the Earth is unique in this regard, which also ties in with the mutual evolution of life and mineral., MAK120709

The Precambrian



The Precambrian is sometimes referred to as an "eon." However, it actually has no rank. It is simply Precambrian time. The Precambrian is that stretch of geological time from the formation of the Earth itself to the start of the Cambrian period. This immensely long stretch of time - some four billion years or more - saw the formation of the Earth as a planetary body, including geosphere, atmosphere, and hydrosphere, as well as the appearance of the biosphere and hence the transformation of the Earth from a dead planet to a living one.

History

During the eighteenth century geologists first began mapping the strata of the earth's crust. In doing so they frequently found a "basement complex" of igneous and metamorphic rocks beneath the lowest sedimentary layers. These were called the "Primitive" or "Primary", although the term "Primary Era' later came to be applied to the oldest sedimentary stage (later to be called the Paleozoic). In 1835 the English geologist Adam Sedgwick used the name "Cambrian" for the oldest sedimentary strata. Thereafter the underlying rocks were term Precambrian - "before the Cambrian". During the twentieth century the term "Cryptozoic" - age of hidden life" - was used to designate this period, whilst Phanerozoic - "age of obvious (or revealed) life" - was used for those periods from which fossils of multicellular organisms are known (i.e. the Cambrian period to the present-day). Although the latter term is still in use, "Cryptozoic" pretty much disappeared in favor of the older and well established Precambrian.

The extent of the Precambrian

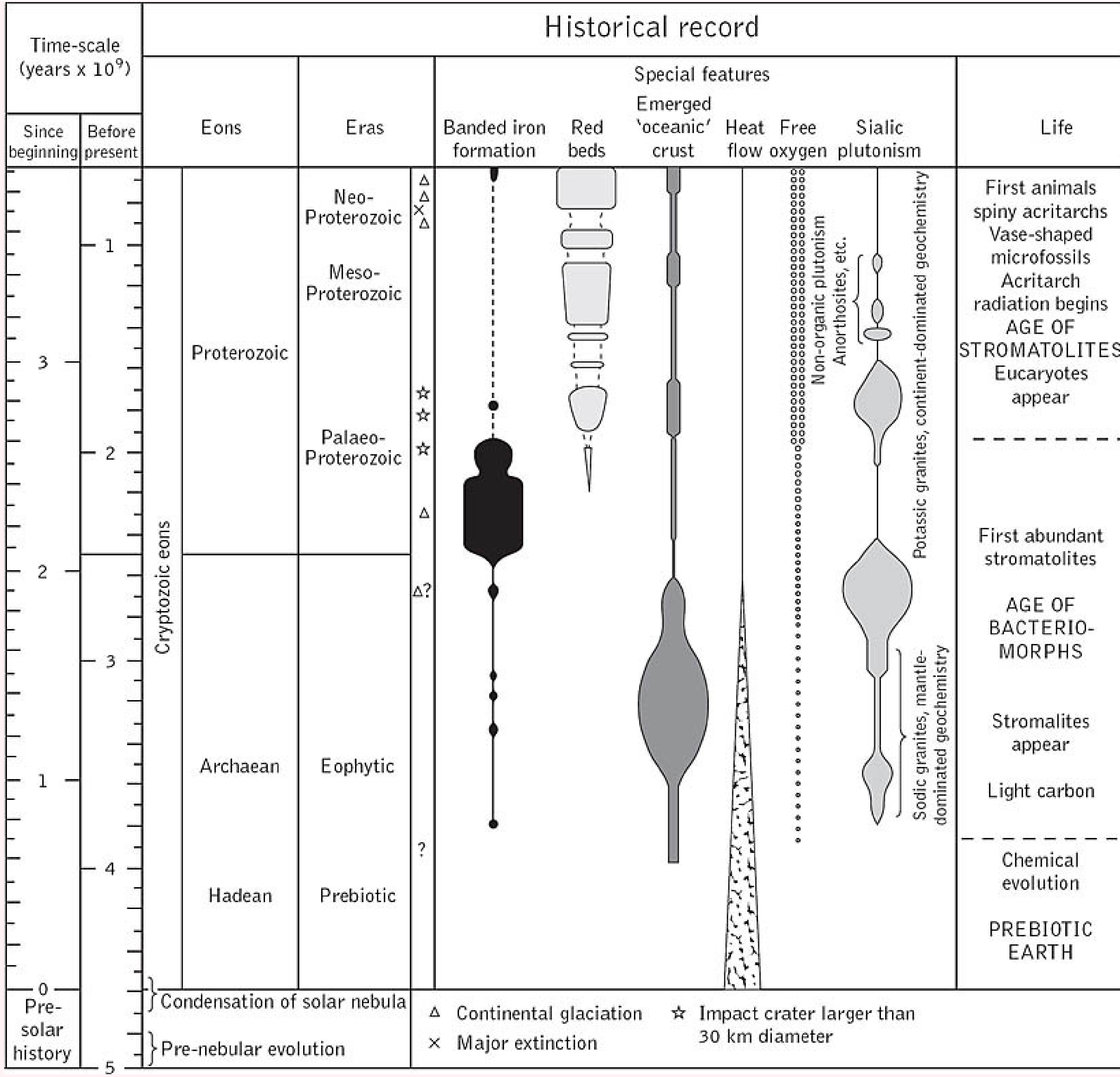
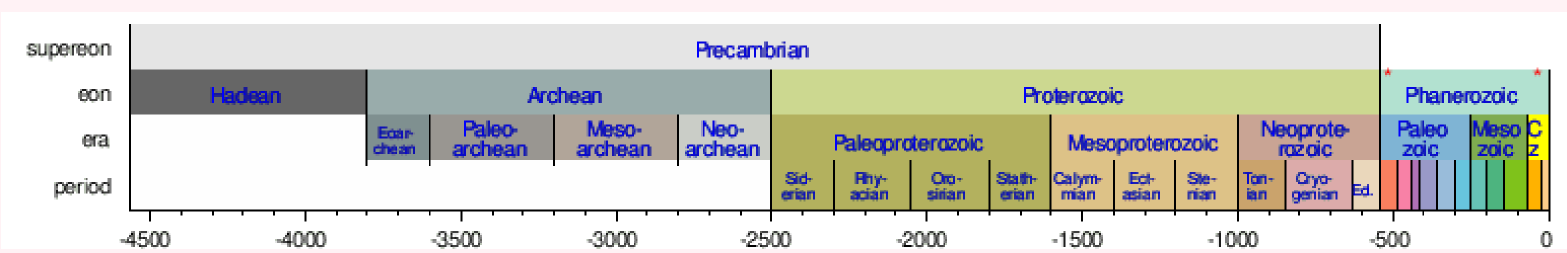


Diagram from Precambrian - Fig. 1., Oasis in space: Earth history from the beginning - Time, Life, Evolution, Earth, Million, and Eon, based on a diagram by Preston Cloud. (Cloud 1988), showing the chemical and mineralogical evolution of the Earth's crust and atmosphere, along with impact craters, glaciation events, and the evolution of life. Although life appears fairly early, following a period of prebiotic chemical evolution, it is only towards the end of the Precambrian that complex organisms arise.



A newer version of geological eras and the Precambrian, from Wikipedia. As shown here, the Precambrian includes by far the majority of geological time. Much of this immensely long interval dominated almost entirely by microbial (and there mostly simply bacterial) life. The fleeting periods shown as narrow coloured bars to the the far right of the chart represent the familiar Phanerozoic geological timescale, characterised by life above the microbial and algae mat stage.

Divisions of the Precambrian

Because Precambrian time is so long, it is useful to divide it into stages or eons. Originally the Precambrian was divided into a more recent ***Proterozoic*** ("age of first life") a preceding ***Archeozoic*** ("first life") and an even earlier ***Azoic*** (lifeless) era. Currently, Archeozoic and Azoic have been replaced by ***Archean*** ("first", "primary") and ***Hadean*** the latter term referring to the hellish conditions of the very early Earth. Late, the term ***Priscoan*** was also used to refer to the period where the geosphere was still forming an life had not yet come into being, this being a synonym of Hadean.

These three eras, the Hadean, Archean and Proterozoic have recently been promoted to the status of eons, although both the Geological Society of America and the International Commission on Stratigraphy have chosen to ignore the Hadean. The Archean and Proterozoic are both divided into various eras. More recently, there has also been a proposal (how successfully this catches on remains to be seen, but we have adopted it here at Palaeos) that the Hadean be itself divided into two, the Hadean proper (referring to earliest stages of the development of the Earth) and the Chaotian, which refers to the formation of the solar system as a whole.

Following are two tables - one (by the ICS) ignoring the earliest stage of Earth's formation (from which there are no surviving terrestrial rocks) and presenting a simple division of Archean and Proterozoic Eons into eras, and the other (based on Harland et al) having a larger number of Precambrian eras and periods. We follow the ICS system, but recognize a separate Hadean and Chaotian eons.

Disclaimer: We didn't make up this horrendous color scheme. Except for the Hadean and Chaotian colors, all of the color coding for time periods is the official scheme used by the ICS.

The Precambrian Time-Scale

eon	era	period	end - began (Mya)
Proterozoic PR	Neoproterozoic NP	Ediacaran NP3	540 - 650
		Cryogenian NP2	650 - 850
		Tonian NP1	850 - 1000
	Mesoproterozoic MP	Stenian MP3	1000 - 1200
		Ectasian MP2	1200 - 1400
		Calymmian MP1	1400 - 1600
	Paleoproterozoic PP	Statherian PP4	1600 - 1800
		Orosirian PP3	1800 - 2050
		Rhyacian PP2	2050 - 2300
		Siderian PP1	2300 - 2500
Archean AR	Neoarchean NA		2500 - 2800
	Mesoarchean MA		2800 - 3200
	Paleoarchean PA		3200 - 3600
	Eoarchean EA		3600 -3800?
Hadean	Early Imbrian		3800-3850
	Nectarian		3850-3950

	Basin Groups 1-9		**3950-4150**
	Cryptic		**4150- c. 4560**

International Stratigraphic Chart, International Union of Geological Sciences: International Commission on Stratigraphy, 2001, published by Micropress.

era		period	when began myrs ago	duration myrs
Proterozoic	Sinian (late Proterozoic)	Ediacaran	610	40
		Sturtian	800	190
	Riphean (middle Proterozoic)	Karatau	1050	250
		Yurmatin	1350	300
		Burizan	1650	300
	Animikean		2200	400
	Huronian		2450	150
Archean				
	Randian		2800	350
	Swazian		3500	700
	Izuan		3800	300
	Hadean		4000	
Priscoan			4560	760

The above table is based in part on the material available at Jeff Poling's Geologic Ages of Earth History page. It uses Precambrian periods and dates from *A Geologic Time Scale 1989* by Harland, W. Brian, Richard Armstrong, Allan Cox, Craig Lorraine, Alan Smith and David Smith.

Summary of the three eons of Precambrian time

The Chaotian and Hadean Eons

Formation of the Solar System and the Earth. Formation of the rocky Earth out of collisions of planetoids. Formation of the Crust - Anorganic Chemical and physical Macrodynamics, Cosmic bombardment from comets and planetoids. Primal Ocean, Organic Substrate, Abiogenesis, Informed biomolecules, reducing atmosphere.

The Chaotian Eon, The Hadean Eon

The Archean Eon

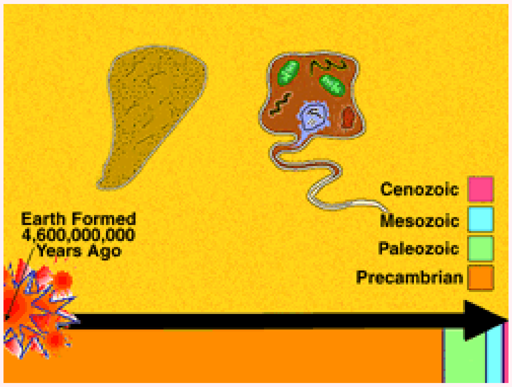
Present crustal structure, Planetary Ocean, Formation of the continents and archaic regime of Continental drift. Gaia (Chemically and thermally self-stabilizing biosphere) - Bioenergetic Processes - Prokaryotes (Archaea, Eubacteria and Urkaria) - reducing atmosphere, Oxygen Crisis and the decline of the Archaea, colonial stromatolites.

The Archean Eon

The Proterozoic Eon
Endosymbiosis (Eukaryotes). Continental drift (present regime) begins. Proterozoic Ice Ages - Precambrian Pangeas. The first multicellular organisms.
The Proterozoic Eon

Precambrian Evolution of Life

The Unicellular Biosphere



As explained above, the evolution of life can be divided into two very unequal periods: the very long Precambrian (lasting over 3 billion years), when life for the most part remained at the microbial grade of organization, and the much shorter Phanerozoic, encompassing the Paleozoic, Mesozoic, and Cenozoic eras (about 540 million years in all), when much more complex, multicellular life, has flourished. The diagram on the left shows the comparative difference in duration of these eras.

Thus throughout most of the period the Earth has been in existence, there has been life, but life of a very primitive kind, analogous to modern bacteria. These single-celled microorganisms are distinguished from more advanced life in that their cells are not compartmentalized into distinct organs, but rather are of a simple and uniform nature. Such uniform cells are called ***Prokaryotes*** (the micro-organism illustrated at the left of the above figure), and they appeared long before the more complex cells, or ***Eukaryotes*** (shown at the right on the diagram). The accepted paradigm at present is that Eukaryotes are built up of Prokaryotes that came together in a symbiotic relation; the different organs of the cell descending from different prokaryotic organisms.

It was only at the very end of the Precambrian that there was a sort of "quantum leap" in evolution from simple microbes to complex multicellular organisms.

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Links

The Divisions of Precambrian Time - an introduction to the Precambrian at the University of California Museum of Paleontology site.

Wikipedia: Precambrian.

Earth Floor- Geologic Time.

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Precambrian (Pamela Gore lecture notes).

Earth - The Genesis of a Living World.

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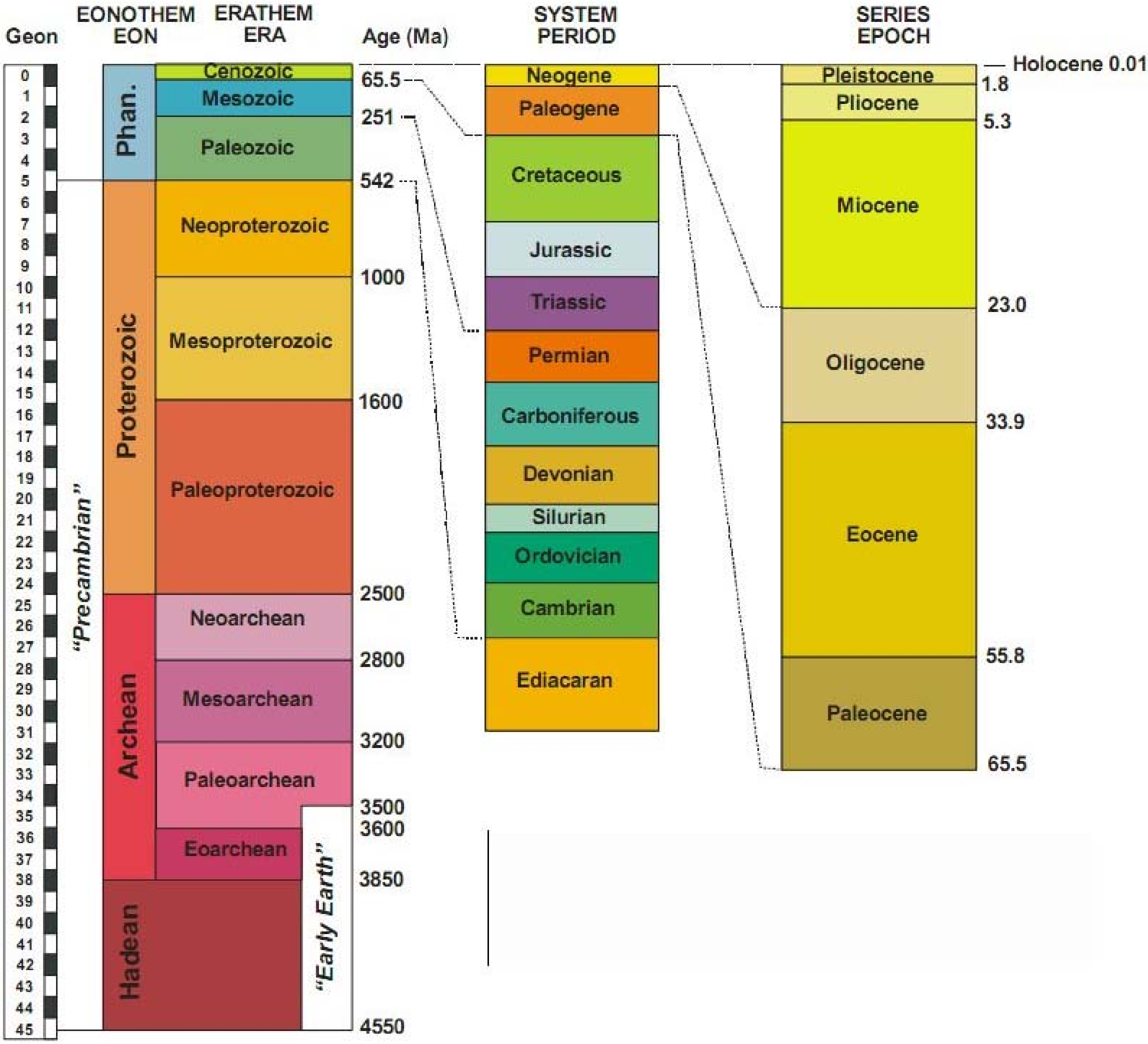
most recent update 28 April 2002 , MAK20110905
checked ATW050726, edited RFVS111109

The Geon



The Geological timescale, showing geons (far left column). International Geological Time Scale from Gradstein et al. 2004. Geon scale from Hofmann 1990, 1992, & 2003. Diagram from Pillans 2004

The following page is copied verbatim from Wikipedia, where it resides as an unhappy orphan (or at least it did at as of 02 Aug 2011). I thought it best to rescue this wonderful deep time neologism and put it to good use. The word geon was advocated in this context by Hans Jorg Hofmann. The above diagram is related to this but I misplaced the record of the url.

The term geon (for geological eon) refers to large geologic time intervals. Geologists traditionally subdivide Earth history into a hierarchy of named intervals: eons, eras, periods, etc. (e.g. Jurassic Period of the Mesozoic Era). Likewise, historians subdivide the history of man into intervals that are comparatively much shorter. In both geological and historical scales, the divisions of equal rank are characteristically of unequal duration, and the identification of a particular interval is primarily based on its fossil, artifact, or cultural content (e.g., Carboniferous, Neolithic, Dark Ages, Ming Dynasty). Both scales are calibrated against numerical ages obtained separately.

An alternative way of referring to the past is to use a scale with intervals of equal duration. We speak of a given decade, century, or millennium. For the enormously long geologic time frame, it is advantageous to use corresponding large, equal time intervals encompassing the events and processes that have shaped our planet. The development of mountain ranges, ocean basins, and continents takes tens to hundreds of millions of years, and large time units thus are convenient for discussing long-term trends. Astronomers use light years and parsecs to deal with huge distances, rather than kilometres. Geologists have geons to refer to large specified time intervals of Earth history. The geon scale is also applicable to other planets with different histories, and to the universe itself.

Two usages of geon have been introduced in geology:

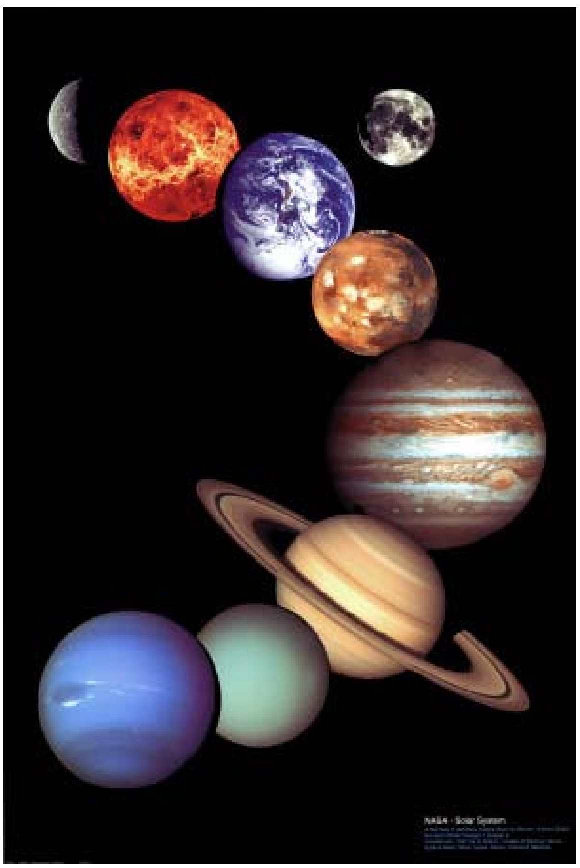
1) A geon is a unit "...taken to represent either the span of the average geologic period, or the thickness of the average stratigraphic equivalent, a matter of 60,000,000 years, and 50,000 feet [~15 km] of clastic depositions" (Woodward, 1929). Utilizing the currently accepted value of 542 Ma, million years ago) for the beginning of the Cambrian Period, and using 11 geologic periods in the Phanerozoic Eon, an updated value for Woodward's geon would be about 49.4 million years. Usage in this sense is not current.

2) A geon is a specified 100-million-year interval of geologic time, counted backward from the present. The geon scale can be likened to a ladder, each interval between rungs representing 100 million years. Geons are named for the leftmost part of the number representing age. For example, the Earth formed about 4550 million years ago, an event that is assigned to Geon 45 (interval below rung 45). Rocks formed at 1851 Ma or 1800 Ma both belong to Geon 18. The extinction of the dinosaurs at the end of the Cretaceous Period (065 Ma) belongs to Geon 0. (Hofmann, 1990, 2003).

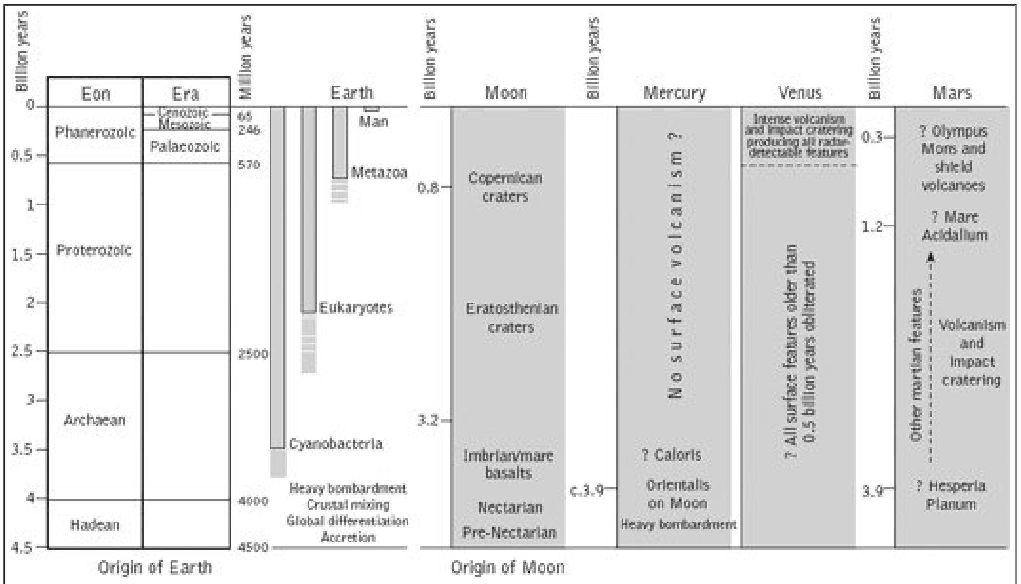
See also **pdf chart**

Planetary Timescales

Geological Time Scales on Earth, Mars, and the Moon



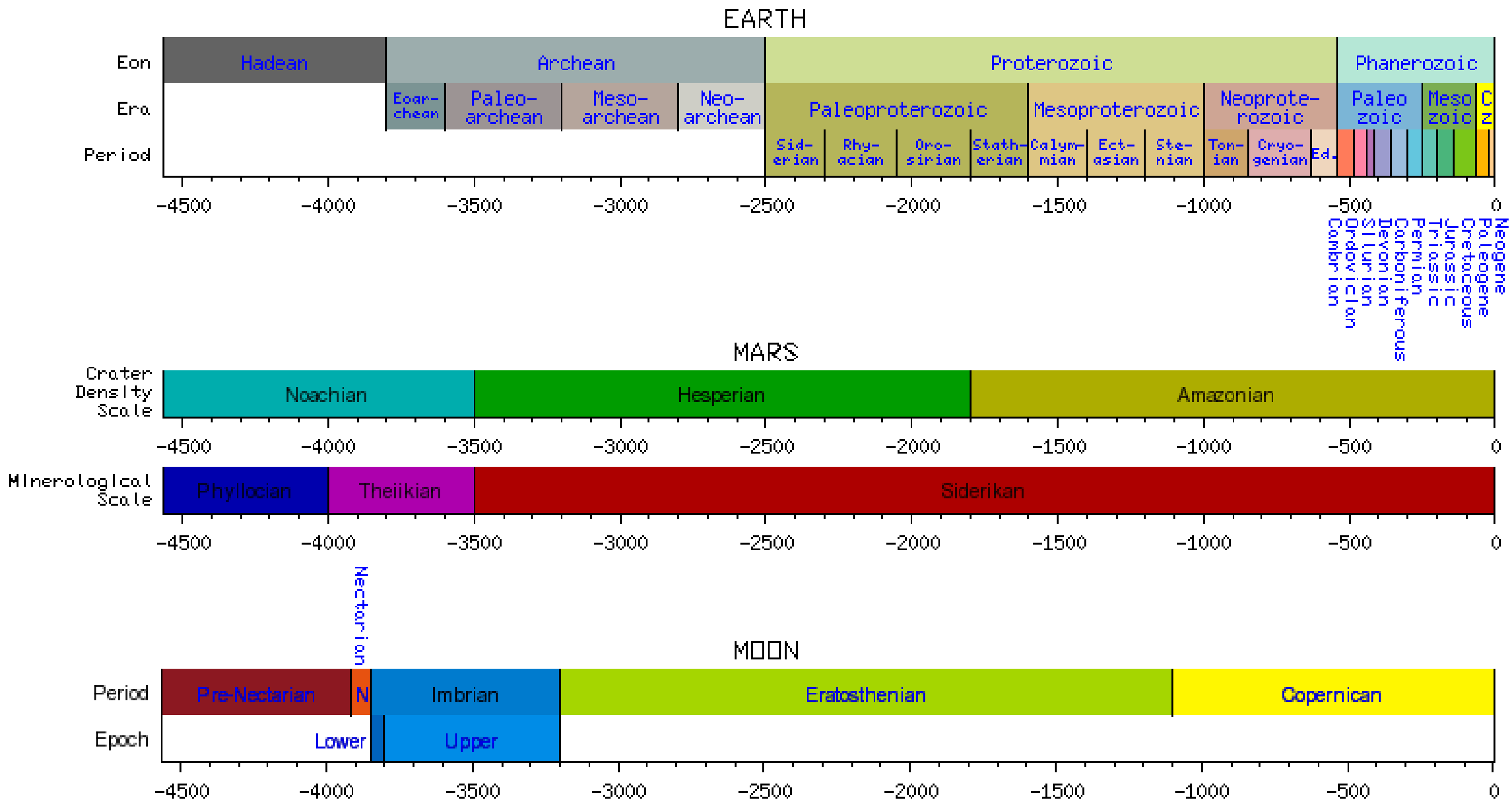
The Solar System - photo by NASA, Public Domain



Radiometric ages for the main divisions of the terrestrial geological column; widely accepted dates for the appearance of terrestrial life forms; and absolute and speculative dates for the Moon, Mercury, Venus, and Mars. Diagram from Age and early evolution of the Earth and Solar System - The development of the Solar System (worthwhile article by G. J. H. Mccall, contains succinct and interesting overview of our understanding of the age and early evolution of the Earth and Solar System)

Geological timescales of other planets

Although astrophysics, astronomy, and cosmology offers insight into the early history and evolution of our physical universe, and the familiar big bang timescale based thereon, our knowledge of details of past ages of actual planetary bodies remains scanty. Apart from the Earth, only two other planetary bodies have been explored so far, the moon and Mars. Actually these offer quiote a good cross section of planetary types, from the lifeless and inert moon, to a planet that was once tectonically and perhaps also biological active but is now dead (Mars) (unless microrganisms turn up at the poles or some other promising location), and of course Earth represmets the ideal "garden world" as science fiction writers might say, a world with the right conditions for higher life, and on which has developed a rich biosphere. MAK110802



Geological Time Scales on Earth, Mars, and the Moon; adapted from Wikipedia

Comparing the geological time scales of Earth and Mars brings into stark focus how little has happened on Mars in the last two or three billion years. It is thought that the last time there was abundant liquid water on Mars was during the Noachian epoch, which ended 3.5 billion years ago. It is supposed that the simplest life-forms may have evolved on Earth about four billion years ago; however, life on Earth didn't get interesting until the "Cambrian explosion," about 500 million years ago, when most of the phyla extant today evolved. Nevertheless, in the window 4.0 to 3.5 billion years ago, it is possible that life got started on Mars. If so, how long it may have persisted is an open question, but unquestionably it would be very simple. Current evidence suggests that the last universal common ancestor of terrestrial life, a single-celled organism, lived during the early Archean eon, perhaps roughly 3.5 billion years ago. (Thomas Gangale, 2007)

Planetary Timescales

Lunar Geological timescale

The Moon, photo by NASA, image from Windows to the Universe

Regretful editor's note: Some years ago I wrote a wonderful (well, I was pleased with it) basic introduction to and overview of the lunar geological timescale. I tend to religiously back up my work, but for some reason this material has totally dissappeared. This being so, and given the vastness of the work of revising and updating Palaeos as a whole, as well as the difficulty to gather the enthusiasm to rewrite the whole thing from scratch, I decided to simply cheat and copy verbatum (apart from editing to condense the quoted material, and Lunar rates of Impact graphic) the following material from Wikipedia - Lunar geologic timescale, along witha few images from other sources. MAK110825

Lunar Geological processes

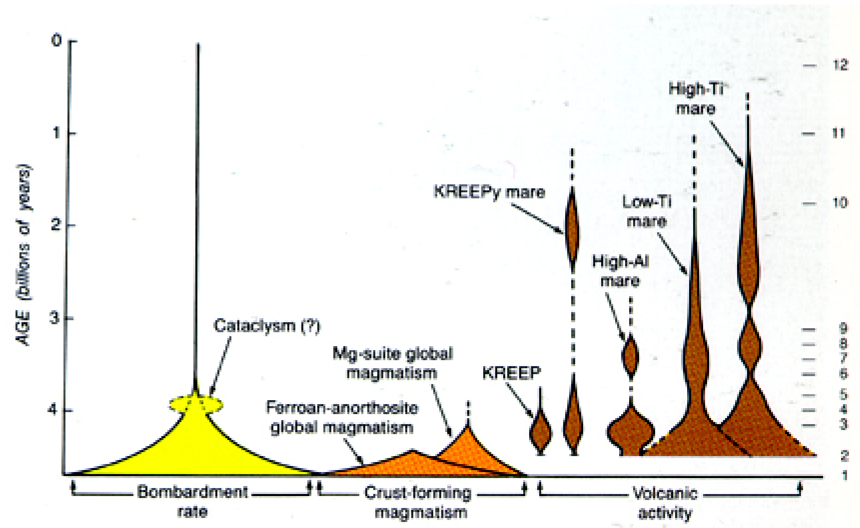
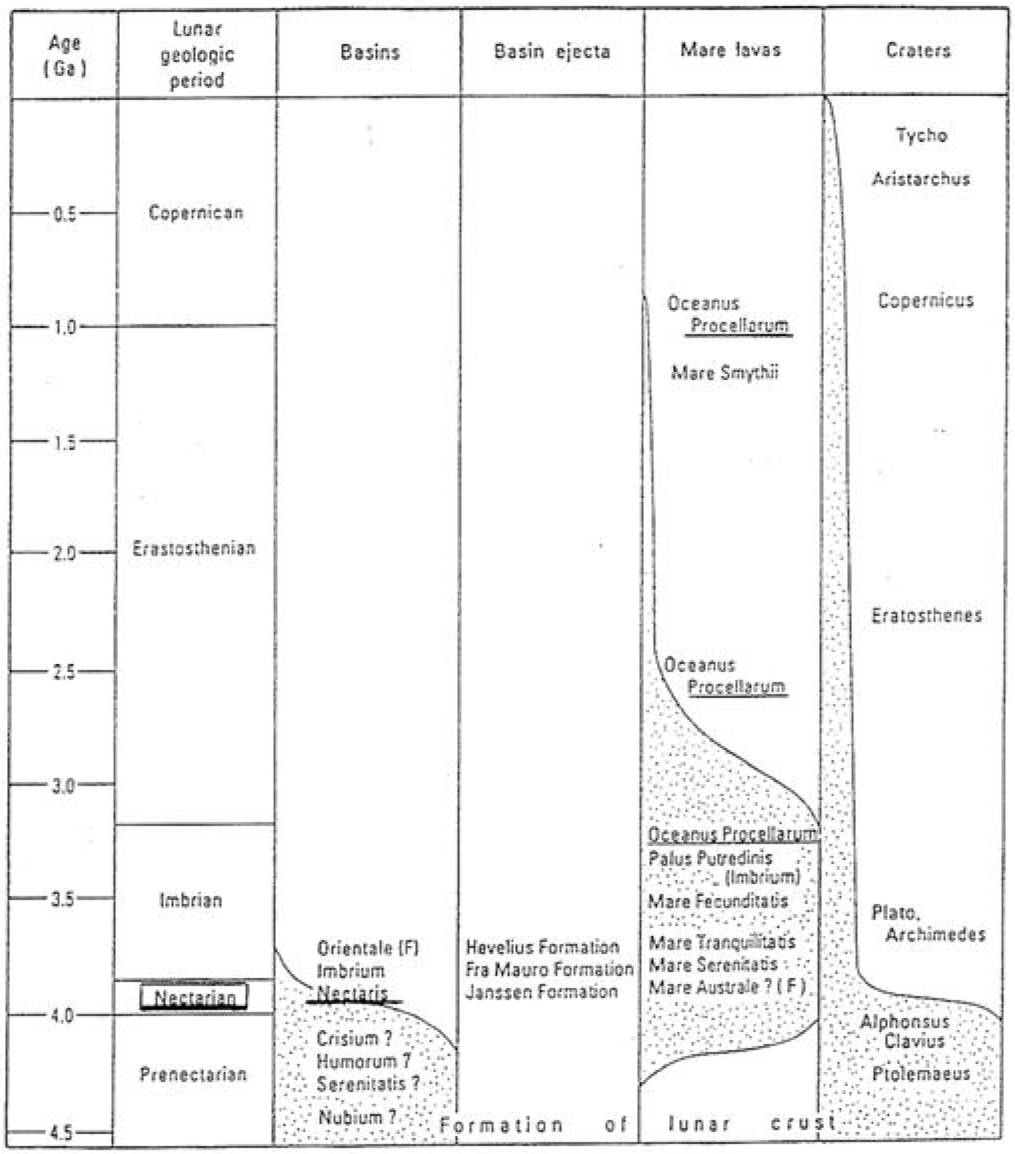


Figure 15. **The rates of impact and magmatism have varied on the Moon over time. Here the width of each envelope corresponds to the intensity of activity. Key dates, numbered at right, are: *1*, Moon forms; *2*, magma ocean solidifies; *3*, age of "average" highland surface; *4*, Orientale and Imbrium basins form; *5*, Apollo 11 and 17 maria; *6*, Luna 16 mare; *7*, Luna 24 mare; *8*, Apollo 15 mare; *9*, Apollo 12 mare; *10*, late Imbrium mare flows; *11*, Copernicus impact; *12*, Tycho impact.**

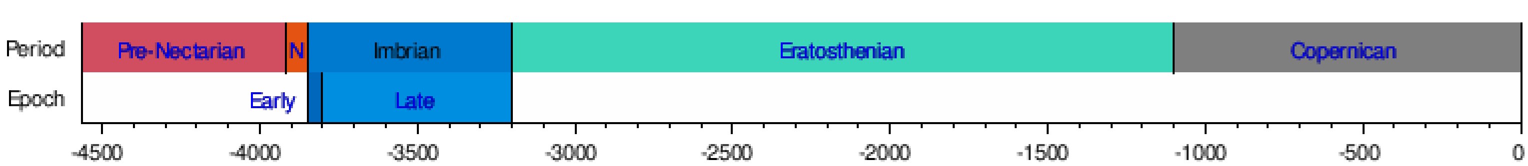
Lunar rates of Impact and Magmaism; from Planetary Geology - The Moon - Part 2 by Scott Hughes

The primary geological processes that have modified the lunar surface are impact cratering and volcanism, and by using standard stratigraphic principles[1] (such as the law of superposition) it is possible to order these geological events in time. At one time, it was thought that the mare basalts might represent a single stratigraphic unit with a unique age, but it is now recognized that mare volcanism was an ongoing process, beginning as early as 4.2 Ga[2] and continuing to perhaps as late as 1.2 Ga (1 Ga = 1 billion years ago).[3] Impact events are by far the most useful for defining a lunar stratigraphy as they are numerous and form in a geological instant.[4] The continued effects of impact cratering over long periods of time modify the morphology of lunar landforms in a quantitative way, and the state of erosion of a landform can also be used to assign a relative age.



Geologic Time Scale for the Moon, by Prof. Robert L. Nowack, from Purdue University EAS 105-The Planets - Lecture 8. The shaded areas in this above schematic representation indicate duration and intensity of the events that formed the lunar basins, maria and craters. (F) indicates a lunar geologic landform on the far side.

The lunar geological time scale has been divided into five periods (Pre-Nectarian, Nectarian, Imbrian, Eratosthenian, and Copernican) with one of these (the Imbrian) being subdivided into two epochs. These divisions of geological time are based on the recognition of convenient geomorphological markers, and as such, they should not be taken to imply that any fundamental changes in geological processes have occurred at these boundaries. The Moon is unique in the solar system in that it is the only body (other than the Earth) for which we possess rock samples with a known geological context. By correlating the ages of samples obtained from the Apollo missions to known geological units, it has been possible to assign absolute ages to some of these geological periods. The timeline below represents one such attempt, but it is important to note (as is discussed below) that some of the ages are either uncertain, or disputed. In many lunar highland regions, it is not possible to distinguish between Nectarian and Pre-Nectarian materials, and these deposits are sometimes labeled as just Pre-Imbrian.



Pre-Nectarian

The Pre-Nectarian period is defined from the point at which the lunar crust formed, to the time of the Nectaris impact event. Nectaris is a multi-ring impact basin that formed on the near side of the Moon, and its ejecta blanket serves as a useful stratigraphic marker. 30 impact basins from this period are recognized, the oldest of which is the South Pole-Aitken basin. This geological period has been informally subdivided into the Cryptic and Basin Groups 1-9,[1] but these divisions are not used on any geological maps.

Nectarian

The Nectarian period encompasses all events that occurred between the formation of the Nectaris and Imbrium impact basins. 12 multi-ring impact basins are recognized in the Nectarian period, including the Serenitatis and Crisium basins. One of the scientific objectives of the Apollo 16 mission was to date material excavated by the Nectaris impact basin. Nevertheless, the age of the Nectaris basin is somewhat contentious, with the most frequently cited numbers being 3.92 Ga, and less frequently 3.85 Ga. Recently, it has been suggested that the Nectaris basin could be, in fact, much older at ~4.1 Ga.[5]

Imbrian

The Imbrian period has been subdivided into Late and Early epochs.

The **Early Imbrian** is defined as the time between the formation of the Imbrium and Orientale impact basins. The Imbrium basin is believed to have formed at 3.85 Ga, though a minority opinion places this event at 3.77 Ga. The Schrödinger basin is the only other multi-ring basin that is Lower Imbrian in age, and no large multi-ring basins formed after this epoch.

The **Late Imbrian** is defined as the time between the formation of the Orientale basin, and the time at which craters of a certain size (DL) have been obliterated by erosional processes. The age of the Orientale basin has not been directly determined, though it must be older than 3.72 Ga (based on Upper Imbrian ages of mare basalts) and could be as old as 3.84 Ga based on the size-frequency distributions of craters superposed on Orientale ejecta. About two-thirds of the Moon's mare basalts erupted within the Upper Imbrian Series, with many of these lavas filling the depressions associated with older impact basins.

Eratosthenian

The base of the Eratosthenian period is defined by the time at which craters on a geological unit of a certain size DL have been almost completely obliterated by erosional processes. The principal erosional agent on the Moon is impact cratering itself, though seismic modification could play a minor role as well. The absolute age of this boundary is not well defined, but is commonly quoted as being near 3.2 Ga. The younger boundary of this period is defined based on the recognition that freshly excavated materials on the lunar surface are generally bright and that they become darker over time as a result of space weathering processes. Operationally, this period was originally defined as the time at which impact craters lost their bright ray systems. This definition, however, has recently been subjected to some criticism as some crater rays are bright for compositional reasons that are unrelated to the amount of space weathering they have incurred. In particular, if the ejecta from a crater formed in the highlands (which is composed of bright anorthositic materials) is deposited on the low albedo mare, it will remain bright even after being space weathered.

Copernican

The Copernican period is the youngest geological period of the Moon. Originally, the presence of a bright ray system surrounding an impact crater was used to define Copernican units, but as mentioned above, this is complicated by the presence of compositional ray systems. The base of the Copernican period does not correspond to the formation of the impact crater Copernicus. The age of the base of the Copernican is not well constrained, but a commonly quoted number is 1.1 Ga. The Copernican extends until the present day.

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A few links

Geology of the Moon

The Moon - Steven Dutch, Natural and Applied Sciences

Lecture 8a The Moon, by Robert L. Nowack

Planetary Timescales

Martian Geological timescale

Mars. Image from Digital Vision/Getty Images, copied from How Stuff Works

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Harried editor's note: The following is copied verbatim (apart from editing to condense the quoted material, from Wikipedia - The Geology of Mars - MAK110723

Geological history

Much of a planet's history can be deciphered by looking at its surface and asking what came first and what came next. For example, a lava flow that spreads out and fills a large impact crater is clearly younger than the crater, and a small crater on top of the same lava flow is younger than both the lava and the larger crater. This principle is called the *law of superposition*. Another stratigraphic principle used on planets where impact craters are well preserved is that of crater number density. The number of craters greater than a given size per unit surface area (usually million km^2) provides a relative age for that surface. Heavily cratered surfaces are old, and sparsely cratered surfaces are young. Old surfaces have a lot of big craters, and young surfaces have mostly small craters or none at all.

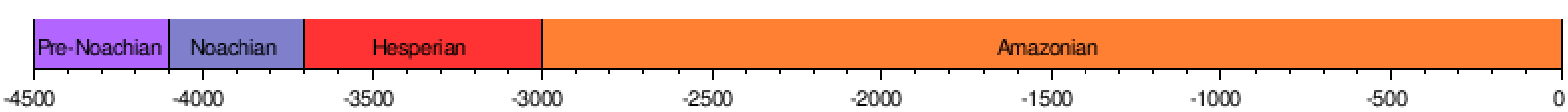
Relative vs. absolute ages

By using stratigraphic principles, we can usually delineate rock units only in terms of their relative age to each other. For example, knowing that Mesozoic rock strata making up the Cretaceous System lie on top of (and are therefore younger than) rocks of the Jurassic System tells us nothing about how long ago the Cretaceous or Jurassic Periods were. Other methods, such as radiometric dating, are needed to determine absolute ages in geologic time. On Earth, we have this information and know that the Cretaceous Period began around 146 million years ago (Mya) and ended 65 Mya with the extinction of the dinosaurs. Absolute ages are also known for selected rock units of the Moon based on samples returned to Earth.

Assigning absolute ages to rock units on Mars is much more problematic. Numerous attempts[1][2][3] have been made over the years to determine an absolute Martian chronology (timeline) by comparing estimated impact cratering rates for Mars to those on the Moon. If we know with precision the rate of impact crater formation on Mars by crater size per unit area over geologic time (the production rate or flux), then crater densities also provide a way to determine absolute ages.[4] Unfortunately, practical difficulties in crater counting[5] and uncertainties in estimating the flux still create huge uncertainties in the ages derived from these methods. Martian meteorites have provided datable samples that are consistent with ages calculated thus far,[6] but the locations on Mars from where the meteorites came (provenance) are unknown, limiting their value as chronostratigraphic tools. Absolute ages determined by crater density should therefore be taken with some skepticism.[7]

Crater density timescale

Studies of impact crater densities on the Martian surface[8] have delineated three broad periods in the planet's geologic history.[9] The periods were named after places on Mars that have large-scale surface features, such as large craters or widespead lava flows, that date back to these time periods. The absolute ages given here are only approximate. From oldest to youngest, the time periods are:



Pre-Noachian Represents the interval from the accretion and differentiation of the planet about 4.5 billion years ago (Gya) to the formation of the Hellas impact basin, between 4.1 and 3.8 Gya.[10] Most of the geologic record of this interval has been erased by subsequent erosion and high impact rates. The crustal dichotomy is thought to have formed during this time, along with the Argyre and Isidis basins.

Noachian Period (named after Noachis Terra): Formation of the oldest extant surfaces of Mars between 4.1 and about 3.7 billion years ago (Gya). Noachian-aged surfaces are scarred by many large impact craters. The Tharsis bulge is thought to have formed during the Noachian, along with extensive erosion by liquid water producing river valley networks. Large lakes or oceans may have been present.

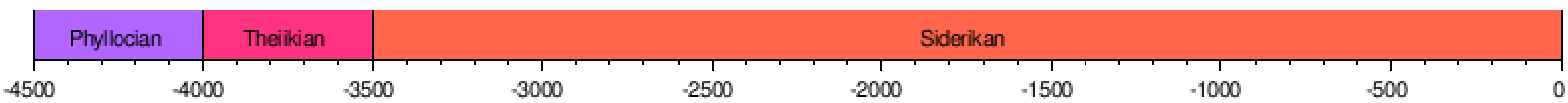
Hesperian Period (named after Hesperia Planum): 3.7 to approximately 3.0 Gya. The Hesperian Period is marked by the formation of extensive lava plains. The formation of Olympus Mons likely began during this period.[11] Catastrophic releases of water carved extensive outflow channels around Chryse Planitia and elswhere. Ephemeral lakes or seas formed in the northern lowlands.

Amazonian Period (named after Amazonis Planitia): 3.0 Gya to present. Amazonian regions have few meteorite impact craters but are otherwise quite varied. Lava flows, glacial/periglacial activity, and minor releases of liquid water continued during this period.

The date of the Hesperian/Amazonian boundary is particularly uncertain and could range anywhere from 3.0 to 1.5 Gya.[12] Basically, the Hesperian is thought of as a transitional period between the end of heavy bombardment and the cold, dry Mars seen today.

Mineral alteration timescale

In 2006, researchers using data from the OMEGA Visible and Infrared Mineralogical Mapping Spectrometer on board the Mars Express orbiter proposed an alternative Martian timescale based on the predominant type of mineral alteration that occurred on Mars due to different styles of chemical weathering in the planet's past. They proposed dividing the history of the Mars into three eras: the Phyllocian, Theiikian and Siderikan.[13][14]



Phyllocian (named after phyllosilicate or clay minerals that characterize the era) lasted from the formation of the planet until around the Early Noachian (about 4.0 Gya). OMEGA identified outcropping of phyllosilicates at numerous locations on Mars, all in rocks that were exclusively Pre-Noachian or Noachian in age (most notably in rock exposures in Nili Fossae and Mawrth Vallis). Phyllosillicates require a water-rich, alkaline environment to form. It correlates with the age of valley network formation on Mars, suggesting an early climate that was conducive to the presence of abundant surface water. It is thought that deposits from this era are the best candidates in which to search for evidence of past life on the planet.

Theiikian (named after sulfurous in Greek, for the sulfate minerals that were formed) lasted until about 3.5 Gya. It was an era of extensive volcanism, which released large amounts of sulfur dioxide (SO_2) into the atmosphere. The SO_2 combined with water to create a sulfuric acid-rich environment that allowed the formation of hydrated sulfates (notably kieserite and gypsum).

Siderikan (named for iron in Greek, for the iron oxides that formed) lasted from 3.5 GYa until the present. With the decline of volcanism and available water, the most notable surface weathering process has been the slow oxidation of the iron-rich rocks by atmospheric peroxides producing the red iron oxides that give the planet its familiar color.

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The Hadean Eon

The Hadean Eon of Precambrian Time: 4520 to 3800 million years ago

Surface of the Earth during the Hadean eon, presumably the Hephaestean period) - Copyright 1994-2011, Streamlined Technology, LLC and Barewalls Interactive Arts, Stocktrek Images original url
see also artwork by Hermann Trappman

The Chaotian Eon ended with a collision between the young proto-Earth and an almost Mars-sized body (which has been named Theia after the mother of the Moon goddess Selene) (Halliday, 2000) . This ejecta from this gigantic collision eventually formed into the moon, whilst denser matter from both protoplanets ended up as the Earth. The originally molten Earth soon cooled, although the Earth's surface was continually bombarded by meteorites, and the much hotter mantle would have resulted in severe volcanism. At this time, the Earth would have perhaps looked rather like the above drawing, an alien and inhospitable world, which is the Hadean in the popular imagination. However there very soon formed oceans or seas (either through comets or volcanic outgassing), and an atmosphere, and for most of the Hadean, conditions were milder. It is possible that some form of microbial life may have also appeared. If it did it is not certain whether it would have survived the period of intense meteorite impacts known as the "Late Heavy Bombardment" (Gomes et al 2005), , although the tenacity of extromophile microbes might argue in favour. The end of this period, around 3.8 billion years ago, marked the end of the Hadean and the beginning of the Archean eon.

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page uploaded MAK110902

The Hadean Eon

The Hadean Eon of Precambrian Time: 4560 to 3800 million years ago

The Hadean and Chaotian

The name ***Hadean*** was coined by geologist Preston Cloud for the pre-Isuan sequence whose record may not be preserved on Earth but is better known from Moon rocks. Consequently, the time sequence and stratigraphy of the Hadean are largely based on lunar events. For example the Nectarian Era is defined by reference to the formation of the Nectaris Basin (southwestern Nearside). The Hadean has no place in the ICS system followed in the rest of Palaeos. The ICS lumps everything earlier than 3600 Mya into the Eoarchean Era of the Archean Eon. The Hadean, being an informal not stratigraphically defined eon, is here defined as the period from the Tellus (proto-Earth)-Theia impact (circa 4520 mya) to the end of the LHB (Late Heavy Bombardment) period, about 3800 bya. Recently, Goldblatt et al. 2010 have proposed an even earlier eon, the Chaotian, for events pertaining to the formation of the Solar System. Since the Chaotian pertains both to geology and astronomy, this allows us to posit an uninterrupted progression of cosmic evolution from pure cosmology through to pure geology, and continue the history of the Earth back to the early history of stars and galaxies, and ultimately the origin of the universe.

During Chaotian time, the Earth and Solar System formed by coagulation and gravitational contraction from a large cloud of gas and dust around the sun, called an accretion disc. The sun formed the nucleus, shrinking in on itself by gravitational compaction until it reached a stage where it ignited with nuclear fusion and give off light and heat. The surrounding particles within this cloud coalesced into planetesimals which then aggregated to form microplanets (rather like modern asteroids). The energy of the collisions between the larger microplanets, as well as interior radioactive and gravitational heating, generated a huge amount of heat, and the Earth and other planets would have been initially molten.

The Moon formed rather late in this process, about 45 My after the inner planets began to form. The current theory is that a Mars-sized planetoid, sometimes called Theia, collided with the Earth at this time. As astronomical collisions go, this was a mere cosmic fender-bender. The bodies, both molten, merged fairly smoothly, adding about 10% to Earth's mass. The moon formed from the minimal (about 0.01 Earth masses) orbiting debris resulting from this low-speed crash **[3]**. Apparently no one filed an insurance claim.

In the aftermath of collision, the heavier molten iron sank to the down to become the core of the Earth, while lighter elements gradually rose to the surface. The lightest of all became the crust as a sort of "scum" on the surface. There was also an outgassing of volatile molecules such as water, methane, ammonia, hydrogen, nitrogen, and carbon dioxide. An initial steam atmosphere formed of water from comets and hydrated minerals **[4]**. Rain fell to form a oceans 4.3 to 4.4 billion years ago.

Once most of the planetesimals were gone the planetary bombardment stopped, and a stable rocky crust formed on the Earth. This is the age of the oldest rocks on earth and also of moon rocks. Atmospheric water condensed into oceans and proto-life formed in the soup of primordial organic molecules, either in the early oceans or in clay or rocks within the crust itself. These stages are considered in more detail below. MAK & ATW, revised MAK110908

The Geological Time-Scale of the Hadean:

Since the Hadean lacks any official status, we have taken serious liberties in the process of updating this chronology. Originally, we started things off with the Cryptic, but this has now become the Titanomachean, the most recent period of the Chaotian eon. We have arbitrarily cut it off at the Theia Event, since this marks a real and rapid geological change from accretion to differentiation. (usefully, Goldblatt et al. 2010 use this same demarcation point). The "Basin Groups" don't seem to be used in serious geochronology at this point. Consequently, we have dropped them. This time period simply has no name. If it were up to us, we'd call it the Ryderian Era, in honor of Graham Ryder (1949-2002), whose short but amazing career in lunar geology laid much of the foundation for what we know about the Hadean. Following the new timescale of Goldblatt et al. 2010 however, this previously featureless expanse of time has now been divided into five new periods (shown above), although hopefully a Ryderian Era could still be included somewhere. For now, we have decided to follow the very provisional arrangement of Goldblatt et al. 2010, at least until something new comes along. This leaves the following:

Eon	Era	Period	Epoch	when began My ago	duration My	Notes
Archean	Eoarchean			~3800 - 3600 mya		Debatable geochemical evidence for life
Hadean	Neohadean	Promethean	Early Imbrian	3,800-3,900	100-200	Formation of Archean crust
			Nectarian	4,000 - 3,950	50 - 100	Resonance in Jupiter and Saturn's orbits moves Neptune out into the Kuiper belt. Late Heavy Bombardment occurs in the inner Solar System (c. 4100-3800 Ma)
		Acastan		c. 4,100	c. 100	Max age of Acasta gneiss (oldest surviving continental fragment)
	Mesohadean	Procrustean		c. 4,200	c. 100	(continued formation of continents)
		Canadian		c. 4,300	c. 100	Max estimated age of earliest greenstone belt.
	Palaeohadean	Jacobian		c. 4,490	c. 190	Earliest zircons (granite)
		Hephaestean		c. 4,500	c. 10	Magma ocean, differentiation of core, mantle and "protocrust"

Chaotian (earlier)	Neochaotian	4560	~60	Accretion of terrestrial planets and Earth from solar disk; giant impacts, Theia Event; formation of Moon, Sun becomes a main sequence star.

The Dynamics of the Hadean [2]

The Hadean or Pregeologic Eon is the time period during which the Earth was transformed from a gaseous cloud into a solid body. In terms of "Year of the Earth," it begins on January 1 and ends about 26 February. The process of solidification is poorly known, however, and the Hadean may have lasted as long as one billion years.

This is the period during which the Earth's crust [1]was formed. This crust melted and reformed numerous times, because it was continuously broken up by gigantic magma currents that erupted from the depths of the planet, tore the thin crust, and then cooled off on the surface before sinking again into the heart of the Earth.

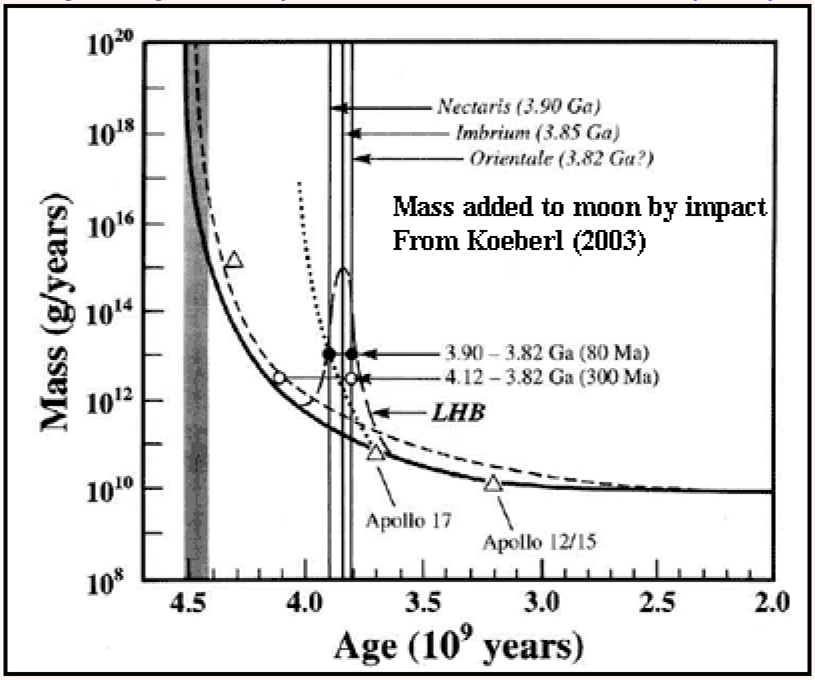
The details of this slow, destructive process are still uncertain. However, it is thought that the heavy elements, like iron, tended to sink towards the center of the Earth because of their higher density, while the lighter components, particularly the silicates, formed an incandescent ocean of melted rock on the surface. Approximately 500 million years after the birth of the Earth, this incandescent landscape began to cool off. When the temperature fell under 1000° C., the regions of lower temperatures consolidated, become more stable, and initiated the assembly of the future crust.

Development of the Earth's Crust

In principle therefore the Earth was a sphere of melted rock, churned by convective movements between the hot inner layers, while the outer, surface regions were in contact with the cold of surrounding space. The dissipation of heat to space began the cooling of our planet. In the magma ocean blocks began to appear, formed from high melting point minerals. These red hot, but solid slabs were similar (although on a very different scale) to the thin edges of crust that we see forming on the surface of flowing lava. The result is what sees in the imaginative reconstruction to the right. Note that, in those times, the Moon, still burning, was only 16,000 km from the Earth (compared to 384,000 km today), and for that reason occupied a big part of the sky. Truly a nightmare landscape!

But those first fragments of crust must also have been very unstable, easily resorbed by the liquid mass of magma and sucked into the depths. Only, with the further cooling of the planet, might those fragments become numerous and large enough to form a first, thin, solid cover -- that is to say, a true primitive crust. This primordial crust might have developed as a warm expanse of rocks (some hundreds of degrees Celsius), interrupted by numerous large breaks, from which enormous quantities of magma continued to erupt. At this early point in the history of the Solar System, meteoric bombardment was intense, and it would have continually opened new holes in the crust, immediately filled by magma. The scars left by this intense meteoric bombardment have been almost totally erased on the Earth by subsequent reworking of the crust. However, the resulting impact craters and lava flows are perfectly preserved on the Moon and on many other bodies in the Solar System whose geological evolution ended long ago.

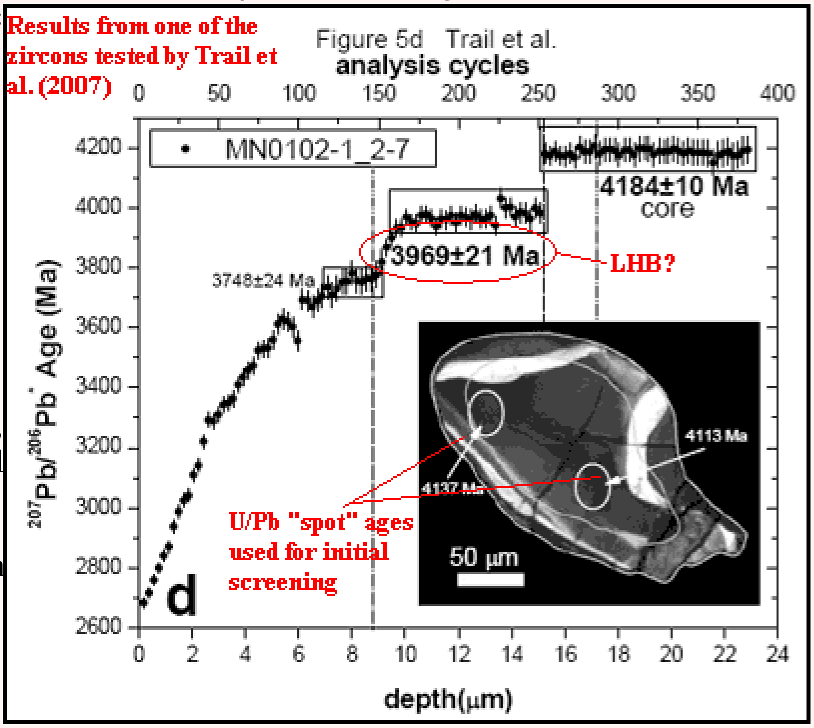
A very few terrestrial locations (primarily Isua in Greenland and Western Australia) preserve rocks dating from near the end of the Hadean. These give mixed signals about the state of the crust at that time. Lead isotope ratios suggest that crust subduction was occurring, implying that Earth had a recognizable crust doing recognizable plate tectonics. Frei ***et al***. (2004). However, the same authors suggest that, while a "protocrust" had differentiated from the underlying mantle as early as 4300 Mya, its composition was basaltic (as apposed to today's granitic crust) and "conceivably without any present-day analogues."



From a petrographic point of view, the primitive crust was similar to basalt, a dark volcanic rock, with less than 53 % SiO_2 by weight. This basalt was formed from the material of the mantle, but had a rather different composition. Perhaps it was similar to the primordial crust of the Moon, much of which still remains in the lunar highlands. The lunar crust is largely anorthosite, a feldspar rich in aluminum, but otherwise chemically similar to the lunar basalts. Bhandari (2002).

According to one school of thought, the composition of the crust began to change by a sort of distillation. Disrupted by highly energetic convective movements, the thin lithospheric covering would have been fragmented into numerous small plates in continuous mutual movement, separated and deformed by bands of intense vulcanism. During this continuous remelting of the "protocrust," heavier rock gradually sank deeper into the mantle, leaving behind a lighter magma richer in silicates. Thus, around the basalts appeared andesites: fine granular volcanic rocks, whose name derives from the Andes, where several volcanoes are known to form rocks of this type. Gradually, a granitic crust emerged.

But there are problems. In addition to mixed signals from isotope analysis of Isuan rocks, workers have also been puzzled by questions relating to the "Late Heavy Bombardment" (LHB). The theory is that Earth was hit by a large number of relatively massive bodies late in the Hadean, over a relatively short period (50 My or so). The evidence for the LHB is quite strong. It comes mostly from lunar astronomy (big craters formed significantly later than the lunar maria) and the lunar rocks recovered from space exploration. The implication, for many geologists, is that the post-Hadean granitic crust was not the product of gradual distillation, but of catastrophic reworking after the protocrust was destroyed by the LHB. Koeberl (2003) (reviewing earlier work).



Trail ***et al***. (2007) have recently performed some particularly elegant studies on zircons ***older*** than the LHB from exposures near the Jack Hills in Western Australia. By way of background, note that zircon crystals are frequently used for dating because they are completely inert up to temperatures of about 900° C. and because the crystals frequently trap heavy metals (U, Th, Lu, etc.), but exclude lead (Pb). Thus, any lead in the crystal must come from radioactive decay.

One potential problem with the method is that zircon crystals can grow by adding material to the outside when exposed to temperatures of several hundred °C -- well below the point at which they begin to "leak" lead. Trail turned this problem to advantage. Using an ion microprobe, Trail measured U/Pb ratios for two different isotopes of uranium, which have different half-lives and which produce different lead isotopes on decay. The microprobe allowed these workers to perform hundreds of measurements at different depths in the crystal -- essentially peeling the zircon back, about 100 nm at a time, to reconstruct its growth history.

Zircons older than 3900 My are incredibly rare, but, after sorting through thousands, Trail et al. found four which (a) passed the internal tests of "concordance" between the two isotope pairs and (b) were over 4000 My old at the deepest levels. The four had significantly different maximum ages and showed somewhat different geological histories, both before and after the LHB. However, ***all four*** turned out to have a substantial secondary growth layer at 3950 ±30 My, just at the beginning of the LHB as estimated from lunar sources. Evidently, something heated up at about this time, on at least a regional basis; but not by so much that these zircons leaked or melted. This is consistent with the LHB, and also with some specific new ideas about the LHB which are discussed below.

The Primordial Atmosphere

As a result of the high temperatures at the center of the Earth, and due to volcanic activity, the crust emitted halogen gasses, ammonia, hydrogen, carbon dioxide, methane, water vapor, and other gasses. In the following 100 million years, these gasses accumulated to form the primordial atmosphere. This atmosphere was quite similar to the atmosphere of Titan, one of the larger moons of Saturn. The primordial atmosphere is believed to have reached a pressure of 250 atmospheres and would have been extremely toxic to life as we now know it.

But, little by little our planet assumed a more familiar look, with a dense gaseous cloud zone we could call an atmosphere, a liquid zone with oceans, lakes and rivers, or hydrosphere, and a solid zone, or lithosphere with the first outlines of what would one day become continents. The process of cooling and consolidation of the Earth's surface was accompanied, as still occurs in volcanoes, by strong outgassing of new atmosphere, formed essentially from methane (CH_4), hydrogen (H_2), nitrogen (N_2) and water vapor, with smaller amounts of noble gases and carbon dioxide. Most of the hydrogen, the lightest component, escaped into space, as also happens today. The other gases and vapors accumulated, including water vapor. The water did not condense at this point, early in the Hadean, because the temperatures of the crust was still very high.

Image: This started as a pre-Huygens Mission NASA rendering of Titan by Steven Hobbs. Then we started adding things ... . Don Dixon also has interesting recreations of the Hadean.

Formation of the Oceans

At the same time, another important series of events began to unfold that led to the formation of sedimentary rocks through the processes of erosion, drift, and accumulation. These processes began to occur as soon as the surface cooled enough to allow the water cycle to establish itself In fact, the primitive Earth long remained covered in darkness, wrapped in dense burning clouds into which continuously poured water vapor from volcanic emissions. When temperatures finally cooled sufficiently, the clouds began to melt into rain, and the primordial atmosphere

produced storms of unimaginable proportions, under which the Earth groaned and flowed. At first, falling on incandescent rock, the rain evaporated, but the evaporation gradually cooled the crust until the water could accumulate in the depressed regions of the Earth's surface, forming the first oceans. On the primordial continents, the first river networks were created, and they transported detritus torn from elevated regions and then deposited on the bottom of the primordial seas. The metamorphism and remelting of the products of the erosion ultimately produced magmas and lava increasingly rich in silicates, and therefore of different composition from the mantle and the primitive crust.

The timing of these various events continues to be a problem. We have already mentioned some evidence for the existence of a protocrust and some form of plate tectonics at a very early date. Relatively recent work has only strengthened the case for oceans before 4000 Mya. Wilde ***et al***. (2001). In addition, it appears that things cooled off fairly quickly after the Earth and moon were formed at around 4500 Mya. Wood & Halliday (2005). Accordingly, ocean and crust had a chance to stabilize. Can this be reconciled with the "cataclysm" of the LHB, or did the crust and oceans have to start all over again?

At the moment, the answer seems to be "no." That is, the LHB was a less-than-cataclysmic cataclysm. As Ryder (2003) pointed out, our best information on the LHB comes from the moon. Since much of the moon's original crust remains, why would we think that the crust of the Earth was destroyed? Some workers even argue that life evolved before the LHB and survived to tell the tale. Russell & Arndt (2005). If we understand the argument, Russell & Arndt are asserting that, precisely because the oceanic crust was poorly differentiated from mantle basalt, it was thick, rigid, and non-conductive, providing both physical stability and thermal insulation against the effects of impacts. Continental crust, by contrast, was ultramafic (very dense), thin, and turned over rapidly. This promoted hydration of the upper mantle and also drove the sort of distillation process which created the lighter crust of post-Hadean time. The LHB, if not too extensive, would only have moved this evolution along at a faster rate. ATW

The Birth of Granites

From all these processes, such as the remelting of part of the basaltic primitive crust, accompanied by metamorphism and melting of large quantities of sediments, there gradually formed magmas similar in composition to granites, and therefore able to "float" on basalt.

Fragment by fragment, formed in the beginning from island chains similar to modern-day volcanic island arcs, the continental crust was born, and so the external land cover of the planet. This new type of crust had a unique feature of fundamental importance: its low density kept it riding on the surface. Thus it was able to undergo intense transformations, such as mechanical deformation (tectonics) or metamorphism, but remain always in proximity to the surface. While the primitive basaltic crust has probably been permanently lost, geologists have found some traces of those first outlines of continental crust. In 1983, in western Australia, were found the most ancient rocks known to date. These rocks are dated to about 4.2 billion years. Remarkably, these are sandstones. This means that they were derived from the erosion of other rocks, still more ancient! FMB03xxxx

Hadean Links

Introduction to the Hadean - UCMP; Hadean - Wikipedia; ; The Earth as a Planet - good page on the early Earth, includes material relevant to both the Chaotian and the Hadean Earth in the Beginning (National Geographic - short essay); Geol 02C, Historical Geology, The Hadean Eon (study notes); Hadean Eon - essay web. MAK110907

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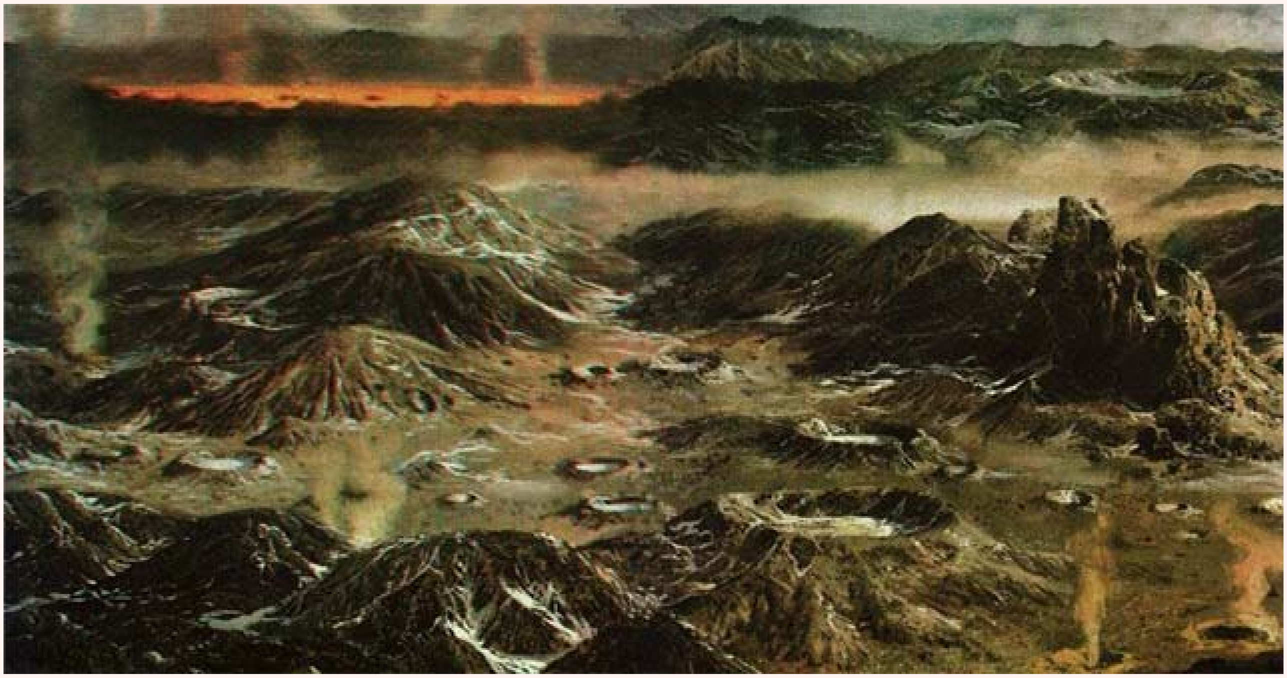
The Palaeohadean Era



Surface of the Earth during the Hadean eon, perhaps in the later Hephaestean period. Artwork by Zdenek Burian.

The Palaeohadean era

In the new timescale of Goldblatt et al. 2010, the Hadean is divided into three eras, which following the convention of the Archean and Proterozoic eons, are rather arbitrarily defined, and indicated by the prefixes ***paleo***-, ***meso***- and ***neo***-. In this case, the earliest Hadean era, the ***Palaeohadean*** (as the authors use the British spelling with its addition "a", rather than the plebian American "paleo") is divided into two periods.

The first, the ***Hephaestean***, began with a molten crust (following the Theia-Tellus collission) which solidified over a period of about 10 My. Even after that time, conditions were extreme. The name is after Hephaestus, the Olympian god of fire and blacksmith of the gods. Although Goldblatt et al. 2010 give an arbitrary time of a hundred million years (one geon) for each period, if specific geological processes are used instead, then that time would obviously differ. So if the Hephaestean is limited to the period of solidification of the crust, that would give the date as from around 4.50 to 4.49 gigayears (give or take ten or twenty million years or so) ago.

For the late Palaeohadean era, the authors suggest the less mythological and more traditional name ***Jacobian*** after Australia's Jack Hills, where the earliest zircons have been found. This assumes that the oldest estimated date (Wilde et al 2001) of 4.4 Gyr is correct, otherwise a new name would have to be found. This was also the time of the formation of the oceans, atmosphere, and possibly even the beginnings of life. If the youngest boundary of the Jacobian is around an arbitrary 4.3 gigayears ago, that would give a duration of about 200 million years.

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The Mesohadean Era

The surface of the Earth as it may have appeared during the middle Hadean, when an ocean, atmosphere, and quite possibly life was present. Artwork by Zdenek Burian (originally intended to represent the Archean era, but the volcanic outgassing and steamy atmosphere makes this evocative work much more representative of the middle to late Hadean, although the scene in the early Archean may not have been that different).

The Mesohadean era

In the Chaotian-Hadean timescale proposed by Goldblatt et al. 2010, the second of the three Hadean eras (the Mesohadean) is divided into an earlier, ***Canadian*** period, named after the earliest crustal material, dated at 4.28 Ga (O'Neil et al., 2008), the Nuvvuagittuq greenstone belt, on the eastern shore of Hudson Bay in northern Quebec (right); although this date has been challenged .

Goldblatt et al. 2010 suggest the following period be named ***Procrustean*** (4.2 to 4.1 Ga) "from Procrustes, whose bed fitted all life". In any case, we can assume that, from the late Palaeohadean through the Mesohadean, was the period when the first continents began to form. To further explain this process, I have resorted to lifting the remainder of this page from Wikipedia in a rather unoriginal manner. MAK110906

Outcrop of metamorphosed volcano-sedimentary rocks from the Porpoise Cove locality, Nuvvuagittuq supracrustal belt, Canada. Some of these rocks have Samarium-Neodymium dated ages in excess of 4.0 Ga and may be the oldest rocks on Earth. Source: NASA, via Wikipedia (public domain)

Formation of the continents

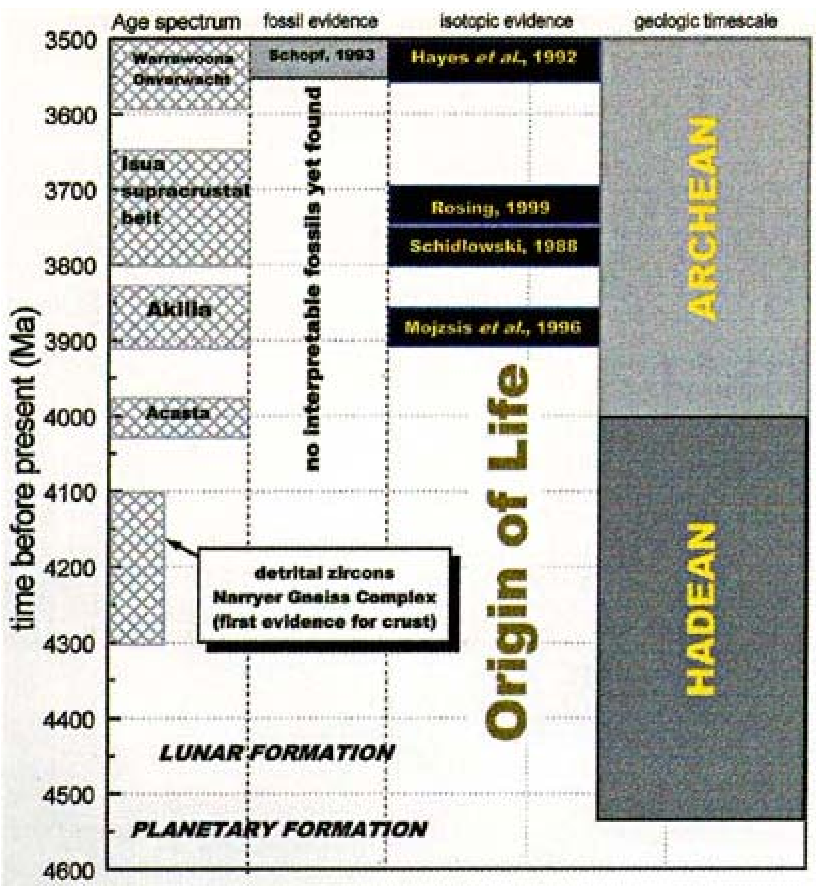
Mantle convection, the process that drives plate tectonics today, is a result of heat flow from the core to the Earth's surface. It involves the creation of rigid tectonic plates at mid-oceanic ridges. These plates are destroyed by subduction into the mantle at subduction zones. The inner Earth was warmer during the Hadean and Archean eons, so convection in the mantle must have been faster. When a process similar to present day plate tectonics did occur, this would have gone faster too. Most geologists believe that during the Hadean and Archaean, subduction zones were more common, and therefore tectonic plates were smaller.

The initial crust, formed when the Earth's surface first solidified, totally disappeared from a combination of this fast Hadean plate tectonics and the intense impacts of the Late Heavy Bombardment. It is, however, assumed that this crust must have been basaltic in composition, like today's oceanic crust, because little crustal differentiation had yet taken place. The first larger pieces of continental crust, which is a product of differentiation of lighter elements during partial melting in the lower crust, appeared at the end of the Hadean, about 4.0 Ga. What is left of these first small continents are called cratons. These pieces of late Hadean and early Archaean crust form the cores around which today's continents grew.

The oldest rocks on Earth are found in the North American craton of Canada. They are tonalites from about 4.0 Ga. They show traces of metamorphism by high temperature, but also sedimentary grains that have been rounded by erosion during transport by water, showing rivers and seas existed then (Lunine 1999).

Cratons consist primarily of two alternating types of terranes. The first are so called greenstone belts, consisting of low grade metamorphosed sedimentary rocks. These "greenstones" are similar to the sediments today found in oceanic trenches, above subduction zones. For this reason, greenstones are sometimes seen as evidence for subduction during the Archaean. The second type is a complex of felsic magmatic rocks. These rocks are mostly tonalite, trondhjemite or granodiorite, types of rock similar in composition to granite (hence such terranes are called TTG-terranes). TTG-complexes are seen as the relicts of the first continental crust, formed by partial melting in basalt. The alternation between greenstone belts and TTG-complexes is interpreted as a tectonic situation in which small proto-continents were separated by a thorough network of subduction zones. (Wikipedia)

The Origin of Life



Timeline of early Earth history and the oldest biogeochemical records. Left column gives ages for oldest rock sequences, middle column isotopic evidence for life in oldest sediments. Diagram copyright from Stephen J. Mojzsis and T. Mark Harrison, Vestiges of a Beginning: Clues to the Emergent Biosphere Recorded in the Oldest Known Sedimentary Rocks - published in GSA Today, April 2000. References: Hayes et al 1992, Mojzsis et al 1996, Rosing 1999Schidlowski, 1988.

Other Links: See also When Did Life on Earth Begin? Ask a Rock.

Ignoring supernaturalism and ancient astronauts, there are two interpretations about the origin of life. Either originated elsewhere in the universe, arriving on Earth from space (Panspermia), or it originated on Earth. But even if life did arrive from another planet in the Solar System, say Mars (via meteorites), or via comets, this would not explain how life could also exist elsewhere in the galaxy, assuming as we have speculatively done here that it does. Regardless of whether it occurs in primordial oceans on the surface of suitable planets and moons (e.g. Titan, Europa), or more fantastically in interplanetary debris or even interstellar nebula, life evolves from abiotic matter as emerging complexity. It is quite likely that life may have appeared on Earth even during Hadean times. Either then, as a result of high energy cometary and asteroid bombardment and even repeated formation and destruction of oceans, life may have appeared and then been extinguished a number of times, or, having appeared once, it may well have survived in even these extreme conditions (Abramov & Mojzsis 2009), for example hydrothermal vents or refuges deep within the crust. Geochemical evidence for life (microbial activity) has been reported from the early Archean, almost as old as the oldest rocks, although such findings remain controversial as abiotic processes can produce similar results (van Zuilen et al 2002; Brasier et al 2006), although this is not to refute the possibility of life during this time. The following diagram summarises the evidence for early Precambrian life. MAK110907

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The Neohadean Era

3950 to 3900 million years ago

The Acastan period

Goldblatt et al. 2010 conclude the division of the Hadean with the not unexpectedly named Neohadean. As with the other two eras, this is divided into two periods. In this case an earlier one called the ***Acastan***, after the Acasta Gneiss, a rock outcrop in the Slave craton in Northwest Territories, Canada, dated at 4.031 to 3.58 billion years old, making it the oldest known intact crustal fragment on Earth, dating back to the original formation of continents. It is, however, in the following ***Promethean*** period where cosmic events start happening. MAK110906

Promethean period and Late Heavy Bombardment

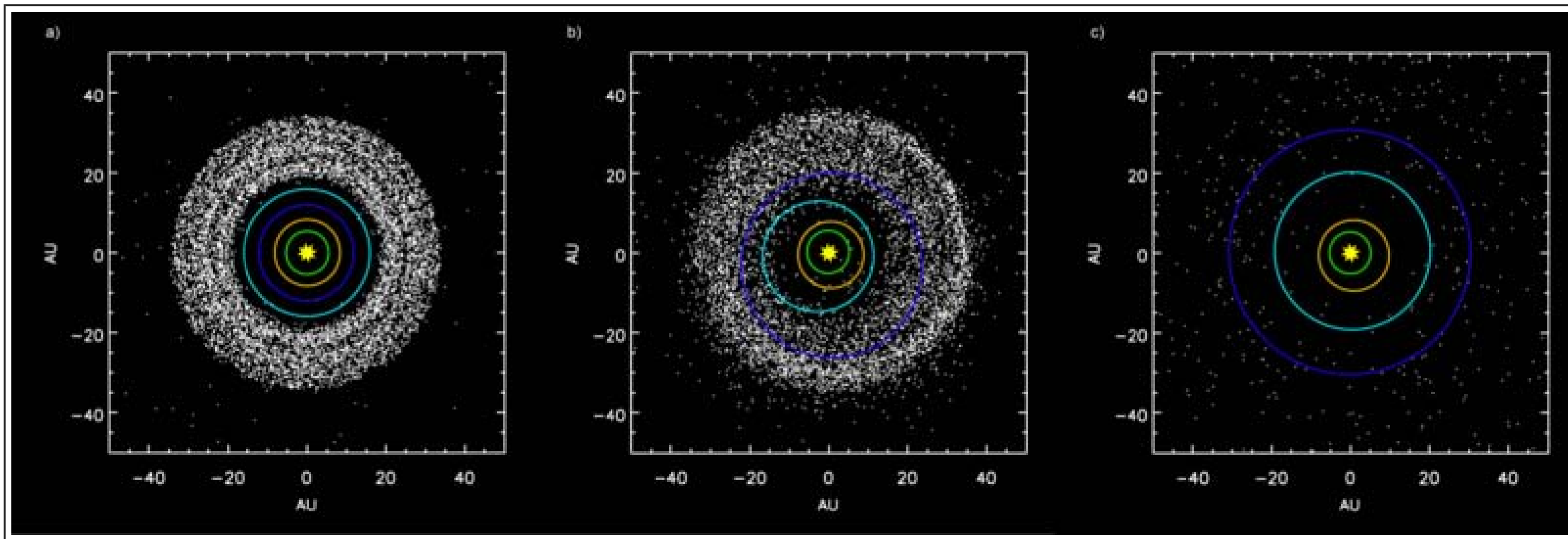
Approximately 4100-3950 Ma, orbital instability of the jovians started the Late Heavy Bombardment (LHB). For the next several geons, the Earth and Moon were struck numerous asteroids and meteorites, the largest of which would have vapourised the ocean and killed any pre-existing life. For this reason, Goldblatt et al 2010 named the Late Neohadean period Promethean. In Greek mythology, Zeus vented his fury on Prometheus by bombarding the Earth (Aeschylus, ***Prometheus Bound*** tr. P. Vellacott, closing speech):

[Dirck van Baburen](#) (c. 1595-1624), ***Prometheus door Vulcanus geketend*** ([Prometheus being chained by Vulcan](#)), [Rijksmuseum](#), Amsterdam. Mercury, messenger of the gods, watches with pity as Vulcan, on Zeus's orders, chains the Titan Prometheus for stealing fire and giving it to mortals. 1623. Image copied from [Wikipedia](#), public domain.

"***The Earth rocks: thunder, echoing from the depth,***
roars in answer; fiery lightnings twist and flash. . .
Sky and sea rage indistinguishably,
The cataclysm advances visibly upon me,
sent by Zeus to make afraid."

One scenario (see diagram below) says Jupiter and Saturn (slowly) migrated into a mutual 1:2 resonance which made a formerly stable jovian system chaotically unstable. The chances that Uranus and Neptune would change places with each other would according to similar theories be 50%. This jovian system disruption would cause:

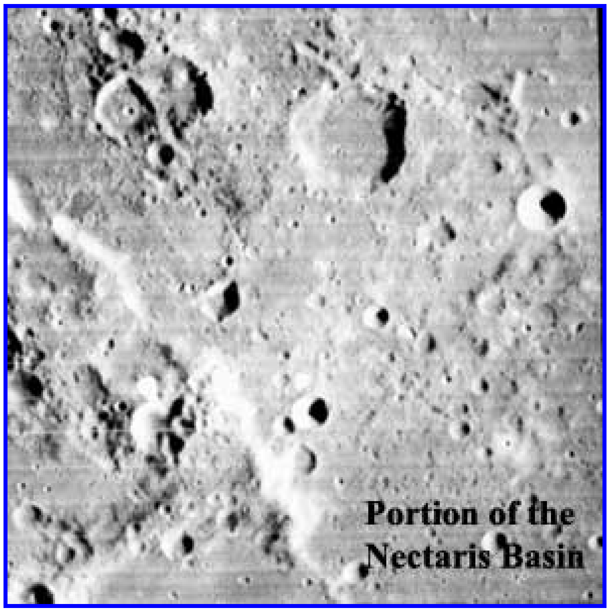
a. Jupiter cleaning up the zone of the current asteroid main belt, inner planets being heavily bombarded by asteroids,
b. Neptune running straight into the zone of outer solar system icy planets, there wreaking havoc, creating a similar but much more intense bombardment within the jovian system, including of course the jovian icy moons. Neptune captured the former icy planet Triton in a retrograde orbit at that time.



Simulation showing Outer Planets and Kuiper Belt:
a) Before Jupiter/Saturn 2:1 resonance.
b) Scattering of Kuiper Belt objects into the solar system after the orbital shift of Neptune.
c) After ejection of Kuiper Belt bodies by Jupiter.
Planets shown: Jupiter (green circle), Saturn (orange circle), Uranus (light blue circle) and Neptune (dark blue circle).
Graphic by Mark Booth - from Wikipedia, based on Gomes et al., 2005

The LHB declines inversely exponentially, so that by ca 3800 Ma the impact levels reaches "normal". rursus20061013

Nectarian



The Nectarian Era is an older term which is here replaced by Promethean period. The Nectarian Era is named for the Mare Nectaris ("Sea of Nectar"), an old basin on the southwest part of the lunar Nearside. This region was formed approximately 3950 to 3850 Mya. The absolute dates vary considerably, but there is general agreement that the Nectarian was relatively short, lasting 50 to 100 My. The Nectaris Basin was created by the impact of perhaps thirteen large bodies within a region only 860 km wide. The current "best guess" is that these objects were derived from the breakup of one or more large planetoids in the asteroid belt, a result of tidal stresses caused by a close approach to Jupiter, or during the outward migration of Saturn. The basins of Nectarian age are the oldest surviving basins on the moon.

Given that the Earth has a substantially larger gravitational field, the effect of the Nectarian bombardment on the Earth was probably severe. Almost nothing from this era remains on Earth, so the geology is somewhat speculative. However, by churning and heating the outer regions of the Earth, these impacts would have promoted the density sorting that eventually produced "light" granite continents floating on the distinctly denser material of the mantle. ATW

Hadean-Archean boundary

The last era of the Hadean in the lunar-based stratigraphy is the Early Imbrian Era. This would correspond perhaps to the second half of the Promethean period, demoting it from era to epoch. In any case, we are here at the upper or younger boundary of the Hadean which, like all other Hadean-alia, is shrowded in ambiguity. Since we've appropriated Goldblatt et al. 2010 chronology in mapping out these early eras of Earth and Solar System history, it's only fair to let them have the last word:

> "The Hadean-Archean boundary is undefined. Nisbet (1982, 1991) suggested the origin of life but the timing of this is as yet unknown. The Late Heavy Bombardment seems intrinsically Hadean and the final impact of this would be the logical choice to terminate the Hadean (Zahnle et al., 2007), being a clearly identifiable event and heralding the start of the continually habitable period. However, this is unresolved in the terrestrial record and the 3.85 Ga rocks of Isua are commonly seen as Archean. A date of 3.9 Ga could be used provisionally, but risks splitting the Late Heavy Bombardment across two eons."

MAK110906

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Hadean-Archean boundary

Notes

[1] The Crust: The more external part of the crust, or Lithosphere constitutes the superficial covering of the Earth. Two kinds of crust are easily distinguished by composition, thickness and consistency: continental crust and oceanic crust. Continental crust has a thickness that, in mountainous regions chains may reach 40 kilometers. It is composed mainly of metamorphic rock and igneous blocks enriched in potassium, uranium, thorium and silicon. This forms the diffuse granitic bedrock of 45% of the land surface of the Earth. The oceanic crust has a more modest thickness, on the order of 5-6 kilometers, and is made up of basaltic blocks composed of silicates enriched in aluminum, iron and manganese. It is continuously renewed along mid-ocean ridges.
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[2] From **Era Precambriana** by Prof. Franco Maria Boschetto, translated from the Italian by ATW040312.
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[3] We wondered how anyone could possibly know this. Actually the evidence is quite good, but also quite heavy reading. Wood & Halliday (2005), Wood ***et al***. (2006). Thanks to Andreas Johansson for pointing out an error in a previous version of this paragraph, thus forcing us to actually read (if not necessarily understand) these papers. ATW070716.
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[4]The comet source is disproven, isotope composition of water implies virtually all must have been from hydrated minerals. rursus061013
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The Archean Eon

Archaean Landscape; image from Space Biology - source, NASA.

The Archean (or Archaean; formerly Archeozoic or Archaeozoic) was a long and, due to its great distance in time, poorly known geologic eon that last a whopping 1.3 gigayears (or 13 geons). That's almost two and half times the entire history of complex life on Earth. Yet a lot was happening at this time; the origin and growth of continents, and the diversification of life (which may or may not have appeared as early as the preceding Hadean). For this entire time span, and for much of the following Proterozoic Eon, the highest form of life on Earth were algae mats, which sometimes formed dome like structures called stromatolites. These are shown somewhat fancifully in the illustration above, in fact the stromatolites would have actually been under several meters of water; the lack of oxygen and hence of a protective ozone layer in the Precambrian atmosphere meant that the sun's rays would be deadly to any unprotected life.

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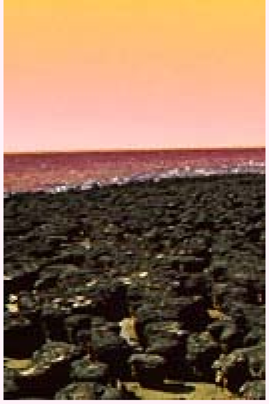
The Archean

The Archean Eon of Precambrian Time: 3.8 - 2.5 billion years ago



The Origin of the Continents

Rocks of the Lower Archean (in geology time is often referred to vertically, because younger rocks are deposited above older ones) are rare, and include the oldest known terrestrial rocks, about 3.8 billion years old. In fact, the "age of the oldest preserved rocks on Earth's surface" has been formally proposed as a definition for the base of the Archaean (more recently however, highly metamorphised rocks, and zircon crystals, have been dated from the previous, Hadean, eon). Most of the oldest rocks are so altered through subsequent metamorphic processes it is difficult to know under what conditions they were formed. The situation is rather brighter with the more numerous rocks of the Meso- and Neoarchean, from 3.2 to 2.5 billion years ago. These are mostly volcanic in nature, consisting of pillow-like structures identical to those of present-day lavas which have formed underwater. The implication is that at this time the entire Earth was covered by ocean. Perhaps the bulk of the continental masses, formed through volcanic outpourings, had yet to appear from beneath the waves.

This general period, from about 3.0 to 2.5 billion years ago, was the period of maximum continent formation. 70% of continental landmasses date from this period (Thus, most of the continents are extremely ancient). Modern Earth sciences recognize that the present continents are built around cores of extremely ancient rock, called "shields". A large part of Australia is a "shield", as is much of Canada, India, Siberia, and Scandinavia.

The Origin of Life

The appearance of life on Earth was preceded by a period of chemical evolution, whereby the relative simple organic molecules gradually aggregated together to form larger and more complex macro-molecules, and finally the first life itself. Scientists claim to be able to repeat all these stages in their laboratories, but doubts have been expressed occasionally.

We do not know when life first appeared on Earth. According to some sources, the oldest fossil microorganisms are as old as the oldest sedimentary rocks. If so, we can assume that life has been around as long as conditions have been suitable. At the time of these first organisms there was probably no free oxygen, as there is now, but rather a "reducing atmosphere" composed of methane, carbon dioxide, hydrogen and water vapor.

The microorganisms of this period may have used methane or hydrogen rather than oxygen in their metabolism. They are therefore referred to as "anaerobic" (non-oxygen-using). Fermentation is modern example of anaerobic metabolism. This type of metabolism is 30 to 50 times less effective than oxygen-based ("aerobic") metabolism, or respiration. The first organisms may have been chemoautotrophs, organisms which obtain their carbon from carbon dioxide by oxidizing inorganic compounds. Later came "heterotrophs," which derive their food from other organisms or organic from matter which they were able to consume, and autotrophs, which create organ carbon compounds from carbon dioxide, using energy from sunlight. The first autotrophs -- the "plants" of the Archean ecosystems -- were quite similar to modern blue-green algae.

Not all of the single-celled organisms of this time were solitary. Beginning perhaps 3 billion years ago, and much more often from 2.3 billion years ago, blue-green algae would form the basic structure of large mats, called stromatolites. Modern-day stromatolites can still be found in sheltered bays in West Australia, where the water is so salty that creatures that would otherwise eat them are not able to exist. The fact that such organisms have survived to the present day gives some idea of how slow their evolution is. The transformation of the biosphere seemed to be as slow as the transformation of the geosphere.

The Geological Time-Scale for the Archean Era

EON	ERA	SPAN (Mya)	Notes and Events

Proterozoic	**Paleoproterozoic**	**2500 - 2300 mya**	More or less conventional plate tectonics
Archean	**Neoarchean**	**2800 - 2500 mya**	First large continental shields
	Mesoarchean	**3200 - 2800 mya**	First widely-accepted fossil evidence of life. First banded iron formations.
	Paleoarchean	**3600 - 3200 mya**	First stromatolites? Formation of relatively stable crust units (possibly even earlier [Nutman ***et al***. 2001], ***but see*** generally negative review [Sankaram, 2002]).
	Eoarchean	**~3800 - 3600 mya**	Debatable geochemical evidence for life (no longer widely accepted)
Hadean	**Early Imbrian**	**3850 - 3800 mya**	Late heavy bombardment of Earth-moon system. Ryder (2001).

Links

Links: Introduction to the Archaean Era - 3.8 to 2.5 billion years ago - UCMP website; Archean Life: several easy pages on the Archean from Prof. Kevin Hefferan (U. Wisc. Stevens Point); Geol 02C: lecture notes from Prof. Bret Bennington of Hofstra.; Peripatus: Archean Era: notes and quotes from our own Chris Clowes (some of which incorporated in these pages); Archean Summary: nice short, unattributed article; Wikipedia has at the time of writing (110909) a still somewhat basic (compared to their coverage of other eras) page.

page uploaded on Kheper Site on 2 June 1998, on Palaeos Site 9 April 2002
text content by M.Alan Kazlev 1998-2002
last modified ATW060902, edited RFVS111016

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The Paleoarchean Era

3600 to 3200 million years ago

The Paleoarchean era

The Paleoarchean (also spelled Palaeoarchaean) is the second geologic era of the Archean, immediately following the Eoarchean. It dates from 3600 to 3200 million years ago, and is arbitrarily defined chronometrically rather than (as with Phanerozoic strata) referenced with specific rock sections. Although the oldest unambiguous microfossils and stromatolites date from this era, it is generally agreed that life appeared earlier. Wikipedia

Geography - The supercontinent of Vaalbara

Vaalbara is theorized to be Earth's first supercontinent, beginning its formation about 3,600 million years ago, completing its formation by about 3,100 million years ago and breaking up by 2,500 million years ago. The name Vaalbara is derived from the South African Kaapvaal craton and the West Australian Pilbara craton. These cratons were combined during the time of the Vaalbara supercontinent. Identical radiometric ages of 3,470 ± 2 million years ago have been obtained for the ejecta from the oldest impact events in each craton. Remarkably similar structural sequences between these two cratons have been noted for the period between 3,500 to 2,700 million years ago. Wikipedia

Paleontology

Pending revision of this page, the following material is lifted ***verbatim*** from Peripatus - Archaean Eon:

"The early Archean [3500-3000 Ma] paleontological record is meagre. Virtually all critical data come from two successions, the Warrawoona Group of Western Australia and the Onverwacht and Fig Tree Groups of South Africa. There may even be redundancy in these two successions, in that some geologists believe that they are tectonically separated portions of a single depositional basin.

"[B]oth successions contain carbonaceous microstructures. These structures are uncommon, and their interpretation as microfossils has been challenged repeatedly (Schopf & Walter 1983; Buick 1991).

"During the 1970s, further research on Onverwacht and Fig Tree cherts produced a second round of paleontological reports (Muir & Grant 1976; Knoll & Barghoorn 1977). The case for the biogenicity of at least some of these structures is stronger. For example, the structures reported by Knoll & Barghoorn (1977) have a well-defined unimodal size frequency distribution with a mean of 2.5 m m; about 25% of the individuals in a large sample population are clearly paired or have a distinct hour-glass morphology comparable to those of cells undergoing binary fission; the cells have a distinct wall layer and collapsed internal contents, much like that seen in younger microfossils; and individual microstructures may be flattened parallel to bedding, indicating their emplacement prior to sediment compaction. Are they fossils? Quite possibly, but given their simple morphology , unequivocal acceptance of biogenicity is impossible.

"Perhaps a nearly thirty year tradition of rejecting previously reported material while presenting new "unequivocal" evidence is at an end. Schopf (1992, 1993) has discovered poorly preserved but convincingly biological filaments in cross-bedded Warrawoona chert grainstones. Having visited the outcrop in question, I regard the early Archean age of these fossils as beyond question."

(After Knoll 1996.)

Middle Paleoarchean - Apex Chert

The oldest plausible fossils reported to date derive from the Apex Chert, a formation of the Pilbara Supergroup occurring in north-western Western Australia (Schopf 1994, p. 6735; Schopf 1999, pp. 88-89). The rocks are dated at 3,465 ± 5 Ma. However, the putative fossils occur in fragments of rock within the chert; thus they are even older, though by how much is unknown. The structures are filamentous, apparently composed of distinct, organic walled cells occurring as a uniserial string, and were originally interpreted as cyanobacteria. Sceptics (notably Brasier et al. 2002) have questioned the biological attribution of these forms but, although the cyanobacterial affinity has been conceded as improbable, the debate continues.

Apex Chert (Pilbara Supergroup): Eleven species of filamentous fossil microbes comprising the oldest diverse microbial assemblage now known in the geological record were discovered in cherts from the Pilbara greenstone belt, northwest Australia. This prokaryotic assemblage establishes that cyanobacterium-like microorganisms were extant and both morphologically and taxonomically diverse at least as early as ~3.465 billion years ago. Barberton: (= Fig Tree?) Bacteria microfossils dating back 3.3 to 3.4 billion years have also been discovered in rocks from the Barberton greenstone belt, South Africa.

Late Paleoarchean - Strelley Group

Strelley Group: Long, fine filaments probably representing thermophilic microorganisms living in the vicinity of a hydrothermal vent have been found in a massive sulfide deposit from the Early Archean Strelley Group (about 3.235 billion years old) of the Pilbara greenstone belt, northwest Australia. Although the temperature of the hydrothermal fluids was about 300°C, the microorganisms more likely developed at temperatures below 110°C and at water depths of about 1000 m. Under such environmental conditions, the microorganisms would have been anaerobic chemotrophs metabolizing in a reducing environment and obtaining their energy and nutrients from the hydrothermal fluids. This deep environment would have provided the microbiota with protection from the harmful UV radiation prevalent at the surface of the Earth during the Archean, when there was no protective ozone layer. (Brack 2002).

Conclusion

"The early Archean record tells us that life was present at least 3500 Ma ago. Microbial ecosystems were driven by autotrophy, most likely photoautotrophy, and oxygenic cyanobacteria may already have appeared. Heterotrophs included prokaryotes and, possibly, primitive amitochondrial eukaryotes capable of feeding by phagocytosis. Depending on the amount of 02 available, the biota could also have included aerobic prokaryotes and mitochondrion bearing eukaryotic heterotrophs (but perhaps not eukaryotic algae; see below, and Knoll & Holland 1995). Although impossible to test empirically, the possibility that early communities included organisms unlike anything represented in the modern biota cannot be excluded. Clearly, early Archean ecosystems remain poorly understood" (Knoll 1996, p. 55).

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Links

Links GeoWhen Database - Paleoarchean; Peripatus - Archaean Eon, Wikipedia

The Eoarchean Era

3850 to 3600 million years ago

The Eoarchean era

As far as official geology and stratigraphy goes, the Eoarchean is still shrouded in mystery. The term Eoarchean Era is used by the International Commission on Stratigraphy in 2000 for everything prior to the 3.6 Bya that arbitrarily marks the start of the Paleoarchean (both replacing Early or Lower Archean). Precambrian chronostratigraphic boundaries (Global Standard Stratigraphic Age (GSSA) were added in 2004, but neither the lower boundary of the era, nor that of the preceding Hadean Eon, was recognised. More recently, in 2009, the Hadean is restored informally, and the boundary placed arbitrarily at 4 gigayears ago, as well as adding a few chronostratigraphic boundaries for the later Archean eras. The 2009 Time Scale by the Geological Society of America, also restores the Hadean, and puts the boundary between the Hadean and Eoarchean as 3850 mya, which better fits the end of the Late Heavy Bombardment (more or less). We have followed that chronology here. - MAK110911

The Isua Greenstone Belt

The Isua Greenstone Belt is an Archean greenstone belt in southwestern Greenland. The belt is aged between 3.7 and 3.8 Ga, making it among the oldest rock in the world. The belt contains variably metamorphosed mafic volcanic and sedimentary rocks. The occurrence of Boninitic geochemical signatures offers evidence that plate tectonic processes may be responsible for the creation of the belt. Pillowed basalts indicate that liquid water existed on the surface at this time.- Wikipedia (includes (as of edit of 15 June 2011) comprehensive list of references)

Paleontology

The most ancient sedimentary rocks – those older than about 3,300 Ma – occur at only a few places on Earth: the Isua supracrustal belt in southwest Greenland, the Barberton area in eastern South Africa, and the Pilbara area of northwest Australia.

The greenstones of the Isua Supracrustal Group date from around 3,700 Ma and possibly more than 3,800 Ma. Unfortunately, although some sequences are thought to be of sedimentary origin, they are strongly metamorphosed (to amphibolite facies) and no fossils have been recovered from them.

However, carbon isotope signatures recovered from these rocks provide indirect evidence that life may have existed in Isua times. "This isotopic evidence stems from the fact that the carbon atom has two stable isotopes, carbon-12 and carbon-13. The 12C/13C ratio in abiotic mineral compounds is 89. In biological syntheses, the processing of carbon [in] CO2 and carbonates gives a preference to the lighter carbon isotope and raises the ratio to about 92. Consequently, the carbon residues of previously living matter may be identified by this enrichment in 12C. A compilation has been made of the carbon isotopic composition of over 1,600 samples of fossil kerogen (a complex organic macromolecule produced from the debris of biological matter) and compared with that from carbonates in the same sedimentary rocks. This showed that biosynthesis by photosynthetic organisms was involved in all the sediments studied. In fact, this enrichment is now taken to be one of the most powerful indications that life on Earth was active nearly 3.9 billion years ago because the sample suite encompasses specimens right across the geological time scale" (Brack 2002).

Mojzsis et al. 1996 (p. 55) claims to have identified biological carbon isotope signatures from &gtn;3,800 Ma aged, chemically precipitated sediments, including banded iron formations (BIFs) and chert, on Akilia Island, southwestern Greenland. However, this interpretation has been challenged by Fedo & Whitehouse (2002) who regard the contested unit as a younger hydrothermal vein. The original claim has been vigorously defended and the final conclusion is as yet unresolved.

More certain is the report from Rosing (1999) of a biological carbon isotope signature from ~3,780 Ma (3,779 ± 81 Sm-Nd date) greywackes and slates with well-preserved sedimentary structures from the Garbenschiefer Formation in the Isua belt.

Some molecular clock analyses suggest an even earlier origin: Hedges 2002 estimates the divergence of Bacteria and Archaea at &gtn;4 Ga, noting however, that "the fidelity of genetic replication and repair systems in the early history of life is unknown, and the different environment of early Earth might have affected rates of molecular change. It is for these reasons that we have less confidence in the time estimates for the earliest splitting events" (p. 842). A phylogenetic tree constructed from highly conserved portions of the iron/manganese superoxide dismutase enzyme sequence (Kirschvink et al. 2000, p. 1404) suggests an age for this divergence of 3 to 4 Ga.

- Chris Clowes, Peripatus - Hadean Era

Links

Links GeoWhen Database - Eoarchean; Wikipedia, Peripatus - Hadean Eon (also pertains to Eoarchean)

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The Mesoarchean Era

3200 to 2800 million years ago

Timescale Chaotian Hadean Archean Eoarchean Paleoarchean Mesoarchean Neoarchean Proterozoic Phanerozoic	The Archean Eon Mesoarchean era

This is just a holding page for now.

The Mesoarchean is a geologic era within the Archean, spanning 3200 Ma to 2800 Ma (million years ago). The period is defined chronometrically and is not referenced to a specific level in a rock section on Earth. Fossils from Australia show that stromatolites have lived on Earth since the Mesoarchean. The Pongola glaciation occurred at 2.9 Ga. The first supercontinent Vaalbara broke up during this time around 2.8 Ga. -- Wikipedia

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The Neoarchean Era

2800 to 2500 million years ago

The Neoarchean spans the period of time from 2,800 to 2,500 million years ago; the period being defined chronometrically and not referenced to a specific level in a rock section on Earth. Oxygenic photosynthesis first evolved in this era and was accountable for the oxygen catastrophe which was to happen later in the Paleoproterozoic from a poisonous buildup of oxygen in the atmosphere, produced by these oxygen producing photoautotrophs, which evolved earlier in the Neoarchean. The supercontinent Kenorland formed during this period, about 2.7 billion years ago. - Wikipedia

The late Archean fossil record (3000-2500 Ma)

Pending revision of this page, the following material is lifted ***verbatim*** from Peripatus - Archaean Eon:

"Schopf & Walther (1983) reported rare trichomes from the ca. 2800 Ma Fortescue Group, Western Australia. The fossils resemble oscillatorian cyanobacteria, but they are not taxonomically diagnostic; similar morphologies occur among both sulfur-oxidizing and sulfate-reducing bacteria. More diverse microfossils have been reported from the ca 2500 Ma Transvaal Supergroup, South Africa. Silicified microstromatolites and associated intraclasts from platform environments contain 1-5 m m diameter coccoids and thin filamentous sheaths interpreted as primary producers as well as tiny rods interpreted as heterotrophic bacteria (Lanier 1986). Chert nodules in deeper basinal limestones contain carbonate-lined filamentous sheaths up to 27 m m in cross-sectional diameter (Klein et al. 1987)."

"Stromatolites become increasingly abundant in younger Archean successions, a pattern as likely to reflect craton growth as evolutionary change. By the end of the eon, extensive carbonate platforms supported widespread mat-building communities that almost certainly included cyanobacteria."

- (After Knoll 1996.)

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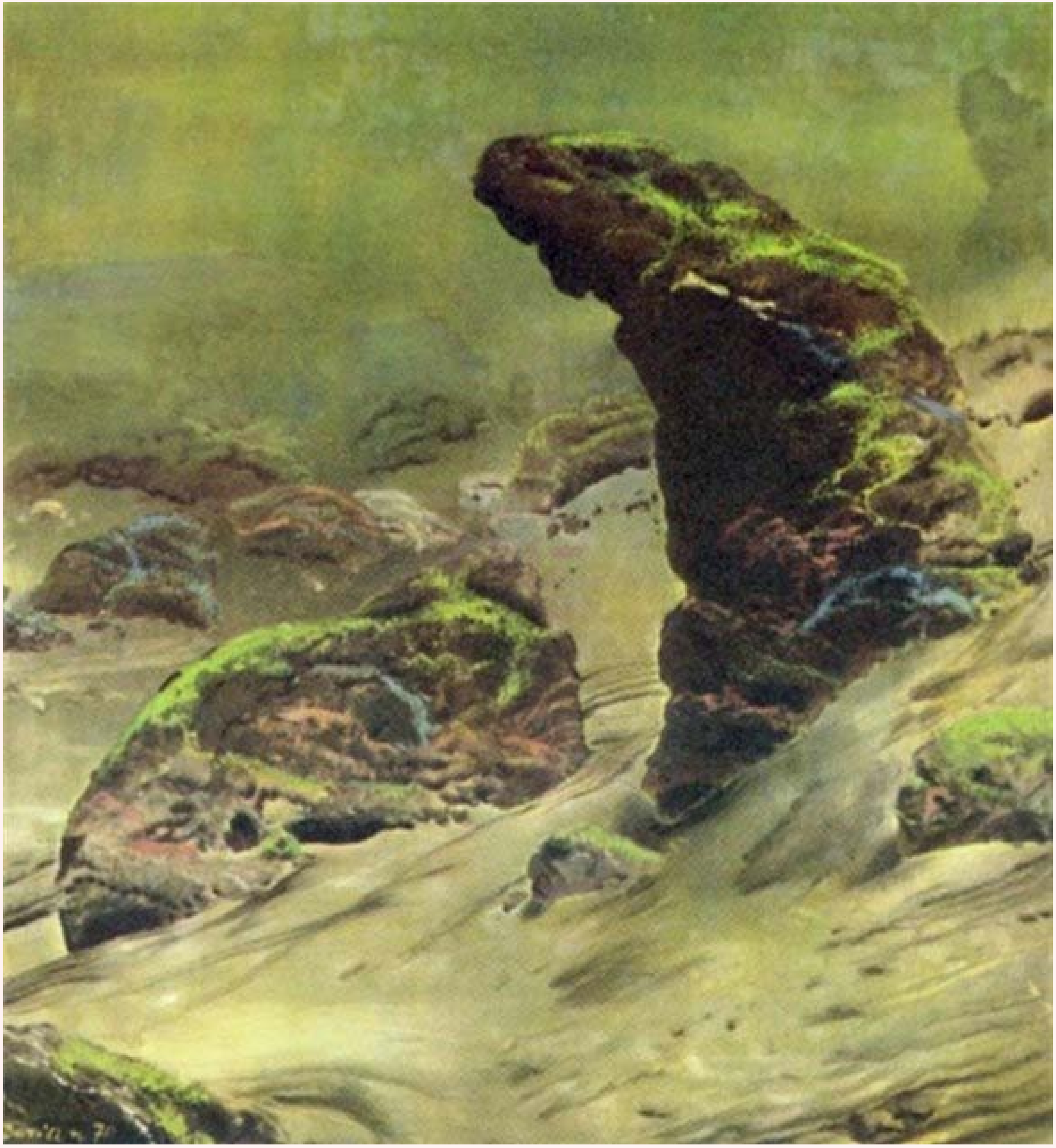
Eoarchean era

| Page Back: Neoarchean | Unit Home | Page Top | Page Next |

The Proterozoic Eon



The Proterozoic sea, by Zdenek Burian

The Proterozoic was the fourth (beginning with the Chaotian) of the eons of Earth history, and the longest, lasting some two gigayears, almost half the age of the Earth. As well as long stretches where nothing seems do happen for hundreds of millions of years (although this was doubtless also an artifact of logarithmic time), this was also a time of momentous changes, including the oxygenation of the atmosphere, the origin and diversification of eukaryote life, the modern regime of continental drift, one or more runaway icehouses during which the entire Earth froze over for tens of millions of years, and finally, the appearance of multicellular animal life, along with the short-lived and bizarre Ediacaran fauna. MAK111015

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content by MAK110921, edited RFVS111203

The Proterozoic

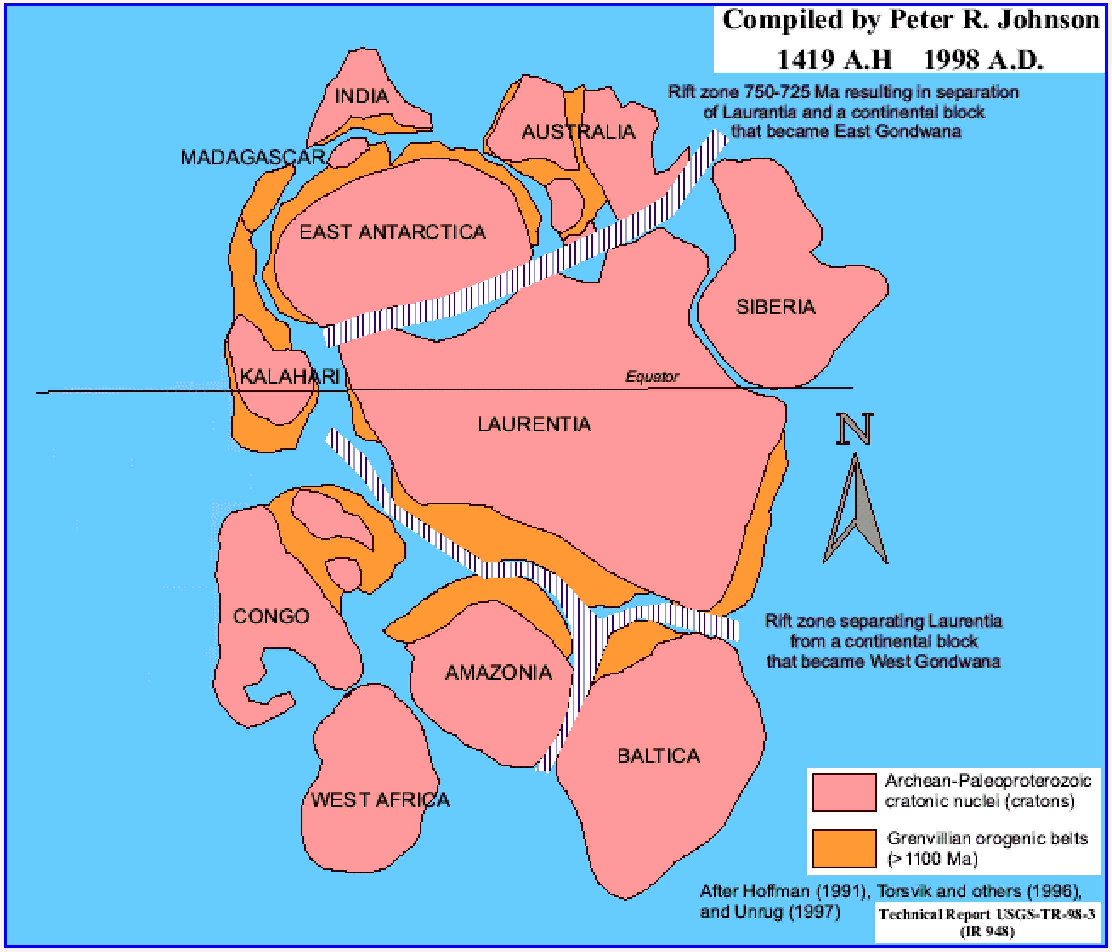
The Proterozoic Eon of Precambrian Time: 2500 to 542 million years ago

Introduction

The Proterozoic is, roughly speaking, the time when more or less "modern" plate tectonics began to govern over other processes in determining the form of the Earth's crust. Although continents were small, they consisted of stable cratons. Mid-ocean spreading ridges did a good deal of the moving, just as they do today. However, everything happened a good deal faster. The magma on which the continents floated was hotter, less viscous, and closer to the surface. Hot spots were probably hotter. The continents moved more swiftly, collided more often and tended to fracture or suture with greater frequency.

Life developed from the infant stage of single celled organisms to an adolescence of Eukarya and early plants, fungi, animals. Perhaps other forms developed as well which we know less about because they failed to explode in the Cambrian Explosion. Like all other adolescents, Life grew much larger, discovered sex, and changed its mind frequently about what it was going to be when it grew up. Undoubtedly it tried out many forms and lifestyles which, had we learned of them at the time, we would have sternly disapproved. Life engaged in risky behaviors, such as carelessly spewing so much oxygen into the atmosphere that it nearly poisoned itself until it learned to adapt. It moved out from the warm geothermal vents where, perhaps, it was raised, and nearly froze to death once or twice by wandering into very serious Ice Ages without its mittens. Somehow, in spite of a number of these very close calls, it grew up into the sort of grown-up Life we know today.

The Geography of the Proterozoic



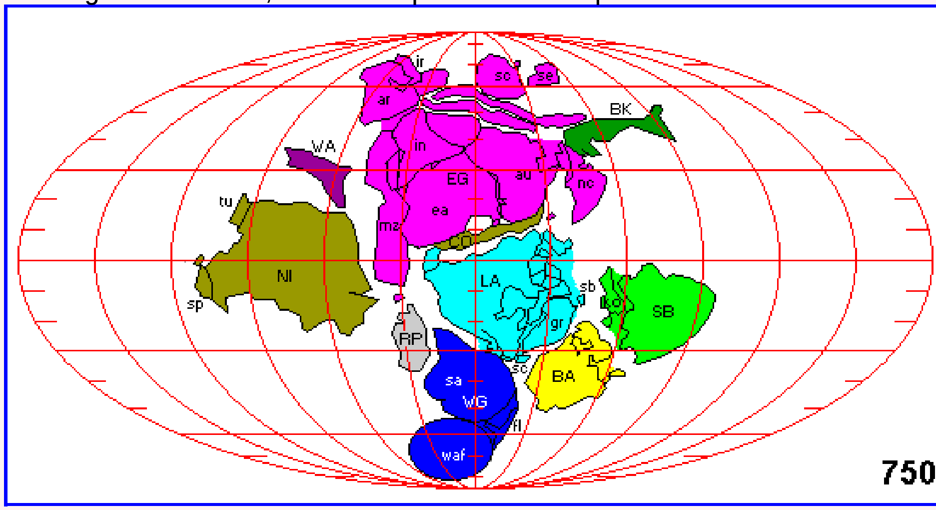
We know very little of the geography of the Proterozoic. As Dr. Christopher Scotese notes on his paleomap site: "With available data, 650 million years is about as far back as we can go." Of course, this has not stopped him (or many others) from pushing the paleomap envelope to about 750 Mya. However, beyond that there are only educated guesses.

One fact now does seem reasonably clear. About 1100 or 1200 Mya, most of the landmass of the Earth was locked up in a continent called Rodinia. How Rodinia assembled is speculative at this point. Since Dr. Scotese is undoubtedly the best educated of the educated guessers, you may be interested to see his concept of Rodinia at its greatest extent (perhaps 1100 Mya).

The map above is from **The Geological History of Jamestown, Rhode Island**. It represents one popular interpretation of the makeup of Rodinia at perhaps 900

- 1000 Mya. Most of the continents are rough blobs. However, we do know that Laurentia was approximately upside down compared to the present day. Therefore the center of the Earth at that time was somewhere in upstate Minnesota -- which is enough to prove that this was truly a ***very*** different world from our own.

About 900 Mya, Rodinia started to fracture; and the pattern of fragmentation has become fairly well known. This map sets up a very nice structure around the Amazonia - Baltica - Laurentia corner which is known as a ***three-armed graben***. This is not some sort of con game or high tech slot machine. It is a true continent-busting confluence of two faults of exactly the type which tore Pangea apart 800 My later and which is trying (but probably failing) to tear up East Africa in the present day. In fact, the Kalahari - East Antarctica - Laurentia corner may be the site of a second graben, just as there were really two such structures involved in the demise of Pangea. Scotese, seems to place most emphasis on the northwest to southeast rift splitting Rodinia apart. The huge bulk of Laurentia and Siberia then rotates clockwise about 120° clockwise as it moves down almost to the South Pole and back up again, hitting West Africa from the ***South*** just as East Gondwana (i.e. North Rodinia), having rotated a bit clockwise, hits it from the Northeast.



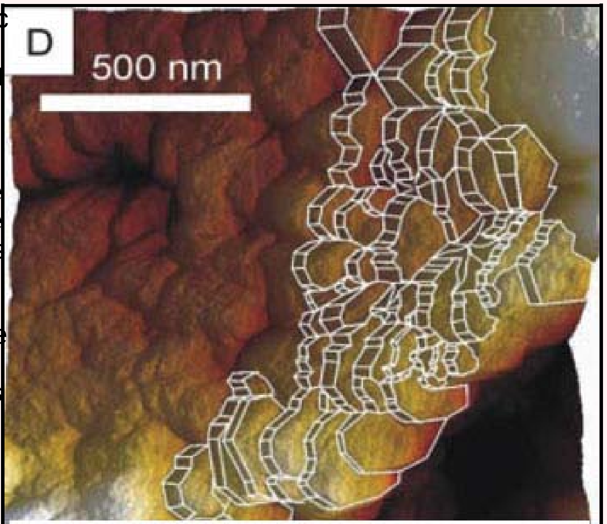
One could imagine a more peaceful scenario in which Laurentia and Baltica simply cut through the "strait" between Kalahari and East Antarctica, while rotating (either way) to reach their Cambrian positions and orientations. There are excellent reasons why this cannot be the case, not the least of which is the far southern paleolatitude of North America (Laurentia) during the latest Neoproterozoic. Nevertheless, in the spirit of being obnoxious, we offer this additional map, from Steven Dutch of the University of Wisconsin. The large, dark green thing in the west on Dutch's map is the Niger block -- actually pieces of both Africa and South America. ***See*** Johnson & Rivers (2004) which supports this this placement. If this version -- not so very different from the map above -- is correct, Laurentia would have a tough time rotating all the way south around these obstacles to reach a Cambrian position roughly where the Niger block is shown, all in only 230 My. Not impossible, mind you, but not really the most parsimonious interpretation from a geometrical point of view.

The Proterozoic Timescale

Eon	Era	Period	when began My ago	duration My
Proterozoic	Neoproterozoic 1000 mya	**Ediacaran**	630	88
		Cryogenian	850	250
		Tonian	1000	150
	Mesoproterozoic 1600 Mya	**Stenian**	1200	200
		Ectasian	1400	200
		Calymmian	1600	200
	Paleoproterozoic 2500 Mya	**Statherian**	1800	200
		Orosirian	2050	250
		Rhyacian	2300	250
		Siderian	2500	200

Proterozoic Life

Acritarchs & Plankton

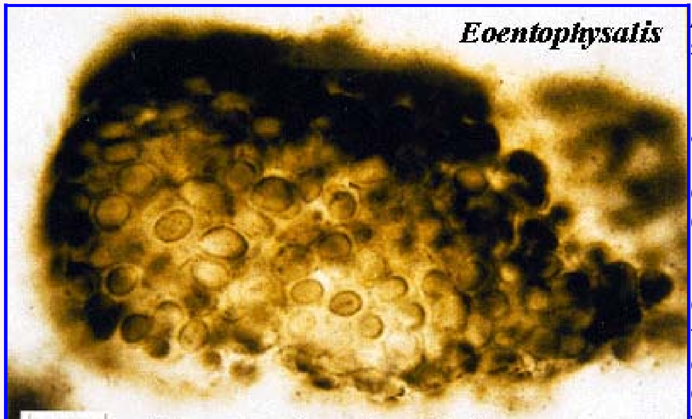


Atomic force electron micrograph of Neoproterozoic acritarch with reconstruction of kerogen structure. Kempe et al. (2002).

The Proterozoic includes over half the history of life on this planet, but the available data about Proterozoic organisms are exceedingly sparse. We usually have a little discussion about plankton at about this point on the Time pages, but we know practically nothing about plankton in the Proterozoic. Consequently, we'll talk mostly about acritarchs instead. And what exactly ***is*** an acritarch? No one is quite sure. Acritarchs are like sharks' teeth from the Phanerozoic or cigarette butts from the 1960's. That is, they are found everywhere, are practically indestructible, and come in a variety of interesting shapes and sizes. They look informative, but ultimately tell us rather little about the organisms or ecosystem which produced them -- other than the fact that it contained sharks or smokers, as the case may be. Acritarchs tell us even less because we don't know what produced them. The typical statement in the literature is: "Acritarchs [are] a group of decay-resistant organic-walled vesicular microfossils ... . Most acritarchs from the Proterozoic and Paleozoic are interpreted as unicellular photosynthetic protists ... ." Huntley ***et al***. (2006).

Although acritarchs have been probed and prodded with almost every sort of device known to man, they have yielded relatively little detailed structural information. They are clearly unmineralized, organic-walled structures. After sitting around for one or two billion years, almost all nano-scale molecular organization has been lost. What is left is ***kerogen***, amorphous platelets of polycyclic aromatic hydrocarbons with no obvious resemblance to any familiar cell wall material. Kempe ***et al***. (2002).

No acritarchs are yet known from the earlier Paleoproterozoic. Biomarker evidence (***i.e.*** the presence of long-chain 2-methylhopanes) suggests that a phytoplankton population was present, consisting mainly/entirely of cyanobacteria. Summons ***et al***. (1999); Falkowski ***et al***. (2004); Canfield (2005).

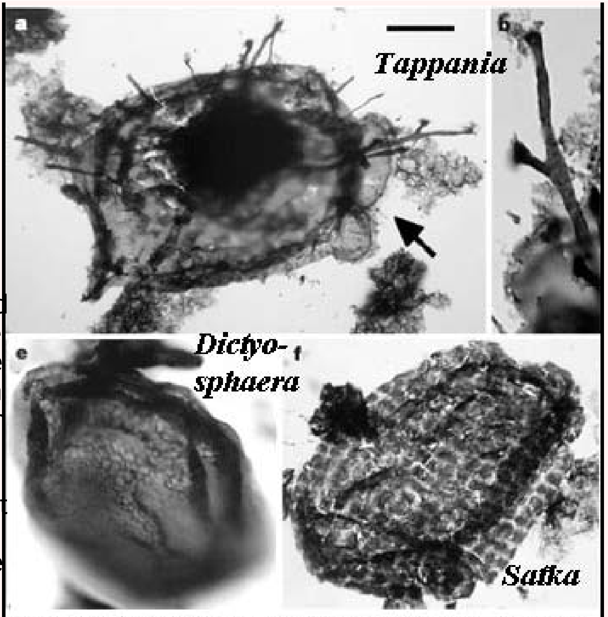


Paleoproterozoic cyanobacterial colony.

Acritarchs are present in the later Paleoproterozoic; but they are rare and consist of morphologically simple spheres (i.e. ***sphaeromorphic*** acritarchs). Javaux ***et al***. (2004). They sometimes look a good deal like prasinophytes (basal green algae), and perhaps that's what they are. More likely, they're below the split between red algae and green algae, like glaucophytes, or even basal to all crown eukaryotes. Many or most acritarchs from the Paleoproterozoic and earliest Mesoproterozoic are probably ***akinetes*** or other bacterial remains. Golubkova & Raevskaya (2005). Akinetes are inactive resting stages of cyanobacteria induced by cold, lack of food, or similar environmental conditions unfavorable for growth -- the sorts of stimuli that generally lead organisms to seek metabolic stasis and/or admission to graduate school. Meeks ***et al***. (2002) (review).

Other types of fossils from near the Paleoproterozoic-Mesoproterozoic boundary include coiled or worm-like forms such as ***Grypania,*** and possibly related structures resembling beads on a string. Porter (2004). Some of the ***Grypania***-like fossils approach 1 mm in width, which seems unreasonably large for a bacterium or even a colonial bacterial structure. Yet the earliest ***Grypania*** are about a billion years too old to be actual worms. So perhaps -- for lack of any other hypothesis -- these are very early Eukarya, possibly outside the crown group.

By the early Mesoproterozoic (Calymmian), the evidence for a eukaryotic grade of organization becomes more definite. This judgment is based on: "(1) wall structure and surface ornamentation (2) processes that extend from vesicle walls (3) excystment structures (openings through which cysts liberate their cellular contents) (4) wall ultrastructure and (5) wall chemistry." Javaux ***et al***. (2004). In particular, large cells with processes extending beyond the wall (i.e. ***acanthomorphic*** acritarchs) are thought to be impossible without a eukaryotic cytoskeleton. ***Id***. Oddly enough, this agrees reasonably well with recent "molecular clock" work, which likewise places the primary radiation of the Plantae in the Calymmian. Yoon ***et al***. (2004). Mesoproterozoic acritarchs include specimens with new morphological features: ellipsoidal shape, vesicle pores, and a multi-celled or colonial appearance. Huntley ***et al***. (2006).



Acritarchs from the Mesoproterozoic Roper Group. Javaux et al. (2001). Bar = 35, 10, 15 & 40 µ.

Javaux *et al*. (2001) studied well-dated samples from the Roper Group of northern Australia. They recovered specimens of the controversial, but almost certainly eukaryotic, ***Tappania***. Note the relatively large size and the long, irregular processes which penetrate the outer wall. A bacterial origin isn't completely impossible, but the more likely explanation is a eukaryote with a well-developed cytoskeleton. In any case, some of the acritarchs known from this era are relatively enormous, such as ***Chuaria circularis*** (better known from the Neoproterozoic), which can approach 1 mm in diameter. Golubkova & Raevskaya (2005).

Another key finding of this study was that the Roper acritarchs showed clear ecological zonation, with different populations characteristic of inshore, nearshore, and distal shelf environments. The authors speculate that communities were limited by nutrient mineral runoff, since abundance and diversity seem higher in marginal marine settings. However, there is no guarantee that acritarch diversity reflects biotic diversity generally.

Slightly later (Ectasian) communities from the Ruyang Group of North China are dominated by ***Dictyosphaera***, an acritarch also found in the Roper Group. Kaufman & Xiao (2003). This cosmopolitan distribution is typical of Proterozoic acritarchs. The authors performed ion microprobe isotopic analysis of individual specimens, and were able to make a rough estimate that Mesoproterozoic CO_2 levels were between 10 and 1000 times higher at present.

Bangiomorpha
Inset (Porter, 2004) shows cross-section with septate division.

It isn't clear that these fossils are crown eukaryotes (***i.e.*** descendants of the last common ancestor of all living eukaryotes). It seems likely, if only because all acritarchs are assumed to have been photosynthesizers; but a good deal of room for doubt remains. However, there is a modest consensus that crown eukaryotes had appeared by Stenian, if not earlier, since these latest Mesoproterozoic acritarchs more closely resemble modern algae. Javaux *et al*. (2004); Porter (2004). In particular, ***Bangiomorpha*** looks like an extant alga and shows a very unusual "intercalary" pattern of cell division that is characteristic only of living bangeacean red algae. Porter (2004). Some acritarchs from this period can be found with surface ornamentation, and not simply processes. The Stenian also marked the first appearance of stalked cyanobacteria. Golubkova & Raevskaya (2005).

Fossils from even the earliest Neoproterozoic (Tonian) include forms commonly identified as fungi and recognizable modern orders of green algae. Falkowski *et al*. (2004); Golubkova & Raevskaya (2005). (We omit detailed consideration of metazoans, including Ediacaran forms, and metaphytes, which appeared in the later Cryogenian and Ediacaran. Peterson & Butterfield (2005). These are discussed extensively below, and in the sections devoted to those eras). Morphological features new to the Neoproterozoic include "polyhedral vesicles, bulb-shaped vesicles, barrel-shaped vesicles, triangular and hair-like processes, funnel-tipped processes, processes that fuse at the tips, and flange ornamentation about the vesicle equator." Huntley *et al*. (2006) (examples and internal citations omitted).

Generally speaking, the data from the Cryogenian are poor, but suggest continuity with the Tonian forms without dramatic changes in morphology or even diversity. Porter (2004). The first fossil remains of testate amoebae appear late in the Cryogenian -- the first good evidence of heterotrophic Eukarya. Porter (2004). The Ediacaran introduced two new communities, one associated with the Ediacaran animals (or whatever they may have been), followed by one associated with the transitional metazoans of the Doushantuo type. The latter include recognizable modern orders of red algae. Xiao *et al*. (2004). Many acritarchs from this period bore regular processes and surface ornamentation, e.g. ***Appendisphaera***, ***Ericiasphaera***. Golubkova & Raevskaya (2005).

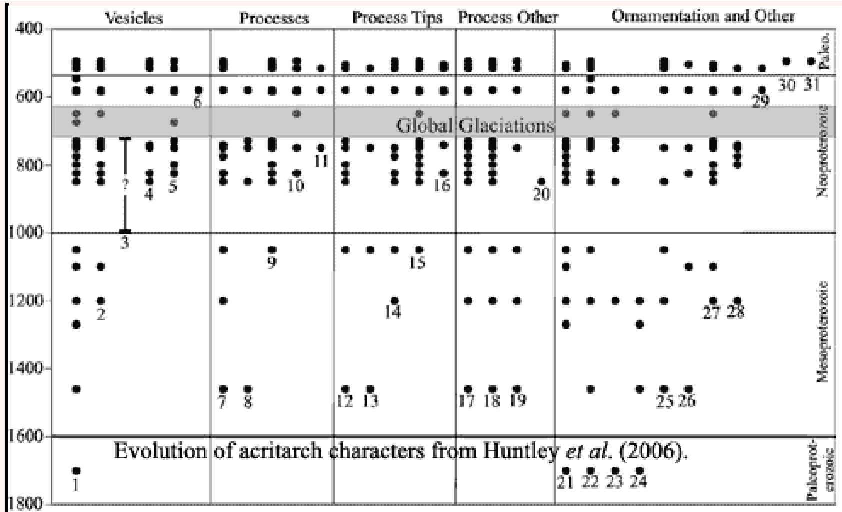


Fig. 5. Stratigraphic occurrences of morphological characters utilized in this study: (1) spherical vesicle; (2) ellipsoidal vesicle; (3) barrel-shaped vesicle; (4) bulb-shaped vesicle; (5) polyhedral vesicle; (6) medusoid vesicle; (7) cylindrical process; (8) dome-shaped process; (9) tapered process; (10) hair-like process; (11) triangular process; (12) rounded-tip process; (13) capitate-tip process; (14) blunt-tip process; (15) pointed-tip process; (16) funnel-tip process; (17) hollow process; (18) interior of process communicates with interior of vesicle; (19) branching process; (20) processes fuse at tip; (21) enveloping membrane; (22) excystment-like structure; (23) internal bodies in vesicle; (24) concentric ornamentation on vesicle surface; (25) plates on vesicle; (26) multi-celled appearance (vesicles contained in a larger envelope); (27) colonial appearance (aggregation of vesicles); (28) pores in vesicle wall; (29) flange ornamentation; (30) crest ornamentation; (31) costae meshwork surrounding vesicle.

A number of efforts have been made to quantify the pattern of acritarch diversity across the Proterozoic. Knoll (1994); Porter (2004); Huntley ***et al***. (2006). In general they verify the that, after an initial burst of diversification in the later Paleoproterozoic, development was gradual or even static until the Neoproterozoic. Surprisingly, evidence for a diversity or even abundance bottleneck as a result of the Cryogenian "snowball earth" episodes is weak to almost non-existent. ***See also*** Olcott ***et al***. (2005) (biomarker evidence). It might be fairer to say that the diversity curve began to take off in the Tonian and was, at most, slowed down in the Cryogenian.

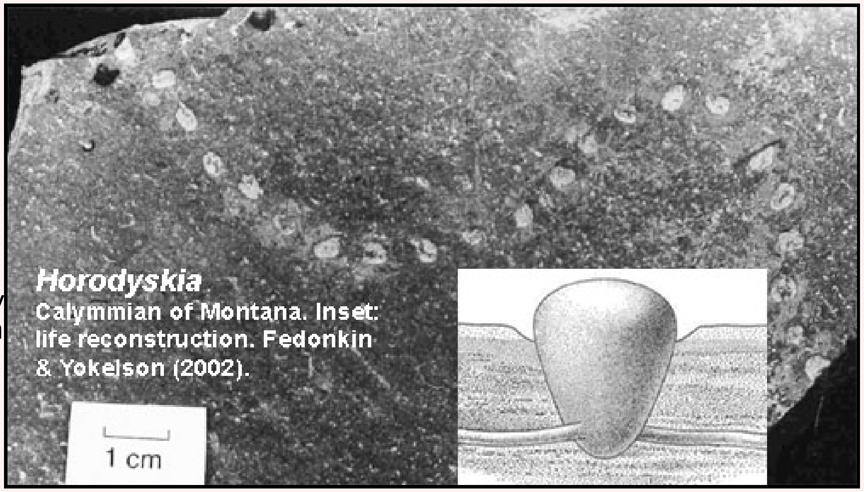
Animals

In the long term, the most successful animal group of the Proterozoic were the sponges. We are somewhat reluctant to speak much about Proterozoic sponges because we developed some very peculiar and idiosyncratic ideas about the evolution of sponges in another part of Palaeos. Those speculations have been summarized elsewhere in what is, just possibly, the worst-written essay on this site. We tentatively stand by what was said, if not how we said it.

Here we will be more conservative, as we are summarizing the current state of a huge topic about which no two scientists seem to agree. We will introduce only two home-made ideas. The first deals with the phylogenetic position of ***Kimberella***. The second is yet another take on the famous embryos of Doushantuo mentioned in the previous section. The plan (if we can stick with it) is to avoid too much heavy thinking and concentrate on the thoughts of more qualified people.

We will begin with a brief orientation which covers the first 95% of the Proterozoic in a couple of paragraphs. We will then cover the Ediacaran fauna, which we will call "Vendobionta," following the terminology introduced by Seilacher. We will put special emphasis on on the "rangeomorph" vendobionts and some ideas developed by Narbonne (2004). We will briefly apply those ideas to ***Kimberella***, a vendobiont often compared to mollusks. In brief, we suspect that, whether or not ***Kimberella*** actually is a basal mollusk, it can also be interpreted as a not-particularly derived rangeomorph vendobiont. After this, we will talk a little about Precambrian sponges as a sort of warm-up to the Doushantuo demilitarized zone. Finally, we will walk gingerly through the Doushantuo minefield itself. The Weng'an locality of the Doushantuo Formation has been the site of ferocious scientific combat since February 6, 1998, when Li ***et al***. (1998) announced the discovery of small sponge body fossils and embryos from Weng'an. We take no sides in this free-for-all, but we introduce a possibility which (so far as we know) none of the combatants seems to have considered: that the embryos of Weng'an are the embryos of vendobionts. ATW081205

Animals Before the Ediacaran?



Horodyskia
Calymmian of Montana. Inset: life reconstruction. Fedonkin & Yokelson (2002).

In the old days of molecular phylogeny, roughly speaking the decade between 1995 and 2005, it was common to read "molecular clock" papers confidently announcing that Metazoans had evolved in the Mesoproterozoic, if not earlier. Fortunately, it is no longer necessary for us to spend pages tearing into these contentions. More recent papers, using vastly more sophisticated techniques, arrive at results which are considerably more consonant with the fossil record. Peterson ***et al***. (2008) is a good example, and a good study.

Peterson's group takes considerable care to calibrate their molecular analysis with multiple time points from the fossil record. They find (with generous error bars) that the Fungi diverged from Metazoa at some point in Stenian or Tonian time. We use "Metazoa" to mean toads > toadstools. This is over-inclusive, and we continue to use it only for the sake of consistency with other parts of Palaeos. When most people use the term "animal" they generally mean something more like sponges + Spinoza. In that sense, animals began to evolve in the Cryogenian, with the evolution of the principal sponge clades. Peterson ***et al***. find that most of the high-level animal clades then diverged in the Ediacaran and radiated in the Cambrian. When evaluating these results, it is important to recall that we are speaking of genetic divergence times. Fossils with detectably clade-specific characteristics ("apomorphies") may not appear until long after a clade has diverged genetically from all others. Given that understanding, the results reported by Peterson's group are entirely credible. Since they are closely constrained by the fossil record, such studies represent a synthesis of the currently available molecular and paleontological data.

Parmia
Fedonkin (2003)

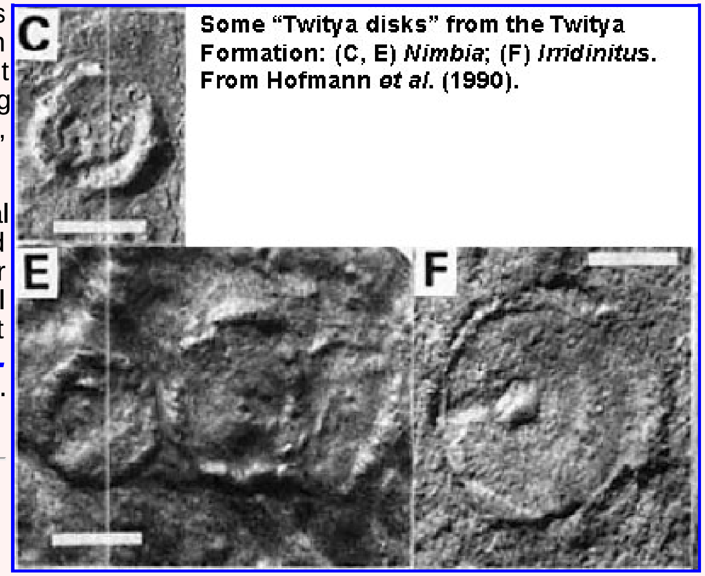
Some results from paleontology have also suggested an early start for Metazoa. The more promising of these candidates have been reviewed by Fedonkin (2003). Of these, one of the most interesting is the very simple, beads-on-a-string creature, ***Horodyskia***. Fedonkin & Yochelson (2002). ***Horodyskia*** is not uncommon in bottom sediments of Calymmian age (Mesoproterozoic, c. 1500 Mya) or younger in North America and Australia. The conical beads, or "zooids," are plainly connected by something, presumably a stolon. The strings seem to be of relatively uniform length. Zooid size is uniform for each string, but varies considerably between strings, reflecting zooid growth with time. Proportional spacing between zooids is maintained, presumably by resorbtion of alternate zooids. Thus the putative young strings have many small zooids, while older strings are the same length, but have a small number of larger zooids. This kind of coordinated growth suggests, as Fedonkin and Yochelson note, a "tissue-level" organization rather than a colony of individuals.

Horodyskia doesn't really enter into our equation. Fedonkin (2003) loosely refers to ***Horodyskia*** as a "metazoan." Few seriously assert that ***Horodyskia*** is descended from the last common ancestor of frogs and fungi -- much less that it is an "animal" in the sense defined above. Some workers are still not completely convinced that ***Horodyskia*** is even eukaryotic. Knoll ***et al***. (2006). Cooperative multicellularity evolved independently in at least six ***living*** eukaryote groups (red algae, green algae, 2-3 groups of chromists, slime molds, fungi, metazoans). The surprise is that there are so few known ***extinct*** multicellular clades.

Fedonkin (2003) also mentions the worm-like ***Parmia*** and ***Sinosabellidites***, two worm-like organisms of early Neoproterozoic age. ***Parmia*** looks like an unholy cross between a sea cucumber (Holothuroidea) and an annelid worm. It is known only from the Tonian of the Russian Platform. ***Sinosabellidites*** and several similar forms are slightly younger organisms from China. All show closely spaced annulations, on the order of 200µ apart. However, Dong ***et al***. (2007) interpret organisms of this type as algae, with any apparent proboscis reinterpreted as a holdfast. In short, the evidence for advanced metazoans before the Ediacaran is not compelling. ATW081205

The Ediacaran Environment

The environment in which Ediacaran metazoans evolved is only a little less controversial. Some of the issues are discussed above, in the section on acritarchs. The Ediacaran begins with the end of the "Snowball Earth" episode of the Marinoan Glaciation, at about 630 Mya. The current feeling seems to be that this was followed by an increase in atmospheric oxygen or, at least, in oxygenation of the oceans. The main point of contention is whether the oxygenation occurred in some stepwise fashion -- through a series of rapid "events" (Fike ***et al.***, 2006; 2007; Scott ***et al.***, 2008) -- or proceeded more gradually (Grey & Calver, 2007; Shen ***et al.***, 2008).



Some "Twitya disks" from the Twitya Formation: (C, E) *Nimbia*; (F) *Irridinitus*. From Hofmann *et al.* (1990).

The ocean floors where animals developed were quite unlike those of the Phanerozoic. Mobile herbivores were exceedingly rare or absent, as were burrowing worms. Consequently, the sea floor was often covered in an algal/bacterial mat. Much of the mud and bottom ooze of the Phanerozoic is the product of constant churning by animal life. Likewise many of the hard substrates were created by corals and other calcifying animals. Before animals, the usual bottom was a firm, living bacterial blanket, with occasional, usually small, carbonate outcrops built by calcifying bacteria. Dornbos et al. (2005).

The first metazoans lacked any obvious way to move, and also lacked any obvious mouth, gut, or central cavity. Consequently, it is unclear what they ate, or how they fed themselves. McMenamin (1998) argued that the earliest animals hosted symbiotic photosynthetic algae. This hypothesis is currently out of favor because many of the best known animal fossils of the Ediacaran appear to come from deep water -- well below the depth where sunlight could penetrate. Peterson ***et al***. (2003). One currently popular belief is that these organisms absorbed dissolved organic carbon compounds directly from seawater. Sperling ***et al.*** (2006). This would require some fairly peculiar ocean chemistry, but many workers find it entirely plausible. ATW081206.

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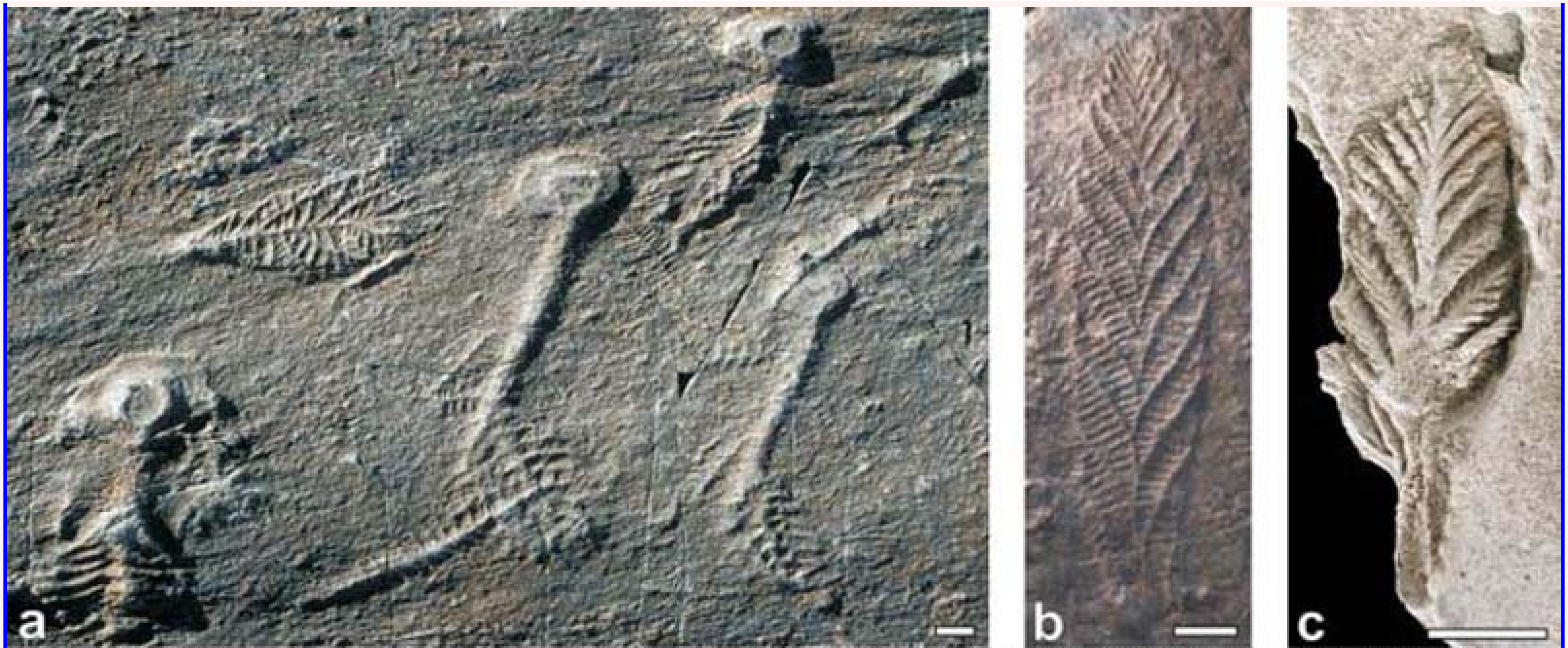
The Proterozoic 2

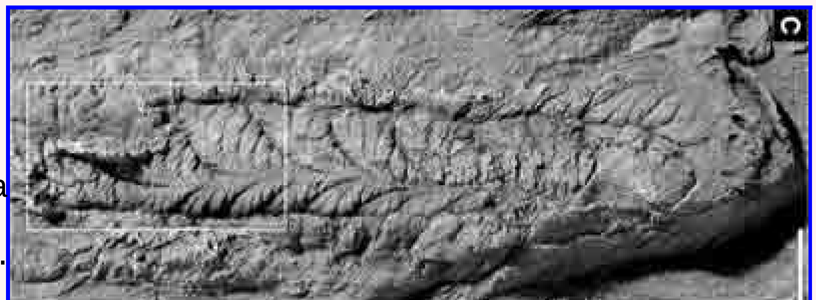
The Vendobionta

So, what were the earliest Metazoa? Apparently, they were the Vendobionta or Ediacaran organisms. They appear just before the end of the Marinoan Ice Age, more or less at the boundary between the Cryogenian and Ediacaran Periods. The oldest known representatives of the Vendobionta are probably the "Twitya disk" forms from the Twitya Formation in the McKenzie Mountains of northwestern Canada. Hofmann ***et al***. (1990). These are pictured on the previous page. It remains unclear whether these are body fossils, or simply the holdfasts of something more elaborate. They include some very long-lasting "form taxa," (i.e. shapes without known animal shape-makers), and so the answer may be "holdfasts" (see also image 'a' below). However, that is unlikely to cover all of the disk-animals. In fact, Peterson ***et al***. (2003) have expressed some doubt whether ***any*** of these structures -- even those plainly attached to other structures -- actually functioned as holdfasts.



Rangeomorph vendobionts from Newfoundland and England. (a) Mistaken Point (Newfoundland) rangeomorphs, showing holdfast structures (scale = 2 cm). (b) *Charnia* from Charnwood, England (scale = 2 cm). (c) Unnamed rangeomorph from Spaniard's Bay (Newfoundland) (scale = 0.25 cm). All from Narbonne (2005).

Narbonne (2005) has reviewed the vendobionts relatively recently and has begun to connect some of the dots from the evolutionary data. His opinion is particularly helpful, because he has studied the extraordinary three-dimensional vendobiont fossils from Spaniard's Bay in Newfoundland (Canada) (image 'c' above). Narbonne follows Waggoner (***e.g***. Waggoner, 2003) in dividing the post-Twitya vendobionts into three assemblages: the Avalon, White Sea, and Nama.



Unnamed rangeomorph from Narbonne (2004). Scale bar = 5 mm

The Avalon Assemblage. The oldest, longest-lasting, and perhaps the best characterized assemblage is the Avalon. It appears between 600 and 560 Mya, and some elements of this fauna survived into the Cambrian. It is best known from several localities in Eastern Canada and from Charnwood Forest, England. However, elements of the fauna were quite cosmopolitan. They are found at virtually all depths and latitudes, limited only by the availability of wall-to-wall (bacterial) carpeting. Note that this kind of distribution is not quite what one might expect of a fauna expanding along some trend line of increasing ocean oxygenation -- but too little is known about the details of timing, ocean chemistry, and paleolocation to make much of it.

The members of this fauna fall into two morphological types: "medusoids" (disks) and the fern-like "fronds." Typical genera include ***Charnia***, ***Ivesia***, and ***Bradgatia***. Narbonne calls the fronds "rangeomorphs" after the well-known ***Rangea*** **[1]**. In an important paper, Narbonne (2004) showed that the rangeomorphs appear to be built on a fractal architecture. That is each extension of the original structure gives rise to smaller structures which are "self-similar," i.e. have the same morphology as the parent structure. Close examination of the Spaniard's Bay rangeomorph in figure (c) above shows that each frond gives rise to "frondlets" of the same shape, which develop third level structures of the same shape, and so on. Contrast this pattern with some typical metazoan growth patterns, involving the addition of segments at the same scale along a single axis, or unsegmented and determinate growth.

In addition to physical association and fractal development, the members of the Avalon Assemblage share a number of characters, including the complete absence of motility, the absence of any means of sediment clearance (as judged by mass-mortalities apparently caused by thin layers of sea-borne volcanic ash), a remarkable resistance to post-mortem compression, completely indeterminate growth, and a strong tendency to incorporate sediment centrally as a

structural element. McMenamin (1998); Peterson ***et al.*** (2003). These features, including fractal development **[2]**, are often found in the Fungi. Based on these similarities, Peterson's group speculates that many Avalon vendobionts were "analogous," or possibly related, to Fungi. We are less shy than Peterson ***et al***. about the phylogenetic consequences. Whether the vendobionts are actually metazoans or not, it is hardly surprising to see organisms with a mosaic of metazoan and fungal characters a few tens of My before animals first become obvious in the fossil record. This is exactly what we ***ought*** to see at or near the base of Metazoa (toads > toadstools).

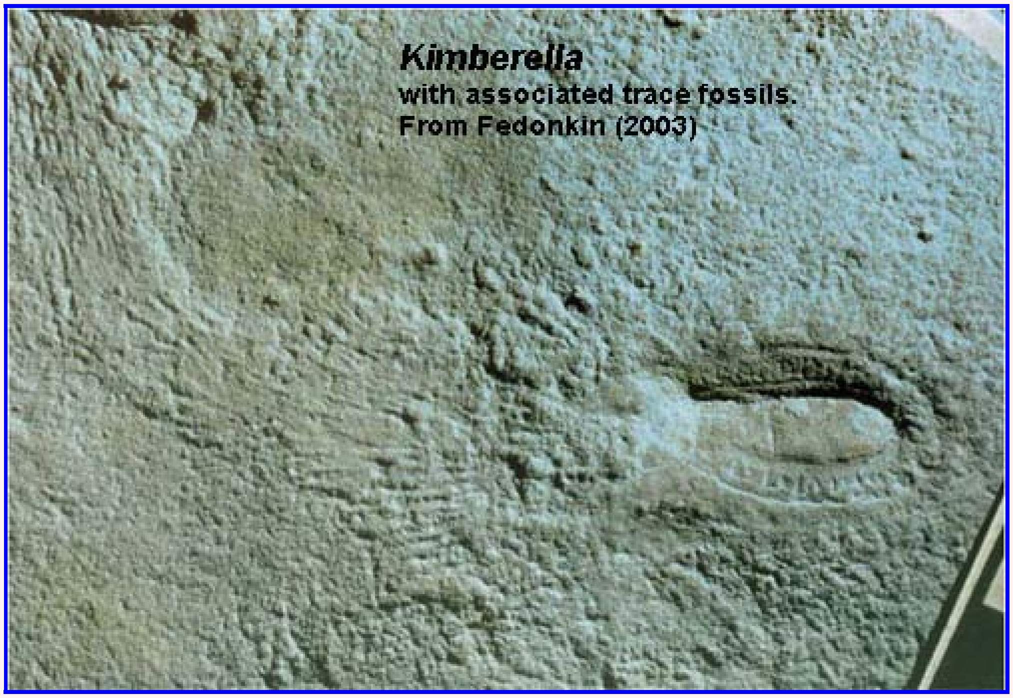
Two other structural observations from Narbonne's (2004) study of the Avalon fauna from Spaniard's Bay are worth mentioning. The first is that these vendobionts have more structural support than was supposed. It is hard to tell in most images, but Narbonne indicates that rangeomorphs were supported by bracing which formed an "organic skeleton" below the branching elements. The word "below" here is important. Although most reconstructions show rangeomorphs with a fern-like upright habit, a significant number of workers have expressed the view that rested on, or even buried in the sediment. ***See, e.g.***, Grazhdankin & Seilacher (2002). However Narbonne found (a) bracing which would be superfluous for a supine organism and (b) that both sides appeared identical in partially overturned specimens, again suggesting that both sides were exposed to the same environment. At least some of the frond animals therefore seem to have been erect.

Finally, Narbonne illustrates, but does not discuss, something we can only call the "corn cob" rangeomorph. This beast illustrates three structural themes of many vendobionts. First, as Narbonne notes, the "frondlets" which form the basic structural unit can bend, curl up, merge etc. and form many different shapes, including marginal rows of buttons. That marginal row looks disturbingly like ***Kimberella***'s marginal ornament, to our way of thinking. The second motif is the envelope which surrounded the corncob beast for at least 2/3rds of its circumference. We wonder how common this is. Many good images of vendobiont fossils suggest something of the sort. A few species (***Ernietta***) are acknowledged to have some such structure. McMenamin (1998). Could the mantle of ***Kimberella*** be derived from such an envelope?

One thing is certain. The corncob animal cannot have been erect. At least some of the frond animals were therefore supine. However, it may also have been a reproductive part, embryo, or developmental resting stage. Vendobionts are never easy.

The White Sea Assemblage. The White Sea assemblage is found in sandy bottoms in temperate paleolatitudes during a relatively brief time span, from 556 to 550 Mya (Waggoner, 2003) and possibly as late as the base of the Cambrian (Narbonne, 2005). "Characteristic fossils of this assemblage include the bilaterally symmetrical forms, such as dickinsoniids, ***Kimberella***, and ***Spriggina***; the annulated concentric forms ***Kullingia*** and ***Ovatoscutum***; and all but one of the triradially symmetrical discoid forms, such as ***Tribrachidium***." Waggoner (2003: 107). "Worm burrows" suggest the presence of bilaterians (Narbonne, 2005), although trace fossils are notoriously difficult to interpret. This fauna is most diverse in relatively shallow waters (Narbonne, 2005).

One of the seriously peculiar things about some vendobionts is their fundamental geometry. Two well-known examples are the triradial symmetry of ***Tribrachidium***, and the pentaradial symmetry of ***Arkarua***, both White Sea medusoids from Australia. Many vendobionts exhibit an alternating symmetry, with structures diverging from a central axis on alternate sides. In some cases, this is the result of flattening a fundamentally ***spiral*** pattern of growth. In others (particularly from the White Sea Assemblage), alternating growth seems to be the genuine body plan.



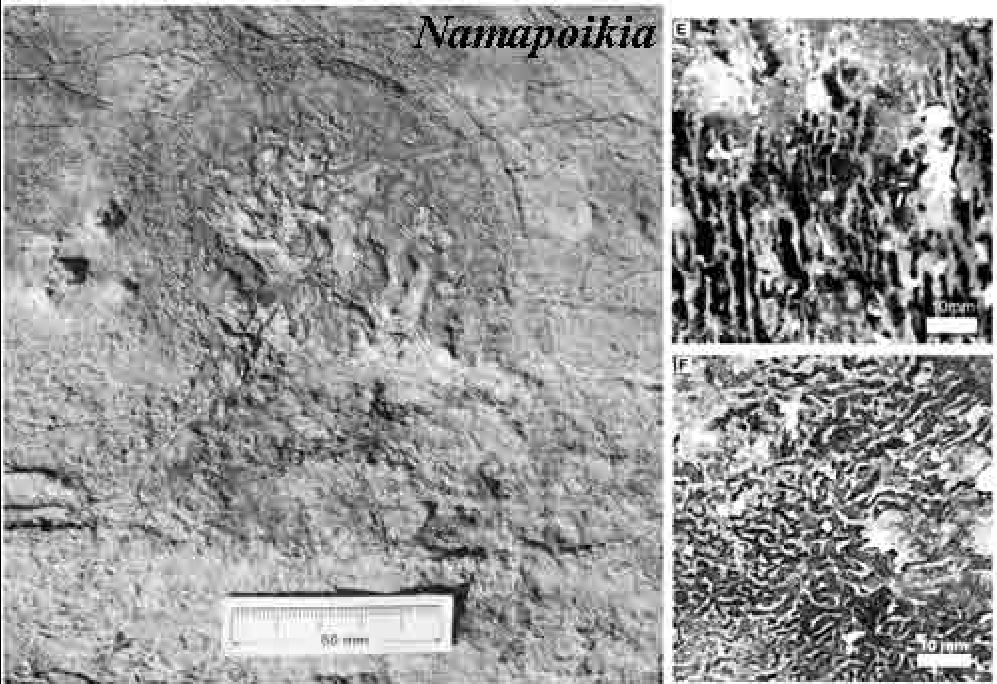
Tribrachidium could conceivably be interpreted as an abbreviated spiral pattern. Some remains of ***Tribrachidium*** seem to show the three main arms at very different vertical levels. On the other hand, ***Pteridinium,*** which looks bilaterally symmetrical at first glance, seems to be based on a truly triradial plan, with two long branches forming the "segments" and one short branch forming a sort of spine. McMenamin (1998); Grazhdankin & Seilacher (2002).

The features of the White Sea communities which have attracted the most attention are (a) trace fossils strongly suggesting mobility; (b) some sort of segmentation (almost always of the alternating symmetry type); (c) a clear anteroposterior axis and (d) ***Kimberella***, which has all of the above to one extent or another, as shown in the remarkable image from Fedonkin (2003).

Based on such characteristics, numerous workers have associated various vendobionts with specific taxa of living organisms, e.g. ***Kimberella*** with Mollusca, segmented forms with Anellida or Arthropoda generally, medusoids with Cnidaria or even Echinodermata. Others have been referred to as "soft-bodied trilobites." McMenamin (1998) (arguing that there is actually no close relationship). We will resist the temptation to use more muscular language here, and simply note that the evidence is not yet strong enough for any firm conclusions. After all, no one would suppose that rangeomorphs actually were ferns, or ***Ernietta*** a mushroom, based on basic morphology and ***lack*** of motility.

Perhaps, given the present strength of the scientific tide dragging the vendobionts into crown group animals (last common ancestor of all living animals and all of its descendants), it may be worth a few more contrarian comments to explain our doubts. The key characteristics are symmetry, metameric organization, and motility. As we have seen, vendobiont metamerism and symmetry are peculiar and often show a radial or alternating-side pattern. That pattern is more like a plant than an animal. And we have seen from ***Horodyskia*** and the annelidomorph algae that metameric (repeating) structures are not necessarily unique to crown group animals.

Similarly, while vendobionts and animals both have large, motile forms, the vendobiont style of motility is peculiar. Fedonkin (2003) not only provides the image of ***Kimberella*** traces shown here, but also an image of similar traces radiating over 360° (or close to it -- the block is broken off in one sector). Whatever this preserves, it cannot be locomotion. From the same area of the White Sea, he reproduces ***Yorgia*** together with lighter imprints of the same organism, possibly the same individual. Together, they seem to show discontinuous movement, like a series of left footprints ending with the remains of a left foot. Quite possibly, this represents locomotion, but locomotion unlike any animal plausibly present in the Ediacaran. At the end of the day, there is good reason to suspect that the vendobionts are metazoans; but we have a hard time seeing them as crown group animals.



Complete individual, with (E) longitudinal and (F) transverse sections. From Wood *et al.* (2002).

The Nama Assemblage. The Nama Assemblage is somewhat younger than the White Sea communities. Its limits are approximately 549 to 542 Mya. That is, it overlaps the earliest Cambrian. Like the White Sea fauna, the Nama creatures are more abundant in shallow waters. Unlike the White Sea fauna, the Nama Assemblage is found at tropical paleolatitudes and in carbonate settings. Typical members are ***Namacalathus*** (image from Grotzinger ***et al.***, 2000) and ***Cloudina***. These have been discussed elsewhere in our unfortunately chaotic and badly written essay on the origin of certain sponges. A recent addition with characters conforming to the model is ***Namapoikia***. Wood ***et al.*** (2002).

The Nama Assemblage is more likely than the White Sea group to include the last common ancestor of demosponges and Demosthenes. If nothing else, members of this assemblage have calcified skeletons. In particular, various members have a mosaic of characters similar to well-known metazoans in or very close to crown group animals: inverted conical shapes, perforated exoskeletons, some double-walled regions, twisty "thrombolitic" internal structures, curved structural bracing, association with calcifying bacteria. These are characteristics found in archaeocyaths (probable sponges just basal to crown group animals) and some of the "small shelly fauna" both abundant in the Terreneuvian Epoch (earliest Cambrian). Interestingly, the Nama animals lack all of the putative animal characteristics of White Sea organisms. None are motile, bilaterally symmetrical, segmented, able to leap tall buildings in a single bound, etc.

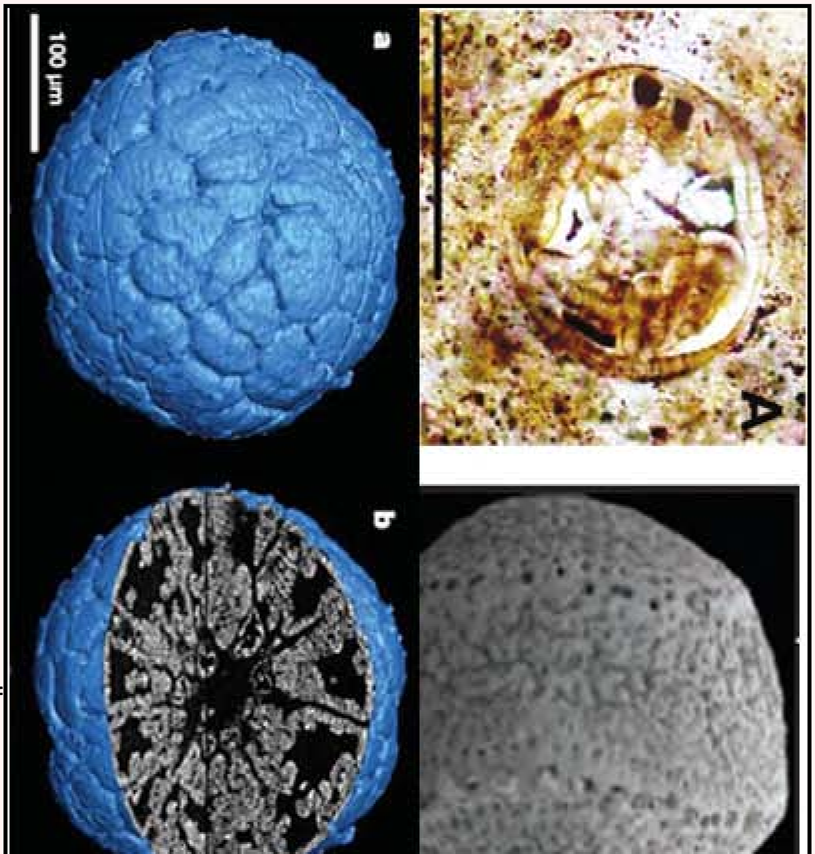
We have, obviously, been unable to disguise our bias here, in spite of our earlier promises to the contrary. Having once again dynamited our own credibility, we will make a transparent attempt to salvage it by warning the reader, once again, not to take the argument too seriously. The current prevailing view is that ***Kimberella*** is a mollusk and that the inhabitants of the White Sea fauna were largely members of advanced animal clades, while the Nama assemblage consists of relatively uninteresting niche specialists.

It may be appropriate to close this section with a reference to the unnamed "Dengying form" of Xiao ***et al.*** (2005). The morphology of the living animal is unclear. It plainly doesn't fit well into any of the three conventional fauna described above. The overall plan is a sort of cross between a branching Avalon form and a"quilted" White Sea organism. However, it may have been weakly calcified, like a Nama creature, and some of the detailed cross-sections look vaguely stromatoporoid. If nothing else, the Dengying form should remind us that this part of phylospace is still mostly unexplored, and almost anything is still possible. ATW081218.

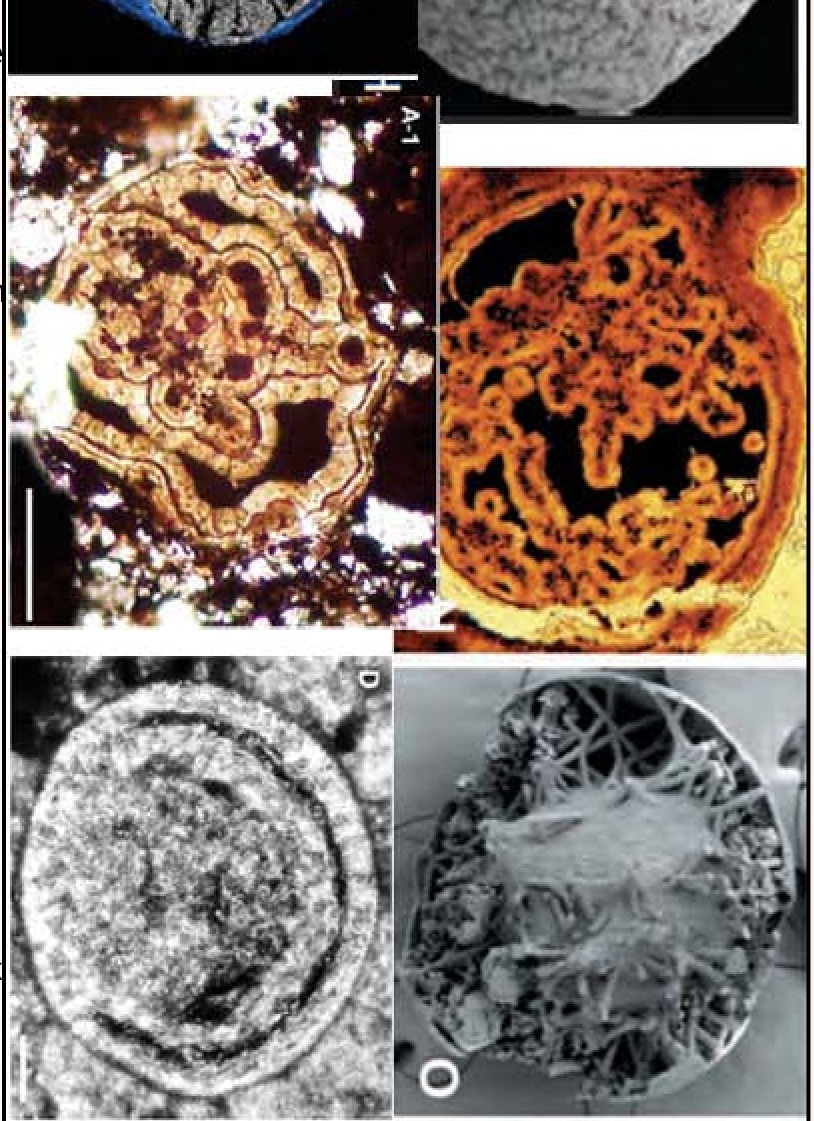
The Proterozoic - 3

The Embryos of Doushantuo

We come, at last, to the most difficult and contentious of the Ediacaran animal issues. The February 6, 1998 issue of **Science** carried a brief report by Li ***et al.*** describing some microfossils from phosphorites of the Ediacaran Doushantuo Formation, at a site in Wengan (or Weng'an **[3]**) County in central Guizhou Province. The main point of the paper was that these Ediacaran remains included monaxonal sponge spicules (suggesting demosponges) and small structures interpreted as early sponge embryos and eggs. Then, Chen ***et al***. (2000) (a large group including two of the three authors of Li ***et al***., 1998) reinterpreted some of the spherical objects as specifically bilaterian embryos. This announcement generated a remarkable amount of press coverage; and, more to the point, it opened a scientific free-for-all which continues to this day. Researchers have since referred the putative embryos to at least four different Linnaean kingdoms and any number of animal phyla. Some have argued that the embryos are pseudofossils and have no place on the Tree at all.



These embryos -- if that is what they are -- pose baffling problems of interpretation. Many of the authors who have addressed the issues are names to conjure with. However, many, perhaps most, have changed their views, or have at least heavily qualified them during the course of the last few years. For example, Prof. Shuhai Xiao has moved from being an unbeliever (Xiao ***et al.***, 2000) to championing a very specific cnidarian affinity for at least some of the specimens (Xiao et al., 2007). Prof. Whitey Hagadorn was one of the authors of Chen ***et al***. (2000). However, he has become an apostate, relegating most specimens to "stem metazoan" status (Hagadorn et al., 2006) and co-authoring Xiao's (2007) paper assigning others to the Cnidaria. These examples might suggest convergence of scientific opinion on a cnidarian interpretation. In part, that seems to be the case. However, two groups have recently published thought-provoking arguments that the embryos are actually bacterial (Bailey ***et al***., 2007) or protistan (Matz ***et al.***, 2008) structures.



Upper left (a & b) X-ray tomographic reconstruction of an Early Cambrian embryo from the Kuanchuanpu Fm. Scale = 100µm. Donoghue *et al.* (2006). Middle left: *Vernanimalcula* cross-section. Scale = 40 µm. Chen *et al.* (2004). Bottom left: Embryo in cross-section. Scale = 50µm. From Li *et al.* (1998). Top right: embryo in cross-section. Scale = 50µm? Chen *et al.* (2002). Middle right: cnidarian embryo. from Xiao *et al.* (2007).. Bottom right: cross-section and reconstruction of internal structure of embryo. Xiao *et al.* (2002). All except top left from Ediacaran Doushantuo Fm.

We are reluctant to get involved in these issues. In addition to overcoming our usual handicaps of indolence and ignorance, a reasonable explanation of the problems would require a small book, possibly even a large one. Yet that book could come to no firm conclusion, and it isn't obvious to us that the project is important enough to merit the investment. The internal anatomy of these structures is very poorly preserved (Donoghue ***et al.***, 2006), dominated by phosphorite artifacts and inconsistent from specimen to specimen. Any real evolutionary signal may well be hopelessly swamped by taphonomic noise. Phosphorites can create an alarming variety of morphological artifacts in the process of phosphatization (Chen ***et al***., 2002; Bengston & Budd, 2004) -- a problem made worse by the presence of two or three distinct modes of phosphatization at Doushantuo (Dornbos ***et al***., 2005; Dornbos ***et al***., 2006). In addition, occasional specimens preserved in chert (***i.e.***, silicified, rather than phosphatized) are found in the same beds. Yin ***et al***. (2004).

One reason for this variety is that the the embryo fossils are found in intraclasts. Intraclasts are typically grains of partially fossilized material ripped from the sea floor, or from some nearshore mudflat, during a storm or other high-energy event and thoroughly mixed with everything else which is being churned around at the same time. In the case of Doushantuo, the grains were deposited by storms above the fair-weather wave base (the depth at which normal waves don't stir things up). Zhou ***et al.*** (2002). As a result the intraclasts were knocked around, (presumably) abraded, and further mixed by wave action before finally settling again.

Plainly, no one has a really good handle on the environment(s) in which the embryos developed, or what their various histories may have been. Like these fossils, scientific opinion in recent years has been thoroughly mixed by high-energy currents, subjected to all kinds of alterations, and -- unlike the fossils -- has not yet had an adequate opportunity to settle and consolidate. Consequently, we will defer further discussion of these odd varmints (the fossils, not the scientists) to another day. ATW081219.

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checked ATW050821, edited RFVS111112

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Notes

[1] Actually not so well-known after all. Recent abstracts suggests that the genus ***Rangea*** is a ***nomen dubium***. In any event, the more inclusive taxon is, formally, Rangeomorpha Pflug, 1972; and the original citation is: Pflug HD (1972), ***Zur fauna der Nama-Schichten in Südwest-Afrika, III. Erniettomorpha, Bau und systematische Zugehörigkeit***. **Palaeontographica A,** 139: 134-170.

[2] There is a considerable literature on the fractal growth of fungal hyphae. Our math is not up to it. However, it is plain that the fungal pattern is different, in that it lacks the long-range order seen in vendobionts. This is a critical difference, because long-range order suggests that transcription factors may be at work. On a related subject, students often make the assumption that the observed pattern in a body plan is the result of selective growth. That may be the case. However, the morphology may also be explained by a pattern of selective cell death.

[3] 瓮安 is pronounced ***Weng-an***, rather than ***Wen-gan***.

[4] Someone always wants the math. To be precise: $\delta^{34}S = (((^{34}S/^{32}S)_{sample}/(^{34}S/^{32}S)_{standard}) - 1) \times 1000$, where the standard is usually a particular meteoric sulfur ("CDT") with a composition 95.040% ^{32}S, 0.749% ^{33}S, 4.197% ^{34}S, and 0.015% ^{36}S.

[5] In case you have zoned out completely, we repeat that these are stable isotopes. This discussion has nothing whatsoever to do with carbon dating or radioactivity. Carbon dating uses an unstable isotope of carbon, ^{14}C and a completely different set of analytical techniques.

[6] The mutations involved in the biochemical shift probably occurred in the Paleocene, or even earlier; but grasses started off slowly. It was only in the Miocene that they began to grow, so to speak, like weeds.

[7] Once upon a time, in our distant youth, we attended a school almost unbelievably similar to Hogwarts, where we received the relatively serious discipline of 10 demerits for "cynicism" from one of the masters, a Snape ***anlage*** named Mr. Wischert. We have never forgotten or forgiven this monstrous injustice.

[8] Maybe not so unshakable, after all. Peterson ***et al.*** (2008) may signal that that molecular clock-making has finally come of age.

[9] Solely for our own benefit we include notes on the following scenario, with facts taken from abstracts and other uncitable stuff. It actually looks as if a triple conjunction was required.

One of the few bacteria with only a photosystem II ("PSII")-like complex is ***Rhodobacter***. Assume the primitive state is a bacterium like ***Rhodobacter***, but having a PSI system as well. Interestingly, it is unclear whether the ***Rhodobacter*** PSII complex uses manganese at all. If it does, the metal specificity is low and the oxidation is only from MnII to MnIII. Mating this kind of reaction system with PSI would accomplish nothing. However ***Rhodobacter*** does possess an enzyme which can do the MnII to MnIV oxidation: superoxide dismutase ("SOD"). This enzyme is one of the scavenger enzymes which removes toxic high-energy oxygen free radicals (or their precursors -- I can't recall which). These free radical agents are, in turn, produced when Ribulose-1,5-bisphosphate carboxylase/oxygenase ("Rubisco") makes a mistake. Rubisco frequently makes mistakes because it has low substrate specificity. Since Rubisco is the key carbon-fixing enzyme in photosynthesis, it follows that SOD would coordinate with PS I, which contains the rubisco.

SOD normally returns its excess redox potential to general cell metabolism via some shunt into the shikimate(?) pathway. The shunt is weird and cumbersome. It seems natural that it would find some other way to blow off excess steam. On the other hand, it is unclear why it would evolve a partnership with PSII, rather than PSI. The answer may have to do with the effect of pH on the redox potential of the MnII/MnIV couple. An increase of pH from 7 to 8 reduces the redox potential of Mn oxidation by a full 25%. PSII is normally in the business of pumping protons across membranes, thus creating a transmembrane pH differential. Thus, evolution has an opportunity to fine-tune the SOD reaction by associating it with PSII as well as PSI.

There is a considerable literature on the effects of ultraviolet light and temperature on both photosystems and on SOD which might be used to elaborate this hypothesis and coordinate it with the geochemical record. It would also be useful to look at the several bacterial taxa which have PSI only. Is there coordination with SOD, as expected? Are there other common enzymes which use the MnII/MnIV couple. Kopp ***et al***. (2005) don't think so. Are there any cases in which SOD uses some other unconventional pathway to recycle superoxides? Probably: see fungal lignin digestion materials. Finally, we should look at the effects of methane haze on UV and visible sunlight. At a guess, a significant drawdown of methane would be necessary before any of this would work well enough to be worth evolving. Note the remarks on the pre-GOE "methane greenhouse" by Kopp ***et al***. (2005). Indeed the ***increased*** mass-independent sulfur fractionation in the Siderian may represent increased penetration of solar UV, as suggested by Farquhar ***et al.*** (2007). This would be a natural result of a (latest Archean?) methane drawdown. ATW 090118.

We were shocked and delighted to find that Kirschvink & Kopp (2008) recently published a somewhat similar hypothesis, even using some of the same arguments, plus a pile of new molecular fossil data we haven't had a chance to work through. Every once in a while, it seems, we inadvertently stumble on something plausible. ATW090223.

The Paleoproterozoic Era

The Paleoproterozoic Era of the Proterozoic Eon: 2500 to 1600 million years ago

Hadean
Archean
Eoarchean
Paleoarchean
Mesoarchean
Neoarchean
Proterozoic
Paleoproterozoic
Siderian
Rhyacian
Orosirian
Statherian
Mesoproterozoic
Neoproterozoic
Phanerozoic

Introduction
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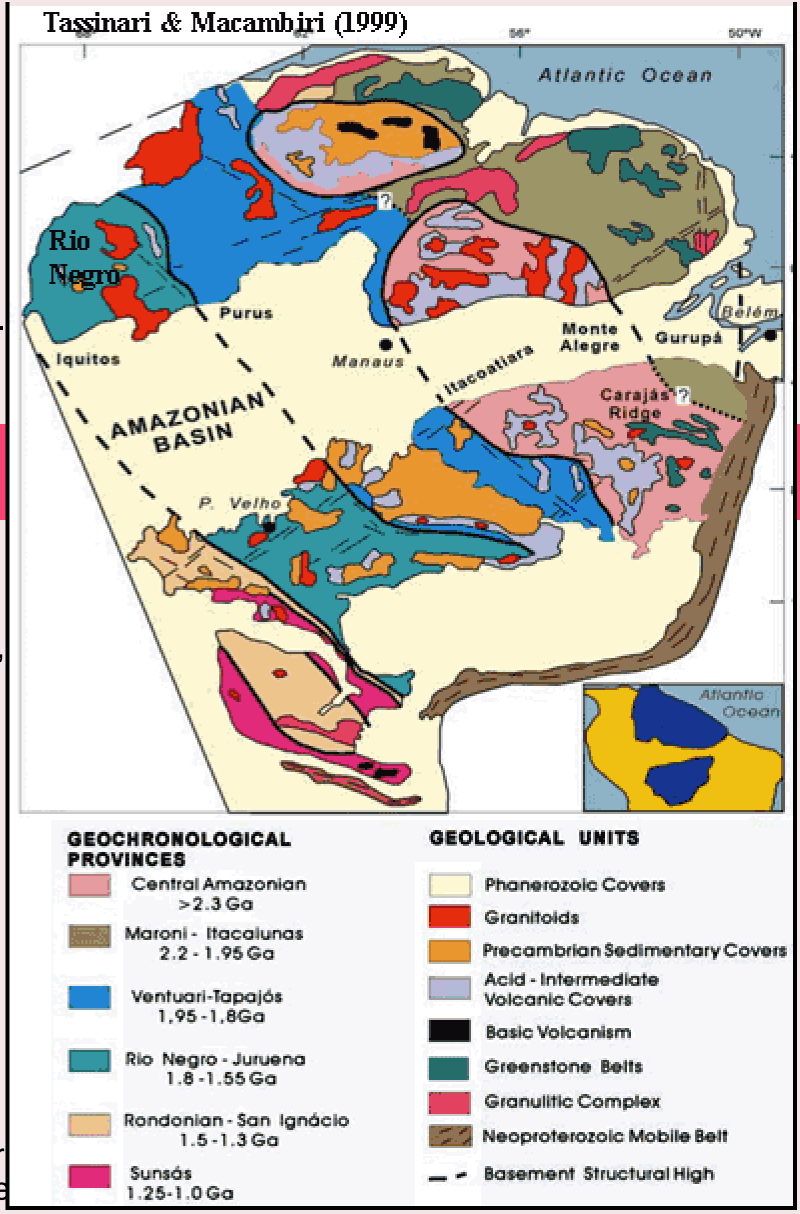
Introduction

The Paleoproterozoic is, by quite a wide margin, the longest era of geologic time. It covers 900 million years, about 20% of the entire history of the Earth. This era saw the evolution of most types of bacteria with which we are familiar today, and the earliest eukaryotes. Most importantly, the early Paleoproterozoic included the Great Oxygenation Event ("GOE") during which, for the



first time, atmospheric free oxygen exceeded 0.001% of its present atmospheric level ("PAL"). ATW090224.

Geography

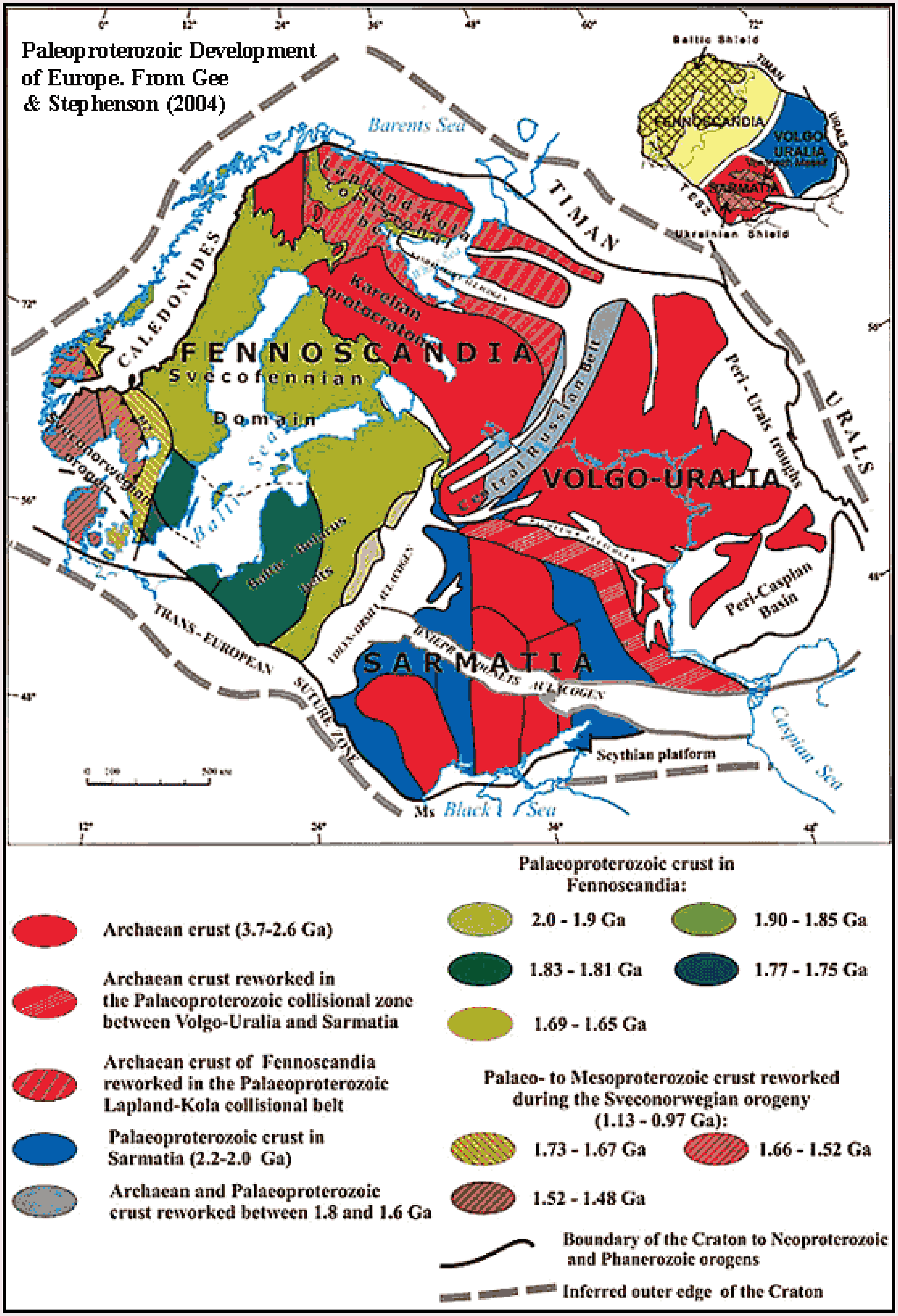
Modern Plate tectonics began with the Paleoproterozoic. The Paleoproterozoic was the era of continental shield formation. By and large, the Earth's Archean crust seems to have been both fragmented and somewhat unstable. Some paleogeographers assert that an episode of continent formation -- in fact a supercontinent -- was present at the end of the Archean. Kump & Barley (2007). However, if that was the case, then those continents were unstable and disappeared without a trace over the next few hundred My. The majority view is that modern style continents and familiar plate tectonics began not long before the Paleoproterozoic.

Continental shields formed from small cratons. It was during the Paleoproterozoic that small islands of crust were first stitched together to form the stable nuclei of the continents we know today. This may something of an overstatement, since relatively broad islands of Archean stability are found in the rocks northeastern Canada and Greenland (the Laurentian or Canadian Shield), Western Australia (Pilbarra Craton), and South Africa (Kapvaal Craton). These became the nuclei of the North American, Australian, and (in part) African continents, respectively. However, even in these cases, the continental craton in its present form was the product of suturing several smaller units. That suturing process largely occurred in the Paleoproterozoic. In other cases (e.g., India, South America, and North China), both crust and shield were largely products of the Paleoproterozoic.

Now that we have extruded this patently over-broad generalization, we had best defend the thesis with some concrete examples.

For example, the core of South America formed around Amazonia in the Paleoproterozoic. The geologically stable core of South America is the Amazonian craton, roughly coterminous with northern and central Brazil and the inland areas of Venezuela, both Guyanas, and Suriname. Most of western South America is composed of ephemeral orogenic mountain ranges which come and go on timescales of a few 100 My. Other bits and pieces have joined (Uruguay) or left (Central Texas?) Amazonia at various times in the geological past. However, the unchanging hub of all this activity was Amazonia. The only other significant cratons now associated with South America, the São Francisco and Rio de la Plata, are both immigrants from Africa. Iacumin ***et al.*** (2001).

The only large stretches of Archean basement remaining in Amazonia are located in the eastern section of Amazonia, mostly in the southeastern corner. Most of the rest of Amazonia was intruded and sutured together in the Paleoproterozoic. The only significant exception is the northwestern Rio Negro Province, which lies along the Brazilian-Columbian border. This province formed as an extension of Amazonia in the Mesoproterozoic. Tassinari & Macambira (1999); Sial ***et al.*** (1999). For the subsequent development of the region, ***see*** Brito Neves ***et al***. (1999).



Baltica, the core of Europe, formed from the merger of three cratons in the Paleoproterozoic. The formation of Baltica - the continent which was to become Europe -- is one of the best-known examples. Baltica formed in the Paleoproterozoic from the fusion of three cratons: Fennoscandia (Scandinavia, the Baltics, Belarus, Eastern Poland, part of Scotland, and northern European Russia), Volgo-Uralia (the Volga Basin of Russia), and Sarmatia (the Trans-Caucasus region, the Ukraine, Moldavia and part of Romania). Gee & Stephenson (2006). The process of consolidation was complete by the end of the Paleoproterozoic. Virtually all further growth in the Proterozoic came by way of extensional tectonics and the incorporation of bits and pieces of other adjacent continents. Bingen ***et al***. (2008).

India has a similar history. Similarly, India appears to be an amalgamation of four cratons. One of these is a small, late accretion to the southern tip (southern Tamil Nadu and Kerala). The rest consists of three Archean cratons which consolidated at the end of the Paleoproterozoic. Sankaran (1999).

The shift in continent-building style is correlated with a shift in large volcanic belts from marine to terrestrial settings. Recently Kump & Barley (2007), devised an ingenious test of the general concept. They collected a large database of reasonably characterized "large igneous provinces." LIPs are broad areas of volcanic activity. They are usually manifestations of the chafing and irritation which occurs when two cratons come in contact. During the Archean, the vast majority (80% or more) of LIPs happened under water. At the beginning of the Proterozoic, the proportions abruptly reverse. About 80% of known Proterozoic LIPs were terrestrial. The most parsimonious explanation is that cratons were now consolidating, so that the boundaries between adjacent cratons most often lay in the interior of larger masses -- continents.

The trigger may have been the accumulation of a critical amount of rigid continental crust. In fact, something more fundamental may have happened -- a change in the tectonic behavior of cratons somewhat analogous to a change of state between two crystal forms. The break between Archean and Proterozoic LIP locations is quite sharp, and the ~80% level is fairly steady for the rest of Earth history. The Early Paleoproterozoic is also the earliest time that normal plate boundaries, boundaries between essentially rigid crust elements, are seen in the geological record. Stanley (1998). Stanley also notes that the total volume of continental crust first approached present value at the end of the Archean. It seems likely that the volume of continental crust, the formation of continental shields, and the development of "normal" plate tectonics are related, although the mechanics have not been worked out. ATW090224.

Geology and Geochemistry

Introduction to the Jargon

The Great Oxygenation Event: oxygen in the atmosphere and formation of an ozone layer which blocked ultraviolet radiation. The most significant event of the Paleoproterozoic is surely the Great Oxygenation Event. Shortly after the beginning of the Paleoproterozoic, something drastic happened (or began to happen) to the atmosphere. Oxygen increased from being an insignificant trace gas to at least 0.001% of its present level, and probably to between 1% and 10% of the present atmospheric level. Even the 0.001% number would cause the formation of an ozone layer, which would block lethal short wavelength ultraviolet radiation from reaching the surface. It would also supply enough oxygen to the surface waters to permit the evolution of bacteria with the ability to live by using oxygen to digest organic compounds. Presumably, all this was due to the evolution of oxygen-producing cyanobacteria.

Most of the data is geochemical. Most of what we actually know about the Paleoproterozoic is geochemistry. This, admittedly, is dull stuff. A couple of paragraphs might have been enough to stupefy your average ravening horde of Mongol invaders ***and*** their horses. We are also bitterly and resentfully aware that Andrew H. Knoll of Harvard is the only living organism with the ability to write clearly on this subject. This is monstrously unfair. Worse, much as we would like to pass the buck – even to some Yankee wingnut who wears two wristwatches – it has simply become too important for us to ignore.

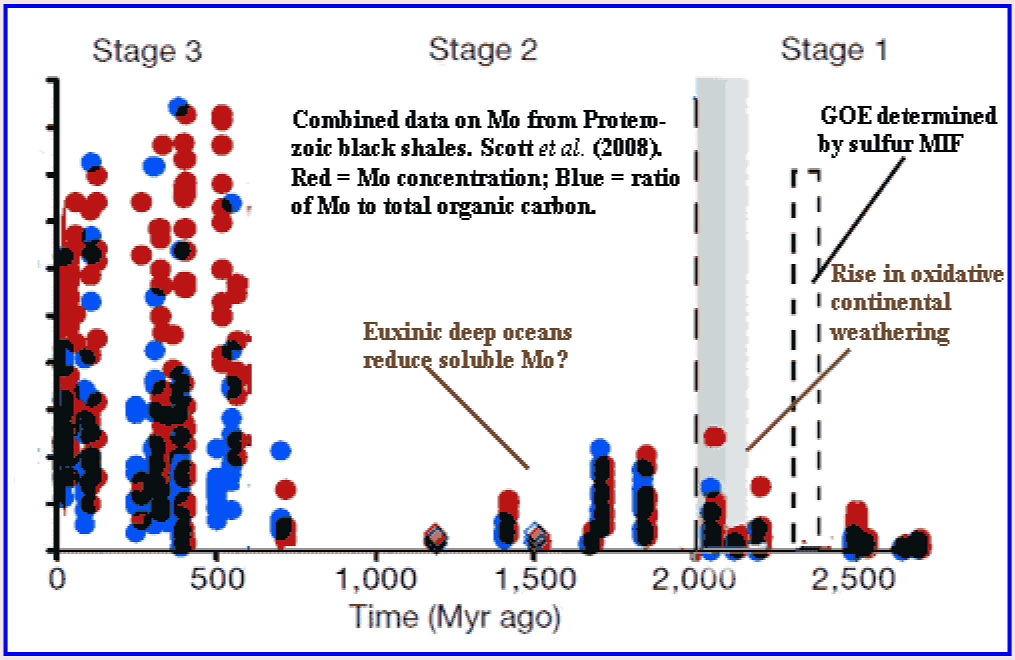
An example of geochemical jargon. Geochemistry tends to be written in an alien jargon, rich in subscripts and allusions to the inorganic chemistry we all forgot after freshman year. Consider the following from Bekker ***et al.*** (2004):

> Sedimentary successions of age ≥2.45Gyr include placer deposits that contain detrital uraninite, siderite and pyrite, reduced shallow-water facies of iron formations, highly carbonaceous shales that are not enriched in redox-sensitive elements and palaeosols that are not oxidized.
>
> Early diagenetic pyrite in these successions has $\delta^{34}S$ values consistent with a seawater sulphate content of <200 µM ... . In contrast, sedimentary successions younger than 2.22Gyr contain red beds, $CaSO_4$-rich evaporites, and shallow-water iron formations that are oxidized. These successions overlie oxidized palaeosols and have $\delta^{34}S$ records that are consistent with seawater sulphate concentrations >200 µM.
>
> ... The recent discovery of mass independent fractionation (MIF) in sulphur isotopes has provided a new tool for tracing changes in the oxygen content of the atmosphere. Sulphur of sulphides and sulphates from sedimentary units older than 2.47 Gyr has values of MIF (expressed in terms of $\Delta^{33}S$) ranging from -2.5‰ to

+8.1‰ ... . The only known mechanism for producing MIF in sulphur isotopes is photodissociation in the gas phase ... . Preservation of large MIF signals in the Archean record is probably related to the lack of an ozone shield in the atmosphere, allowing deep penetration of high energy ultraviolet and photochemical dissociation of SO_2 into elemental and water-soluble S species. ATW090224.

Oxidation State (of Sulfur and Other Things)

An increase in oxidation level of many elements by 2200 Mya. The first point is not so hard. The authors are talking about previous work on compounds (uranium, sulfur, iron) which have more than one oxidation state. Before the Paleoproterozoic and in the earliest Siderian (i.e. ≥2450 Mya), these elements tend to be found in reduced form. After the Early Rhyacian (i.e. younger than 2220 Mya), these elements are more often found in their oxidized forms. The most natural explanation for the increase in oxidation levels is an increase in oxygen. Canfield (2005). The implication is that that oxygen became more common in the Paleoproterozoic than it had been in the Archean.



Oxygen did not reach the deep ocean. It is important to keep in mind, however, that this oxygenation was probably restricted to the atmosphere and the surface waters. In the depths, and even in the relatively shallow waters of the outer continental shelves, the oceans remained anoxic. At least most workers seem to think so. There are some possible dissenters (***e.g.*** Rouxel ***et al.***, 2005). Sadly, we confess to being rather vague on ***why*** the depths remained anoxic throughout the entire Proterozoic. Since some ocean mixing was bound to occur, considerable oxygen must surely have reached ocean bottoms at some point in the roughly 1.6 ***billion*** years between the GOE and the end of the Proterozoic. It follows that something was removing this oxygen with high efficiency. The oxygen sink is thought to be iron, but the mechanism eludes us.

The deep oceans were anoxic and sulfidic. Poulton ***et al.*** (2004) note that banded iron formations peter out at the base of the Statherian Period (about 1800 Mya), and that the deep ocean becomes sulfidic about the same time. ***See also*** Anbar & Knoll (2002). They favor a mechanism in which small amounts of atmospheric oxygen caused weathering of sulfur as sulphates (SO_4^{-2}). This was washed into the ocean, and reacted with dissolved iron, re-reducing the sulfur and oxidizing the iron. Both were then deposited as insoluble pyrite (= iron sulfide, FeS). But things are probably more complicated, and there are many opinions about the particulars of the process (***e.g.***, Canfield (2005); Anbar & Knoll (2005)). It seems likely that the process, whatever it was, was mediated by bacteria. Anbar & Knoll (2002); Rouxel ***et al.*** (2005). A remarkable variety of bugs are capable of using (and thus reducing) ferrous iron and other metals to oxidize organic compounds. Kieft ***et al.*** (1999). However, if we are to understand why banded iron deposition was replaced by sulfidic waters and pyrite iron deposition after 1800 Mya, we'd have to have a good handle on how and why banded iron formed in the first place. But banded iron formations remain very poorly understood. ***See*** Kappler ***et al.*** (2005) for one (randomly chosen) recent hypothesis.

Molybdenum as a proxy for continental weathering; suggests that there was also a brief, latest-Archean oxygenation. Most recently, two groups have looked at ancient molybdenum (Mo). Molybdenum has several useful properties. Most notably, it is introduced into seawater almost entirely by oxidative continental weathering and removed from seawater only in euxinic environments. Both groups therefore attempted to use molybdenum measurements from various Proterozoic black shales (presumably produced in euxinic environments) as a proxy for oxidative weathering. Anbar ***et al.*** (2007) examined latest Neoarchean shales in Australia. Their findings suggest that a minor oxidation event, the "Whiff" episode likely occurred even before the Paleoproterozoic. Two days before this paragraph was written (090222) an important confirming paper was published, which we have not yet seen.

The Paleoproterozoic history of molybdenum may indicate a slow, late rise in oxygen, rather than a sudden GOE. The results from the second group, Scott ***et al***. (2008) are summarized in the image. Note the very broad, low peak extending from the latest Archean and continuing into the Mesoproterozoic. The authors argue that the late Paleoproterozoic decline in Mo is due to the spread of deep-water sulfidic conditions. That is, the later Paleoproterozoic oceans had a great deal of euxinic water which depleted the available molybdenum. On the other hand, Scott ***et al***. don't really explain why Mo mobilization peaks so long (200-300 My) ***after*** the conventional date of the GOE, as determined from sulfur MIF (discussed below). We suspect that, like the banded iron story, this is an indication that the actual rise of atmospheric oxygen was an extremely slow process. The GOE, as measured by the usual isotopic proxies, may represent only an early stage -- and not even the earliest stage -- of a development which continued throughout the Paleoproterozoic. For the time being, just keep that suspicion in mind. After much more tedious isotopic analysis, we'll develop the thought a bit more in the Bacteria section. ATW090224.

Sulfur Geochemistry

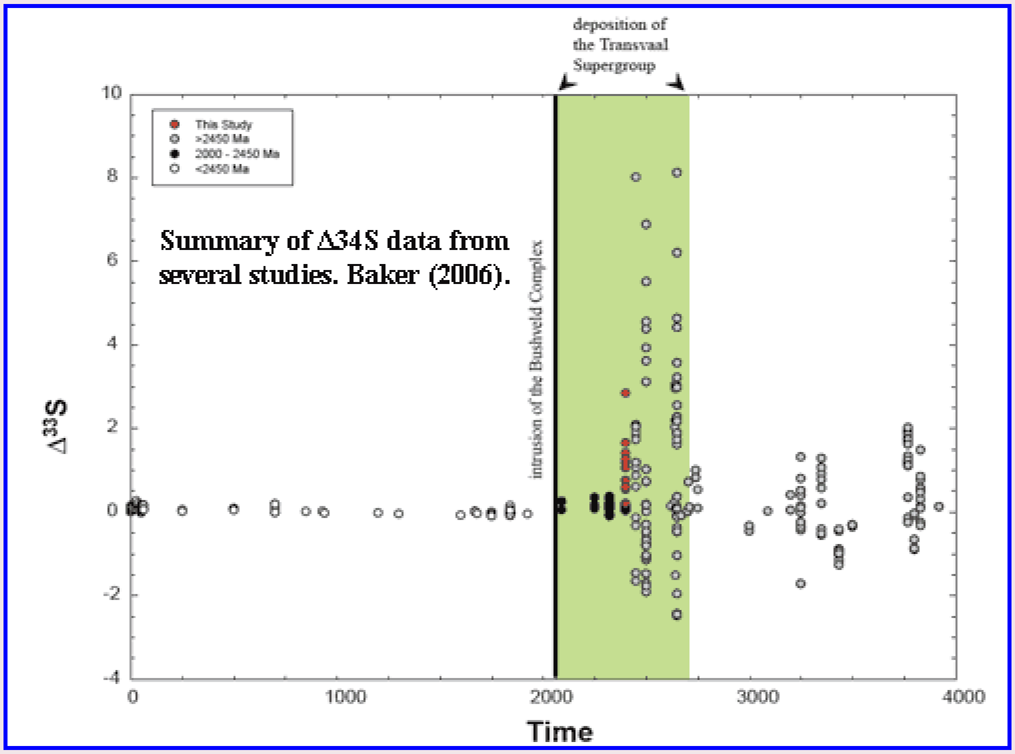
Sulfur Isotope Fractionation

Some reactions tend to separate ("fractionate") naturally-occurring isotopes. But, returning to our quotation from Bekker ***et al.*** (2004), what is this "$\delta^{34}S$" stuff? Sulfur has four stable isotopes: ^{32}S, ^{33}S, ^{34}S, and ^{36}S. The light (^{32}S) isotope, has 16 protons and 16 neutrons in its nucleus. The other isotopes differ in having more neutrons. ^{32}S accounts for 95% of all sulfur atoms on Earth. Most of the rest is ^{34}S. Thus, when looking at isotope ratios, it is often convenient to look at $^{34}S/^{32}S$, compared to the same ratio in a standard material. That comparison (skipping a lot of annoying computation) is expressed as ***$\delta^{34}S$*** **[4]**. The $\delta^{34}S$ differs among materials in nature because some naturally occurring reactions run slightly faster with one isotope than with another. A reaction which favors one isotope over another, leaving a product with an altered isotope ratio, is said to ***fractionate*** the element.

An example of a biological mechanism which fractionates sulfur. For example, some bacteria fractionate sulfur by converting sulfur or sulfides (***e.g.*** hydrogen sulfide gas, H_2S) into sulfates. Compare the behavior of two hydrogen sulfide molecules, one with ^{32}S (light), and the other with ^{34}S (heavy) sulfur. Recall that the mass of a molecule is virtually all in the nuclei, while size, shape and chemistry is virtually all determined by the outer electron shell. The light molecule, having 2 fewer neutrons, is ~6% lighter than the heavy molecule. But molecules of H_2S have the same size, regardless of the sulfur isotope, since their electron clouds are the same; and the outer electron cloud determines size, shape, and chemical reactivity. Now, at the molecular level, temperature reflects the average kinetic energy (= $mv^2/2$) of the molecules in the medium. Thus, on average, the lighter molecules move faster (by 2.5% in this case) at any given temperature. Since the light and heavy molecules are the same size and shape, the faster-moving light molecules, sweep out a larger volume (7.7% larger in this case) in any given time interval. Consequently, the light hydrogen sulfide molecules are more likely to run into a bacterial enzyme and be converted to sulfate. Over time, we may find that sulphates are relatively enriched in ^{32}S ("light"), while sulfides are relatively enriched in ^{34}S ("heavy") sulfur.

Fractionation results reflect competing reactions and may be hard to interpret. However, life isn't that simple. There are other bacteria which perform the reverse reaction and reduce sulfates to sulfides. Non-biological reactions may also produce, bury, oxidize, or reduce sulfur. All of these processes fractionate sulfur to one degree or another. In fact, generally speaking, $\delta^{34}S$ tends to be high when the environment has lots of sulfate, oxygen, and biological activity. Sulfates from the Rhyacian and later have a significantly higher $\delta^{34}S$ than Archean sulfur. This is useful, but a little vague, since lots of different factors can fractionate sulfur (that is, enrich one isotope with respect to another). ATW090224.

Mass-Independent Fractionation



A very few reactions fractionate sulfur isotopes based on factors other than atomic mass. Thus, discussions of sulfur isotope fractionation in the Proterozoic became highly technical, complex, and unsatisfactory by about 2000. ***See*** review by Canfield & Raiswell (1999). However, a few reactions exhibit "mass-independent fractionation." These reactions tend to react preferentially with different isotopes based on nuclear spin states, thermal neutron cross-section, and ... but who are we kidding? You have no idea what we're talking about, and neither do we. The point is that these are subtle quantum properties which do not relate to mass in the simple way explained above.

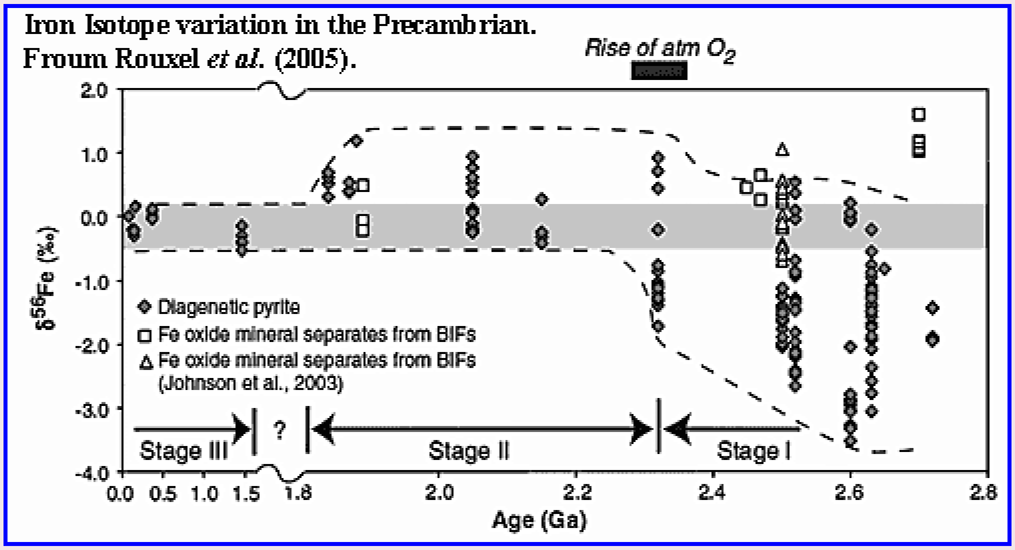
These mass-independent fractionation (MIF) reactions are caused by ultraviolet radiation. Significantly, the only reactions likely to cause mass-independent fractionation under natural conditions are high-energy photochemical reactions. For these reactions to occur ***at all***, highly energetic photons (that is, short wavelength ultraviolet light) must penetrate deep into the atmosphere to react with atmospheric sulfur near the surface. In an atmosphere with more than trace amounts of oxygen, atmospheric sulfur is rapidly (by geological standards) oxidized to sulfate and removed to surface water as acid rain. Furthermore, high energy UV never gets low enough to react with this sulfur, since it is absorbed by an ozone layer.

MIF, and thus UV radiation, can be determined separately from other fractionation. Thus the very existence of mass independent fractionation would tell us a lot -- if we could separate it out from other types of isotope fractionation. We can do just that, because sulfur has ***multiple*** stable isotopes. Imagine some environmental mass-dependent fractionation which favors ^{33}S over ^{32}S. The result is a product which is enriched in the heavier ^{33}S. Since the reaction is mass-dependent, the product will be even more enriched in the even heavier ^{34}S isotope. In fact, the product should be about twice as enriched in ^{34}S, since ^{34}S has two more neutrons than ^{32}S, while ^{33}S has only one extra neutron. Experiments show that this is approximately correct. $\delta^{33}S$ and $\delta^{34}S$ are related in a very simple, linear way for all mass-dependent isotope fractionations. If we plot $\delta^{33}S$ against $\delta^{34}S$ for a series of samples, we get a straight line with a characteristic slope (~1.94), no matter what combination of mass-dependent mechanisms caused the fractionation.

Variation from the characteristic mass-dependent line is expressed as $\boldsymbol{\Delta^{34}S}$. Any non-zero $\Delta^{34}S$ signals mass-independent sulfur isotope fractionation. If the plot of $\delta^{33}S$ against $\delta^{34}S$ does ***not*** yield a straight line, or if the slope is different from 1.94, then $\Delta^{34}S \neq 0$, and we have strong evidence of mass-independent fractionation -- and thus evidence of an oxygen-poor, sulfur-rich atmosphere, with deep UV penetration. (For a more carefully structured explanation of all this, see Baker, 2006).

MIF ends about 2300 Mya, thus free oxygen and an ozone layer must have been present. The point of all this is that mass-independent fractionation is detectable throughout the Archean Eon and in the Siderian period of the Paleoproterozoic. Farquhar ***et al***. (2007). After a relatively brief transition (roughly, the Rhyacian) mass-independent sulfur isotope sorting disappears. Bekker ***et al.*** (2004). According to the sulfur data, the transition must have begun shortly after 2450 Mya and before 2330 Mya. Certainly by 2000 Mya (Orosirian Period), the atmosphere contained significant free oxygen. This does not mean ***lots*** of oxygen. It may have been as little as 0.0002% of the atmosphere (Holland, 2003) -- but enough so that near-surface UV-driven photochemical reactions were blocked by ozone and swamped by seawater sulfate reactions. ATW090224.

Iron Geochemistry



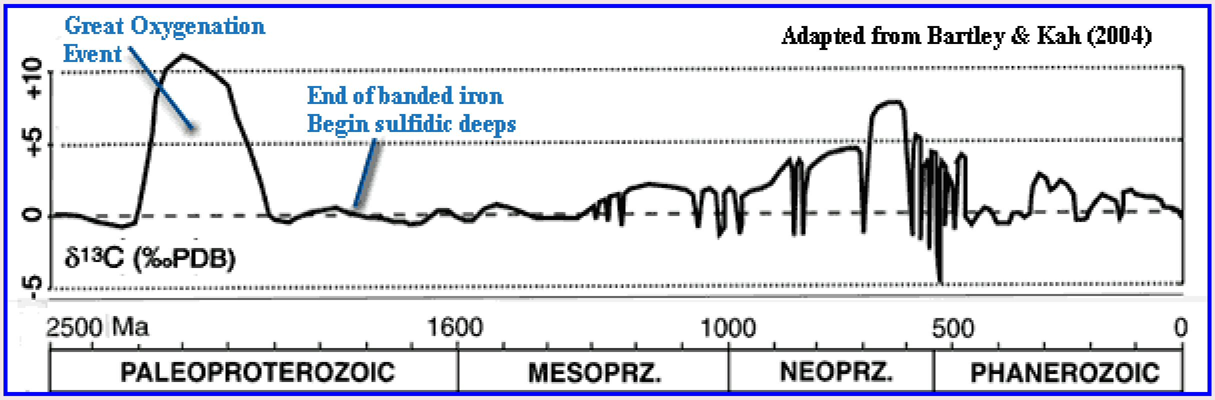
Oxidized iron is also found by 2300 Mya. This timing is generally confirmed from analysis of iron minerals. The 2320 My Timeball Hill Formation in South Africa, one of the units studied by Bekker's Group, contains "a large body of shallow-water hematitic ironstone ore," implying the presence of enough oxygen to oxidize iron to ferric oxide (Fe_2O_3). Holland (2003).

Again, this does not apply to the deep ocean. Holland points out that this oxidation may only apply to the ocean surface waters, as mentioned above. Unoxidized, banded iron formations, continued to form in deeper waters until about 1700 or 1800 Mya (later Statherian Period). Holland (2003); Poulton ***et al***. (2004).

The later history of iron reflects slow oxygenation, not a sudden GOE. Rouxel ***et al.*** (2005) looked at iron isotope fractionation and believe that they can identify three "Iron Ages": (1) an Archean regime dominated by banded iron deposition, with the highly variable, generally negative, δ^{56}Fe characteristic of geothermal releases; (2) an intermediate stage; and (3) a post-1800 Mya period with higher, stable values characteristic of iron supplied by terrestrial weathering. However, as these authors note, there is an odd break in the deposition of banded iron between 2300 and 2100 (***i.e.***, over the Rhyacian). After this, banded iron is formed again until the Statherian, but the δ^{56}Fe signal is now positive and less variable. Rouxel & Co. interpret this as signifying that the iron in Late Orosirian banded iron was dominated by terrestrial sources for some reason. Yet the isotopes remained incompletely homogenized. This seems odd, but it dovetails ever so sweetly with the results of Kump & Barley (2007) discussed earlier. This should be, partially, iron contributed from the spreading terrestrial LIPs --now exposed to a tiny, but increasing, amount of oxygen weathering. This is another important indicator that the GOE was somewhat slower and later than is usually supposed. ATW090224.

Carbon Geochemistry

Sulfur records the passing of an oxygen threshold -- somewhere in the vicinity of 10^{-5} times the present atmospheric level. The carbon record suggests that this level continued to rise.



The GOE as measured by carbon isotopes. Carbon has two stable isotopes, ^{12}C and ^{13}C **[5]**. Enrichment in ^{13}C can be expressed as $\delta^{13}C$, in the same way that an excess of ^{33}S can be expressed as $\delta^{33}S$. There is some continuing debate about the fine points, but universal agreement that $\delta^{13}C$ from marine carbonates shows an enormous peak (a "positive excursion") between 2300 and 2000 My (Late Rhyacian and Early Orosirian Periods). Possibly, this represents two or more closely spaced peaks. One common interpretation of this event is that it represents the creation of a great deal of free oxygen by photosynthetic bacteria. The assumption here is that such bacteria preferentially fixed light (^{12}C) carbon into organic products (as they do today), leaving the atmosphere enriched in heavy (^{13}C) carbon, which was then incorporated into marine carbonates. Holland (2003). Interestingly, the loss of mass-independent sulfur isotope fractionation precedes the positive $\delta^{13}C$ excursion by at least 150 My. Bekker ***et al***. (2005).

Carbon isotope fractionation doesn't necessarily imply widespread photosynthesis. Unfortunately, many natural processes can cause changes in $\delta^{13}C$. These processes include changes in: terrestrial weathering rates, ocean pH, temperature, tectonic activity, volcanic activity, availability of reduced metals, ocean depth, and ocean stratification, in addition to biological carbon fractionation. Even if we restrict ourselves to biological fractionation, we're in trouble. We have little idea of the biochemistry of organisms living more than two billion years ago. We associate biological carbon fractionation today with photosynthesis. Yet we have no guarantee that photosynthesis today follows quite the same biochemical pathways it used two billion years ago. As recently as the Miocene, a minor change in photosynthetic pathways in one plant clade (grasses) caused measurable shifts in $\delta^{13}C$ **[6]**.

We don't even have a guarantee that the dominant biological fractionation reaction was photosynthesis. It may have been, for example, fixation of methane and/or formaldehyde -- both of which may have been much more common at the end of the Archean than they are today. Goldblatt ***et al***. (2006); Fuerst (2005). Recall also that any biogenic $\delta^{13}C$ signal is a function of both biological activity and the selectivity of the biochemical reactions involved. In other words, the critters causing ^{12}C depletion need not have been all that common, if their biochemistry was very efficient at separating light carbon atoms from heavy carbon atoms. Since the current data on Paleoproterozoic biochemistry are rather limited -- to say the least -- we simply don't know enough to draw confident conclusions.

Methane metabolism may be a better explanation for the carbon peak. One thing we ***do*** know is that methane metabolism has a much stronger tendency to fractionate carbon isotopes than does photosynthesis. Methane is also a stronger "greenhouse gas" than is carbon dioxide. For that reason, a good many researchers have played with the potential significance of methane for the GOE. The usual snowball crew have argued that the Late Archean was a "methane hothouse," and that the GOE supplied oxygen for a huge drawdown of methane, resulting in a global ice age, etc. Kopp ***et al***. (2005). While we tend to be a little suspicious of global ice ages, we have no reason to doubt the methane drawdown. Thus the huge $\delta^{13}C$ excursion of 2300-2100 Mya doesn't necessarily require an increase in oxygen much above the ~0.001% of present levels necessary to start forming an ozone shield. We suspect that global photosynthetic productivity was much lower than it is today. Perhaps the GOE was a very slow and dignified affair. The steps which appear geochemically sudden may only reflect the smooth and stately crossing of successive oxygen thresholds -- not sudden increases in oxygen.

A mathematical model suggests an initial slow increase in oxygen *and* a GOE. Then again, maybe not. Goldblatt ***et al***. (2006) have devised an interesting mathematical model. Or, at least, it would probably be interesting if we had the vaguest comprehension of the mathematical underpinnings; but we don't. They look a bit like strongly non-linear differential equations fitted to some very rough empirical numbers -- but we're only guessing. Their bottom line is that predicted atmospheric oxygen has two stable solutions. Their assertion is that oxygen levels increased slowly and smoothly until the early Paleoproterozoic, when the ozone layer formed. This triggered a switch to a higher-oxygen regime (1-10% of PAL) with a transient increase ***or*** decrease in methane. One of the main problems with this model is that it cannot explain the geochemical iron record; but it does demonstrate the kinds of erratic atmospheric behavior which might have occurred as a result of initially slow increases in oxygen. ATW090224.

Calendar

The four periods of the Paleoproterozoic might be thought of in the following way.

Siderian: Fully modern plate tectonics; formation of ozone layer.

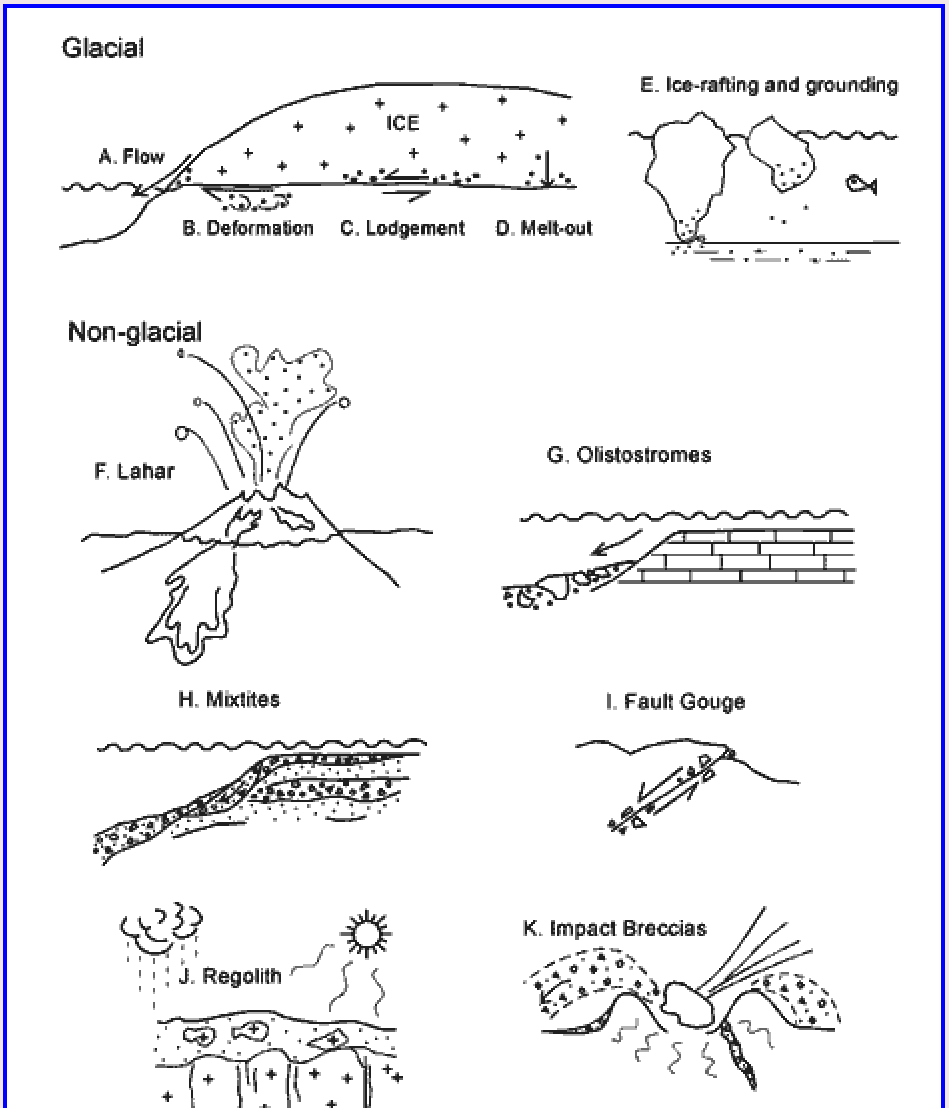
Rhyacian: GOE; hiatus in banded iron; spread of cyanobacteria with at least some (1 x 10 PAL) atmospheric oxygen.

Orosirian: continental weathering develops; banded iron deposition resumes

Statherian: Sulfidic deep ocean; no banded iron deposition; eukaryotes (acritarchs) present.

Date (Mya)	Era	Period	Events
1500	Mesoproterozoic	Calymmian	
1550			
1600			
1650	Paleoproterozoic	Statherian	
1700			Definitive appearance of simple, sphaeromorphic acritarchs. Knoll (1994); Huntley ***et al.*** (2006).
1750			Sulfate-depleted oceans (condition may have begun much earlier). Brocks ***et al***. (2005).
1800			Possible appearance of simple, sphaeromorphic acritarchs (***Valeria***). Hofmann (1999). Begin low (modern) levels of δ^{56}Fe. Rouxel ***et al.***(2005).
1850		Orosirian	End of banded iron deposition. Holland (2003). Sulfidic deep oceans with pyrite deposition. Anbar & Knoll (2002). ***Grypania*** definitely present. Bengtson (2002).
1900			
1950			
2000			
2050			End of large δ^{13}C excursion. Baker (2006). Increased Mo and Mo/TOC (total organic carbon) ratio from continental oxidative weathering. Scott ***et al.***(2008).
2100		Rhyacian	Banded iron deposition resumes. Rouxel ***et al.*** (2005).
2150			
2200			First manganese (Mn IV) deposits. Kopp ***et al***. (2005). Peak of large δ^{13}C excursion. Baker (2006). Possible appearance of eukaryote ***Grypania***. Han & Runnegar (1992).
2250			Placer deposits of reduced minerals become much rarer. Makganyene glaciation (±50My) of Kopp ***et al***. (2005).
2300			Some sedimentary sulfide δ^{34}S-45‰, seawater sulfate >1mM. Suggests sulfate-reducing bacteria with sulfate not limiting. Canfield & Raiswell (1999). Beginning of large δ^{13}C excursion. Baker (2006). Break in banded iron deposition begins. Rouxel ***et al.*** (2005).
2350		Siderian	Intermediate δ^{56}Fe levels begin. Rouxel ***et al.*** (2005).
2400			Transition to zero mass-independent fractionation of sulfur (±50My). Baker (2006). Huronian glaciations (±50My). Kopp ***et al***. (2005). Makganyene glaciation of Kirschvink ***et al.*** (2000).
2450			Frequent placer deposits of reduced minerals still dominate. Bekker ***et al.*** (2004).
2500			Sedimentary sulfide δ^{34}S at-8 to -10‰, seawater sulfate <1mM . Canfield & Raiswell (1999). Terrestrial LIPs begin to dominate dominate. Kump & Barley (2007).
2550	Neoarchean		"Whiff" episode -- a possible early, not-so-great, oxidation event. Anbar ***et al.*** (2007).
2600			

Paleoproterozoic Climate



From Eyles & Januszczak (2004)

Fig. 1. Glacial and nonglacial environments in which diamict facies are produced.

Possible "snowball Earth" episodes at 2400 and/or 2200 Mya. It has become customary to punctuate every discussion of the Proterozoic with exclamatory references to "Snowball Earth" glacial events, like a kind climatological Tourette syndrome. The Paleoproterozoic is no different. The current estimate among snowball aficionados is that the Earth froze up 3 times at various points in the Siderian ("Huronian" glaciations) and once in the Early Rhyacian, between 2200 and 2300 Mya ("Makganyene" glaciation). This is said to be coincident with, and probably related to, the GOE. Kopp ***et al***. (2005). There seems to be some uncertainty about these dates. Kirschvink ***et al.*** (2000) originally dated the Makganyene glaciations to 2400 Mya. This corresponds to the Huronian glaciations of Kopp ***et al***. (2005), but not to Kopp's Makganyene, which he dates to about 2200 Mya. A recent joint paper (Kirschvink & Kopp, 2008) does nothing to resolve the dating problem.

We are dubious about this. We are probably being excessively mistrustful and cynical **[7]**. However, we recommend a close reading of Eyles & Januszczak (2004) for a cold appraisal of snowball earth scenarios. Eyles & Januszczak's critique is largely delivered from a sedimentological perspective; and, if nothing else, you will learn a good deal of useful sedimentology. Their strongest point is that diamictites (poorly sorted conglomerates) and "lonestones" (anomalous large rocks surrounded by sediment layers) are not unique to glacial till and dropstones. ***See*** image. Their bottom line is that most of the evidence for snowball episodes is better interpreted as a heterogeneous collection of regional mass wasting events (landslides, earthquakes, and the like, including -- ***but not limited to*** -- glaciers). Eyles & Januszczak suggest that these may be closely connected with continental rifting.

Fortunately, most of the excellent work reported by both the Kirschvink and Kopp groups has much more relevance to the GOE and the evolution of cyanobacteria than to refrigeration or sedimentology. Accordingly, we will deal with it when we get to those issues. ATW090224.

Paleoproterozoic Life

Bacteria

Did photosynthetic cyanobacteria evolve before the Paleoproterozoic? Just about everyone agrees that the Paleoproterozoic was full of bacteria. Specifically, the Cyanobacteria ("blue-green algae") flourished and caused the Rhyacian (roughly) GOE. However, it is less clear whether cyanobacteria were products of the Paleoproterozoic or just happened to find the era unusually congenial. Evidence from biomarkers and "molecular clock" studies suggest that photosynthetic bacteria were present well back in Archean time.

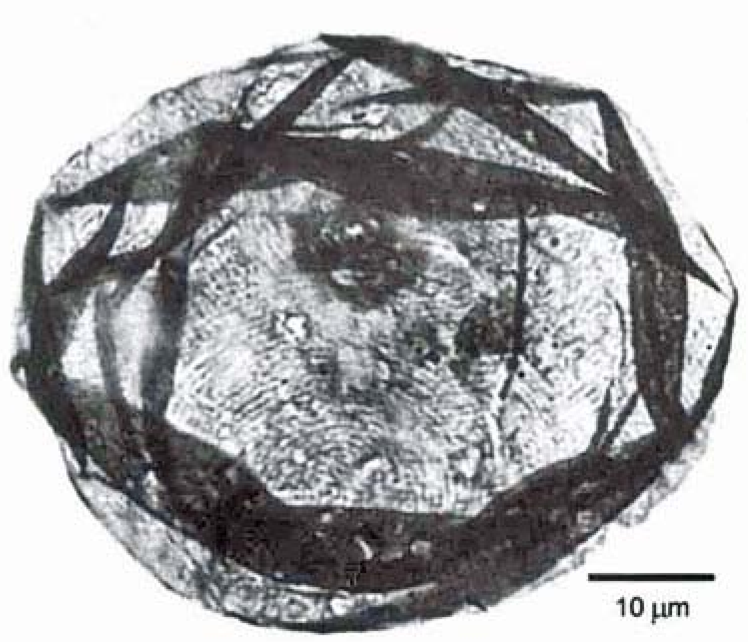
The reader may be aware that we have a deep and unshakable suspicion of molecular clocks **[8]** and some shallower and more easily shaken doubts about "molecular fossils." If so, she will be unsurprised that we do not share this enthusiasm for Archean autotrophs.

Early evolution of photosynthesis is contradicted by the manganese record. On this point, the geochemical evidence collected by Kopp ***et al***. (2005) is worth consideration. These authors point out that the world's earliest and largest manganese deposit cannot be older than 2220 My. This manganese is found as MnO_2, ***i.e.*** with manganese in the insoluble Mn^{4+} (Mn(IV)) oxidation state. Manganese in seawater at more-or-less neutral pH is in the highly soluble Mn^{2+} (Mn(II)) oxidation state. Oxidation from Mn II to Mn IV involves a hefty change in redox potential. That is precisely why manganese is used as the redox "battery" which drives photosystem II and produces free oxygen from water in cyanobacterial photosynthesis. In fact, according to Kopp ***et al***. (2005), photosystem II is the ***only*** naturally-occurring reaction which could explain the geologically sudden accumulation of large amounts of Mn(IV) in one place.

Photosynthesis developed late from the coupling of two pre-existing cycles. This logic compels Kopp ***et al***. to argue that photosynthetic cyanobacteria could not have evolved much earlier than the beginning of the Rhyacian (2300 Mya). This creates a problem, since the sulfur chemistry suggests an earlier date, as discussed above. Fortunately, all is well. One of the most plausible and detailed theories for the evolution of photosynthesis (Allen, 2005) would predict just such a chain of events. The essence is that photosystems I and II were originally independent, homologous ***anaerobic*** reaction systems. In fact, I- and II-like systems are found alone in various bacterial taxa. Alone, photosystem I-like cycles drive drive carbon fixation and oxidize sulfur. Photosystem II-like systems pump protons for ATP synthesis. Oxygen is produced, but it is largely recycled -- with some "leakage." Photosynthesis, as we know it in plants and cyanobacteria, is the reaction system which results when the two photosystems are coupled. When this happens -- abruptly (because it doesn't require much change) -- all of the redox potential from photosystem II becomes available to power carbon fixation. The oxygen from photosystem I is no longer applied to the cytochrome ATP-generating machinery and most can be discarded. Likewise, carbon fixation no longer requires sulfide.

Thus the chain of events involves the evolution and gradual spread of a bacterium with both photosystems in the Siderian or latest Archean. Note that this hypothetical bug is essentially an anaerobic beast, and the two photosystems are not coupled. As this bug spreads, it leaks trace amounts of oxygen (PSII) and oxidizes much of the available H_2S sulfur. However, by the Rhyacian, our bug starts to run out of hydrogen sulfide in the atmosphere and in surface waters. The redox state of the atmosphere has tipped toward oxidation. Continental weathering and outgassing from continental flood basalts (the source of terrestrial large igneous provinces) are pouring sulfates into the air and upper ocean. There is still only a trace of free oxygen, but enough to form an ozone layer. Thus, then, and perhaps only then, would it become strongly advantageous to take high-energy electrons directly from PSII and use them as input for PSI, discarding the oxygen by-product instead of recycling it. Hence: a long period of declining mass-independent sulfur isotope fractionation with only a trace of free oxygen, then a gradual increase in free oxygen and the appearance of oxidized manganese deposits **[9]**.

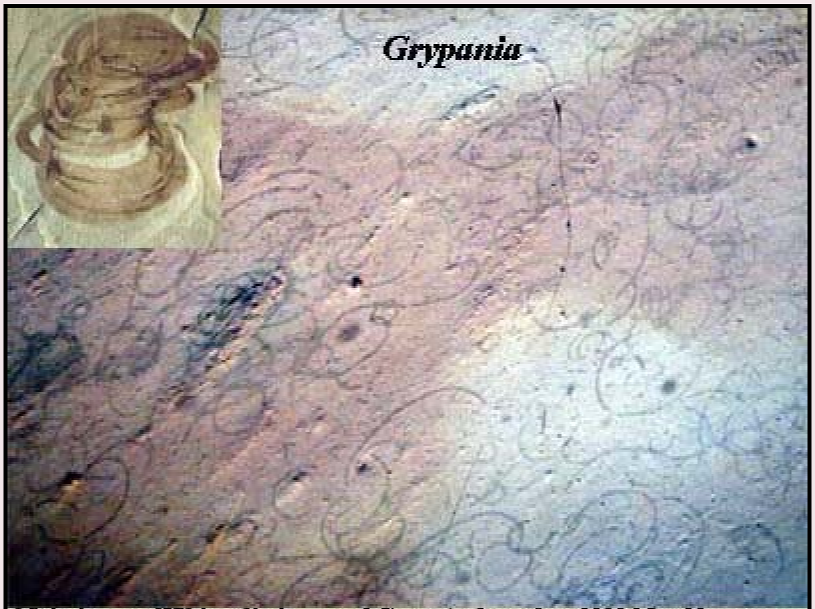
Valeria lophostriata



From Hoffman (1999)

The biomarker evidence for Archean bacteria was found to be contamination. What about those Archean biomarkers? Several papers by Jochen Brocks and others are frequently cited as supporting the presence of photosynthetic bacteria and eukaryotes. Brocks ***et al***. (2003). This work was based on the study of hydrocarbons solvent-extracted from kerogen in shales of the Archean Pilbarra Craton in Australia. However, more recent work by a group of Australian geologists, again including Brocks, casts considerable, probably fatal, doubt on the original results. Rasmussen ***et al***. (2008). The earlier papers had found complex organics which appeared to be breakdown products of chlorophylls and perhaps steroids. Rasmussen's spoilsports compared $\delta^{13}C$ values of the extractable materials to the $\delta^{13}C$ of the bulk kerogen. They also looked at microstructures within the shale. Their results showed that (a) biomarker $\delta^{13}C$ was quite different from the $\delta^{13}C$ of bulk kerogen organics in the rock; that (b) the relatively high (less negative) $\delta^{13}C$ of the biomarkers was typical of organic compounds formed in the Paleoproterozoic or later; and (c) that the kerogen had probably formed under conditions which would have destroyed any biomarkers. Accordingly, the biomarker organics must have entered the shale from elsewhere -- in the Proterozoic, long after the shale was deposited. ATW090224.

Eukaryotes



Main image: Wikimedia image of *Grypania* from the ~2200 Mya Negaunee Iron Fm. of Michigan. Inset: detail of individual from an unknown source.

The evidence for eukaryotes before the very late Paleoproterozoic is not strong. The evidence for eukaryotes in the Paleoproterozoic also looks moderately solid. Then again, so did hedge funds, before 2008. Like hedge funds, eukaryotes are a legitimate part of a balanced and diversified portfolio of ideas about the Paleoproterozoic. However, buying into this evidence -- or into hedge funds -- assumes that one is willing to accept ... certain risks. Notably, their value, in either case, depends strongly on what positions one has already taken and what everyone else in the market happens to believe about them during some given week.

Bengtson (2002: 293-294), wrote that "[t]he earliest fossil now commonly attributed to eukaryotes is the 1.85 billion-year-old Paleoproterozoic ***Grypania***, a coiled, cylindrical organism that may attain half a meter in length and 2 mm in diameter. Because of its complexity and size, ***Grypania*** is commonly interpreted to be a eukaryotic alga." This seems to be the current consensus position. Knoll ***et al***. (2006). Yet, as the image indicates, many workers attribute much older fossils to this genus. Han & Runnegar (1992). Some excellent images of these Michigan specimens may be found at James St. John's (Ohio State Univ., Newark) web site. To us, they look like fission tracks from a Proterozoic cloud chamber, or perhaps Burmese graffiti. ***Grypania*** is interpreted as a eukaryote solely because of its size and relative complexity. Bengston (2002). A few specimens have annular rings suggestive of cellular structures. Knoll ***et al.*** (2006). Those may or may not be good enough reasons.

Simple acritarchs were present by the end of the Paleoproterozoic. More convincing evidence comes only at the very end of the Paleoproterozoic (c. 1700 Mya), in the form of very simple plesiomorphic acritarchs in very low diversity (5-10 species). Knoll (1994); Huntley ***et al.*** (2006). These include ***Valeria lophostriata*** from China perhaps at ~1800 Mya and Australia 1650 Mya. Knoll ***et al***. (2006). See image above from Hofmann (1999). These are round, organic-walled spheres, without processes. Bengston (2002). Acritarchs with distinct processes (***Tappania***) do not appear until slightly after 1500 Mya. Javaux ***et al***. (2001).

The more credible "molecular clock" models also suggest a late -- perhaps very late – Paleoproterozoic origin for eukaryotes. Yoon ***et al.*** (2004). Then again, we probably think this one is credible because it agrees with the other evidence. Even these very late Paleoproterozoic dates may be a shade too aggressive. Porter (2004). However, fossils of this age are so rare that we may never be any more certain. For now, a Statherian origin for eukaryotes seems the most reasonable guess. ATW090224.

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The Mesoproterozoic

"... never in the course of Earth's history did so little happen to so much for so long."

Buick ***et al***. (1995), quoted in Huntley ***et al***. (2006).

The Mesoproterozoic Era of the Proterozoic Eon: 1600 to 1000 million years ago

The Mesoproterozoic was the first period of Earth's history with a respectable geological record. Continents existed in the Paleoproterozoic, but we know little about them. The continental masses of the Mesoproterozoic are more or less the same ones that are with us today. This was the Era of the formation of the first identifiable supercontinent, Rodinia; the first large mountain building episode about which we have detailed knowledge, the Grenville Orogeny (although the Paleoproterozoic Wopmay Orogeny might also qualify); and the high point of the stromatolites, huge mushroom or tree-like colonies of bacteria. It was also the Era when cells discovered sex and, possibly, the joys of communal living as Metazoan organisms. Finally, it was an Era of apparently critical, but still poorly understood, changes in the chemistry of the sea, the sediments of the earth, and the composition of the air. Most significantly, oxygen levels had risen to perhaps 1% of today's levels at the beginning of the Mesoproterozoic and continued rising throughout the Era.

Mesoproterozoic Stratigraphy

The basic outline of Mesoproterozoic history looks like this:

Eon	Era	Period	Began (Mya)	Duration (My)
Proterozoic	Neoproterozoic	Tonian	1000	150
	Mesoproterozoic	Stenian	1200	200
		Ectasian	1400	200

		Calymmian	1600	200
	Paleoproterozoic	Statherian	1800	200

Conical branching Mesoproterozoic stromatolites from the Atar Formation of Mauritania. From the website of Prof. Linda Kah, Univ. of Tennessee.

The subdivisions of the Mesoproterozoic are, obviously, arbitrary divisions based on time. They are not geo- or biostratigraphic units. The base of the Mesoproterozoic is defined chronometrically, in terms of years, rather than by the appearance or disappearance of some organism. This gives us an illusory sense of certainty. Radiometric dating is a good tool, and gets better each decade. However, it creates certain problems. As a practical matter, radiometric dates have an error margin of 1-2%. That sounds good, but it means that two sites, both measured to be at the exact base of the Ectasian, might differ in age by over 50 My. Since the Ectasian is only 200 My long, that's a serious matter. And this accounts only for ***random*** error. Systematic errors can be caused by extraterrestrial events, by geochemical or biochemical sorting of isotopes, and human error. Thus far, biostratigraphy has usually proved considerably more exact. In addition, a thoughtful choice of biological marker can be used as a signal to expect a whole host of ecological changes. The difference between a Changhsingian and an Induan deposit isn't just a matter of a few years. The world changed hugely at the end of the Permian.

By contrast, the transition from Calymmian to Ectasian has no meaning beyond calendar time. The usual reason given for the use of a chronometric system is that we don't have enough biological activity or geochemical change to find useful markers. That is a position which is now a little uncertain and is going to become increasingly tenuous over the next few years. For example, we have a number of good potential markers in the rise and decline of "Christmas tree" stromatolites, in the coming and going of banded iron formations, the appearance of stable carbon isotope (^{13}C) excursions, and so on. These have real meaning for the geologist and paleontologist.

For that matter, we are not completely without biological markers. There has been considerable progress in studying and identifying fossil bacteria and Eukarya. The cyanobacterium ***Archaeoellipsoides*** is one relatively common form, apparently known from several species. It is probably related to the extant ***Anabaena*** and indicates the presence of significant free oxygen. Oxygen levels also had significant effects on ocean chemistry: increasing continental weathering rates and providing sulfates and nitrates as nutrients. It would be remarkable if this didn't result, in turn in new populations of both bacterial and eukaryotic organisms. Since the presence of these cells would be tied directly to important geochemical events, they would make ideal organisms for biostratigraphy.

Clearly, we can't set our clocks by hypothetical organisms depending on, as yet, poorly understood chemistry. We don't know nearly enough about these matters yet. Still, it may not be long before we should think about telling Proterozoic time a different way.

ATW041001.

Resources

Chemistry of the Mesoproterozoic Ocean and Links to Biospheric ... brief & technical, but useful summary of some important geochemistry.

The Grenville. An incredible collection of information and links on the Grenville Orogeny.

Kah - Introduction: the mainpage of Prof Kah's superb website.

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The Ectasian

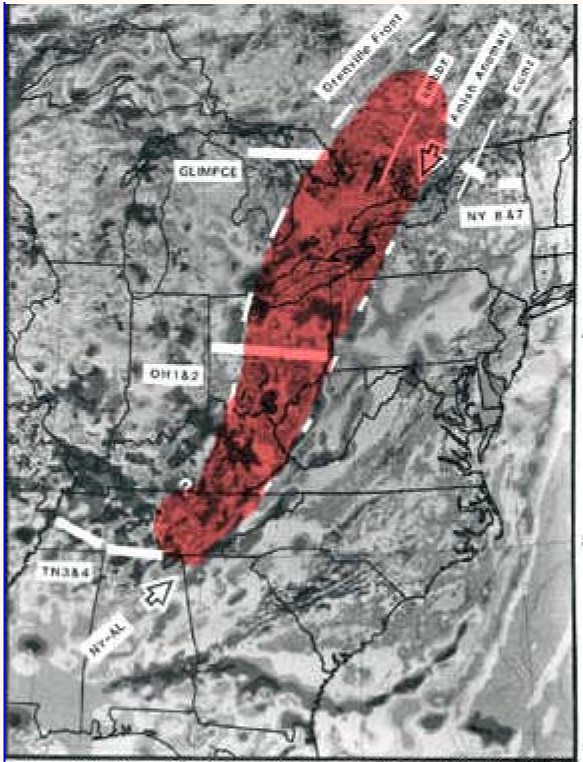
The Ectasian Period of the Mesoproterozoic Era: 1400 to 1200 million years ago

Introduction

The Ectasian may or may not have been an eventful period. However, the end of the Ectasian is the earliest date by which we can be fairly certain that certain really important events had taken place. For example, we do not know when the first eukaryotes evolved, but we can be generally sure that it happened by the end of the Ectasian. The data is not the best; but, as we will see, it is getting better. In fact, we can not only be sure that eukaryotes were present, but that the eukaryotes of 1200 million years ago included both green (Chlorobionta) and red (Rhodophyta) algae. Similarly, we don't know exactly what cratons made up the supercontinent of Rodinia, but we know that it began to assemble by the end of the Ectasian. Further, we now know a good many details about the history of North America, in particular, during this interval. Advanced eukaryotes and supercontinents may have been around for a billion years before the beginning of the Ectasian -- or they may not. However, there is little question that both had developed by the ***end*** of the Ectasian.

Geography

As noted, the Ectasian includes the beginning of the assembly of Rodinia. More particularly, the Grenville Orogeny began in the Late Ectasian, some where between 1300 and 1200 My ago,



Map of Eastern US magnetic anomalies, with Grenville Province in red. Adapted from Culotta *et al.* (1990).

and continued almost through the entire Stenian. A continuous mountain-building episode lasting over 200 My would be difficult to accept; so it is not surprising that the Grenville is probably not a single event, but a series of many events, as various continents and island arcs subducted under, accreted to, or simply bounced off, the eastern and southern margins of North America.

Along the eastern margin of North America, the Grenville orogeny seems to have been complicated and weirdly familiar. It involved at least two episodes in which at least two island arcs attempted, like continent-sized whales, to beach themselves on the North American craton. After considerable confusion and fragmentation, subduction polarity reversed, after which the same arcs were subducted ***under*** the continent. This, in turn, was followed by collision with another continent-sized body, probably Baltica. The net result was a temporary merger between North America and Baltica, with the former island arcs crushed between them. After Rodinia broke up, those same terranes formed the Grenville Province -- a strip about 200 km wide added to North America from the Quebec-Ontario border to Tennessee. Culotta ***et al***. (1990).

The "weirdly familiar" part is that this entire series of events was replayed, in almost every detail, 800 My later during the Acadian Orogeny of Late Ordovician to Mississippian time. This added another 200 km to North America, just east of the Grenville Province. That seems stretch coincidence a bit far. However, we are not aware of anything which would explain the similarity.

Life

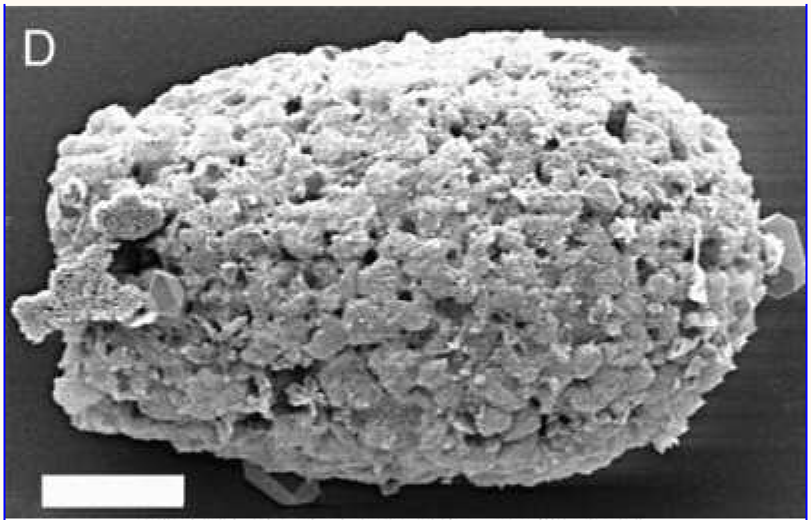
On the current state of the evidence, Eukarya had probably evolved well before the Ectasian. It has become common to cite the 2770 My (Neoarchean) date suggested by Brocks ***et al***. (2003) as the minimum age of Eukarya. While we have serious doubts about this date, it may be sufficient for the present purposes to note that those authors were attempting to estimate the age of the ***stem*** group, badgers > bacteria. That stem is a long one. The same authors show the eukaryotic crown group as younger than 1640 My -- Mesoproterozoic or younger.

Relationship of Groups Mentioned in Text

```
LIFE
|--Bacteria
`--Stem Group Eukarya
   |--Paleoproterozoic acritarchs, etc.
   `--Crown Group Eukarya (s.l.)
      |--Metamonada
      `--Crown Group Eukarya (s.s.)
         |--Plants
         `--Opisthokonta
            |--badgers
            `--people
```

The first solid evidence for ***crown*** group Eukarya (men + Metamonada) is probably the Stenian rhodophyte ***Bangiomorpha***, discussed in the section on Proterozoic acritarchs. Javaux (2006). We aren't going to repeat the basic discussion on acritarchs, and almost all of the probable eukaryotic fossils older than the Neoproterozoic are acritarchs. Thus, so you might want to go back to that one.

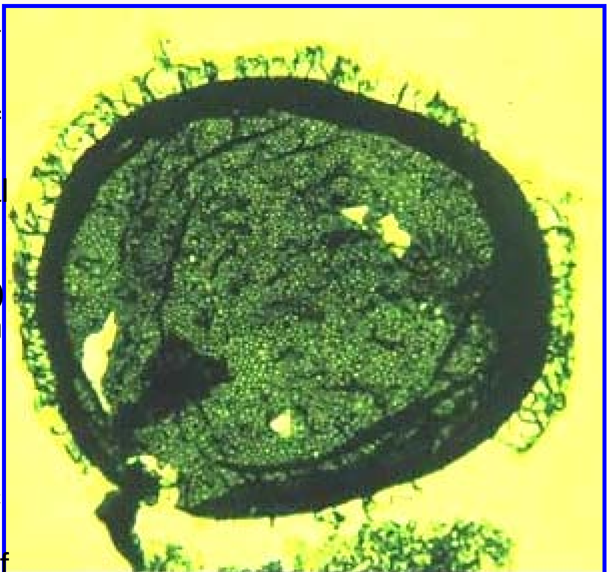
A really conservative definition of the crown group (e.g., people + plants) might even require rigorous evidence for opisthokonts (people > plants). Oddly, no one has identified convincing evidence for opisthokonts at ***any*** point in the Mesoproterozoic. So far as we know, the oldest relevant fossils are Cryogenian (742 My) testate amoebae identified by Porter & Knoll (2000).



Cast of testate amoeba from the Cryogenian of Arizona. Scale bar = 25µ. Porter & Knoll (2000).

So, what organisms left the fossils recovered from the Ectasian? The usual answer is "green algae." However, that's a phylogenetic dodge. The term can mean almost anything from glaucophytes to charophytes. Teyssèdre (2006) makes a very good case for something much closer to land plants than to glaucophytes. His lengthy discussion begins with a pointless attack on a figure from an old paper by Knoll which, as Javaux (2007) has pointed out, probably misapprehends the figure -- and the figure certainly does not represent Knoll's present position. In addition, portions of Teyssèdre's phylogenetic framework are not well supported. All this, and the fact that it was published in French, have ensured that the real substance of his review will be ignored. This is too bad, since it deserves more serious attention.

In essence, Teyssèdre argues that biologists, paleontologists, and biochemists have failed to keep up with each others' progress in this area. Reinterpretation of older work (by, for example, Yin and Shopf) in light of the current understanding of algal diversity and development, allows us to identify these simple Paleoproterozoic acritarchs as as relatively derived charophytes. In particular, Teyssèdre emphasizes the partitioning of the surface, an equatorial zone of weakness, the trilaminar structure of the capsule, and its pronounced aromatic composition. On the last point, we suspect he is mistaken. The organic walls of algae, no matter how resistant, are degraded to kerogen after 1000 My or so, and variations in aromatic content are probably due to variable thermal maturation of kerogens, not to the original composition of the capsule wall. See, ***e.g.***, Wei ***et al***. (2005).



Shuiyousphaeridium, an acritarch from the Mesoproterozoic Ruyang Group of China. From the website of Prof. Shuhai Xiao.

This morphological evidence is still strong enough to make a reasonable case for charophytes in this general time frame – reasonable, although not air-tight. But, speaking of air, the case for these proto-plants is somewhat tightened by models of Proterozoic oxygen which show a sharp rise just before the Ectasian, followed by a steady increase in organic carbon burial during the Ectasian Period. ***See, e.g***. Canfield (2005). This might well occur if, for example, Cyanobacteria were becoming more numerous during the earlier Mesoproterozoic (Calymmian) -- perhaps due to the advantages of some association with stem eukaryotes -- followed by a period in which they began to be put to work as chloroplasts. During this phase, the carbon-fixing capacities of the former bacteria would increasingly serve to construct the structural elements of the larger, eukaryotic cells. Coupling photosynthesis with the construction of eukaryotic structural proteins would not necessarily affect oxygen production, but it ought to result in the sea-bottom burial of more organic carbon.

Unfortunately, all this speculation relies on the fine points of geochemical models which remain somewhat shaky. We will therefore back carefully away from this unstable edifice. Perhaps we will return to it after someone else has done the hard work of establishing a firmer foundation. ATW081005 2008-10-06

The Stenian

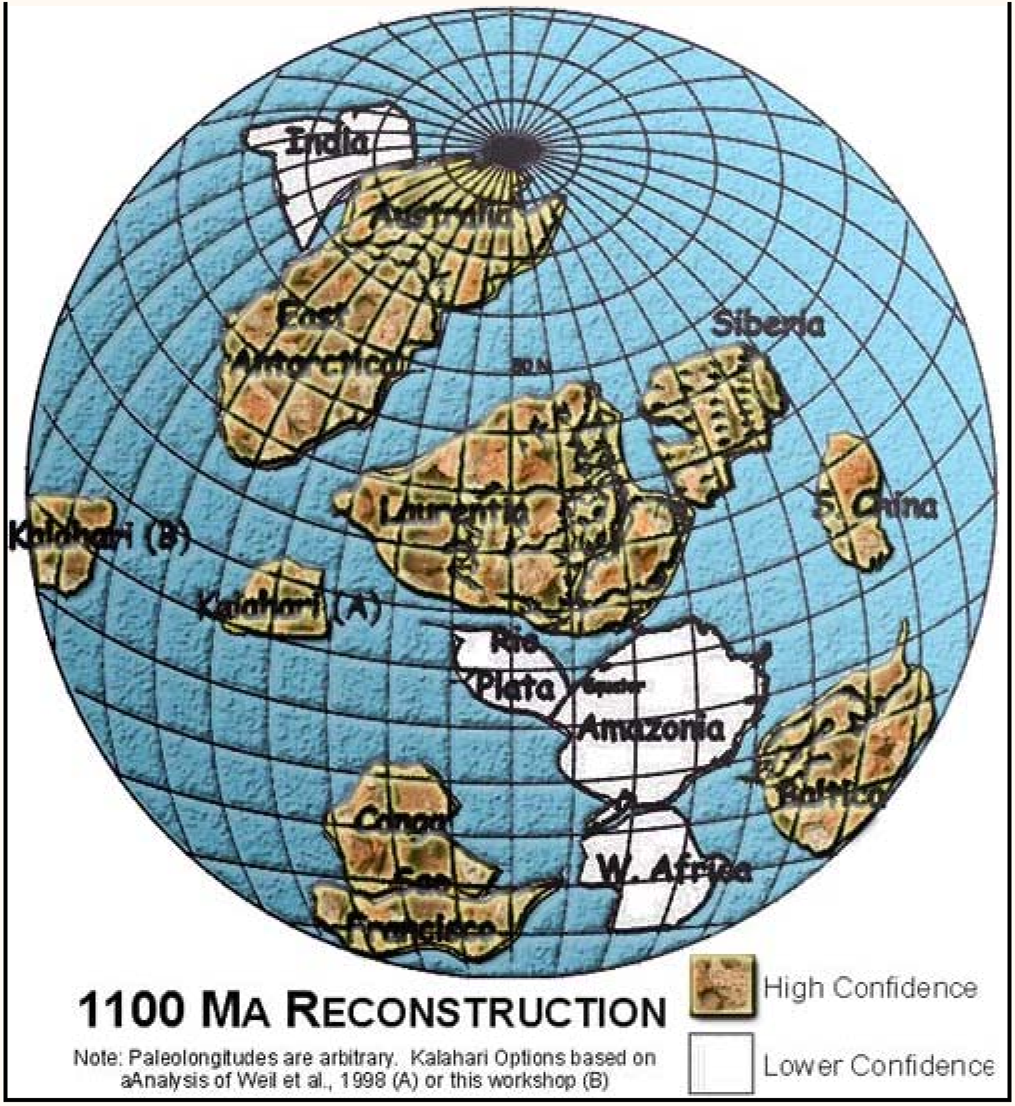
The Stenian Period of the Mesoproterozoic Era: 1200 to 1000 million years ago

Most of the important events we mentioned in the Mesoproterozoic actually occurred in the Stenian, the last Period of the Mesoproterozoic Era. These include the final assembly of the supercontinent of Rodinia, the evolution of sex (probably earlier), and the acme of stromatolite development.

Stenian Geography and the Divine Banana Peel

After much searching we have found a site bold enough to make a stab at a map of the Stenian globe. This reconstruction is adapted from the site of **Prof. Joseph Meert** at the University of Florida, and presumably derives from Pesonen ***et al*** (2003). Prof. Meert, if anyone, appreciates the uncertainties of such a reconstruction. Meert & Torsvik (2003). Nevertheless, this is the state of the art.

As Meert & Torsvik explain, the current reconstructions are based largely on paleomagnetic data which are relatively scarce for rocks this old and which are subject to very significant errors. In fact, the central assumption that the Earth's magnetic field can be modeled as a simple dipole running through the center of the planet has been seriously questioned for dates on the order of 500+ Mya. Meert ***et al***. (2003).

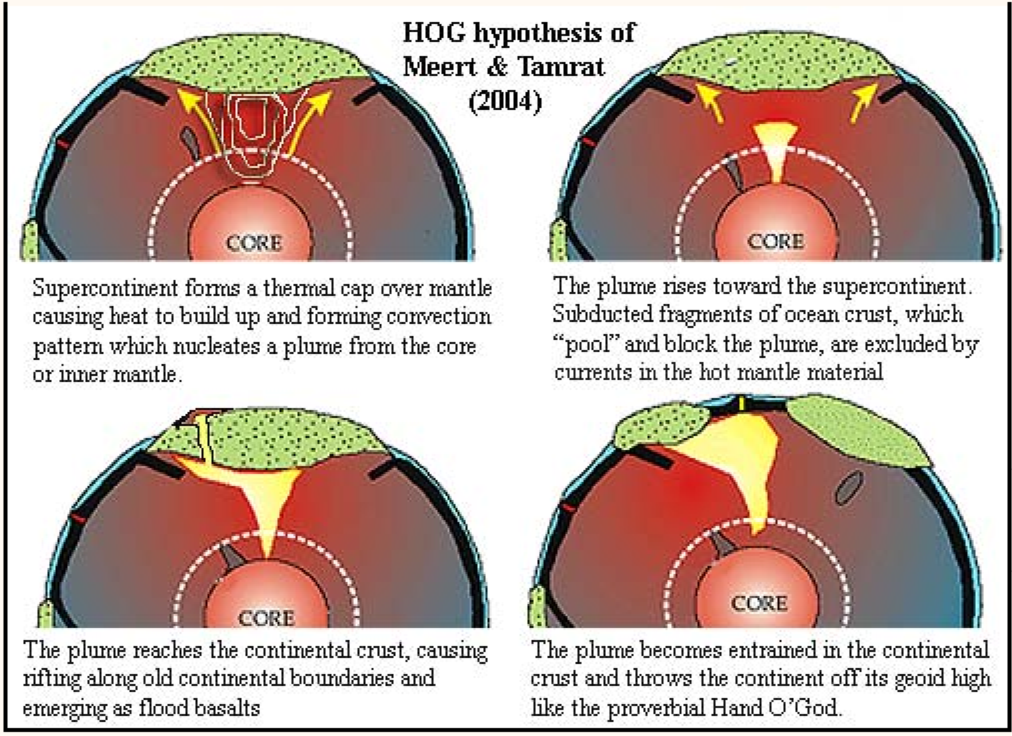


Indeed, unique, almost bizarre, tectonic mechanisms are possible when dealing with supercontinents. Meert & Tamrat (2004). These authors offer (how seriously it is hard to tell) a "Hand O'God" or "HOG" hypothesis. They point out that a supercontinent acts as a large thermal cap on the Earth's surface which tends to trap heat. A supercontinent also represents a physical distortion of the planetary surface with sufficient mass to alter, very slightly, the gravitational field of the Earth. In effect, the continent sits on top of a hill of its own making -- almost literally pulling itself up by its own bootstraps.

The build-up of heat under the mantle initiates, at some point, the formation of convection. The point at which this occurs depends critically on a dimensionless constant, the Rayleigh Number of the mantle material. Unfortunately, this number is not known, even within an order of magnitude, since it is a bit difficult to perform quantitative physical analysis on molten rock at several thousand °C. and millions of atmospheres of pressure. However, reasonable figures are believed to lie in the range of 10^6 to 10^7. In this region convection will occur and will descend to induce a plume within a reasonable geological time, i.e. on the order of 100 My.

This plume rises back up towards the supercontinent (on a similar time scale) and fractures the supercontinent along old lines of continental subduction. The hot plume also becomes trapped under the thickened crust. Thus, within 200 My, a supercontinent creates its own massive hot-spot, setting off catastrophic tectonic activity. Further, the ultra-hot plume effectively grabs the offending continent and throws it off the raised hot spot like the proverbial divine anterior autopodium, wrenching the doomed land mass apart in the process. Meert & Tamrat (2004).

We should pause here to emphasize that the timing is quite uncertain. It seems evident from Honda ***et al***. (2000), on which Meert & Tamrat rely, that the relevant timescale could be anywhere from 10^7 up to



10^{10} years. Without a closer estimate of the Rayleigh number, it is impossible to say. Further, Honda ***et al***. assume constant viscosity, which is an important element of the Rayleigh number. A brief survey of abstracts and lecture notes on the web suggests that mantle viscosities may vary by about two orders of magnitude (by a factor of about 100) depending on depth, heat and chemical composition. In fact, the high temperature, and thus low viscosity, of the plume material may account for the sudden increase in the speed of plate movements as the plume material builds up under the continental mass. So, this may be less the hand o'god than a divine banana peel.

We would put this hypothesis in the filing cabinet marked "interesting but unprovable" were it not for the interesting similarity with the events which are now believed to have occurred at the end of the Permian. At that time, inexplicable and almost unprecedented vulcanism turned much of Siberia into a magmatic bubble-bath. Pangea was ultimately destroyed, and the atmosphere was poisoned, causing Earth's greatest mass extinction. Benton (2003). Prof. Meert has suggested (pers. comm.) that Pangea wasn't around long enough for the HOG effect to apply. However, given the quantitative uncertainties of variable viscosity and Rayleigh Number, the HOG hypothesis may have more generality than its authors give it credit for.

Resources

Joe's Paleomag Home Page: Prof. Meert's very useful home page. This stop is Rodinia Central on the Time Line.

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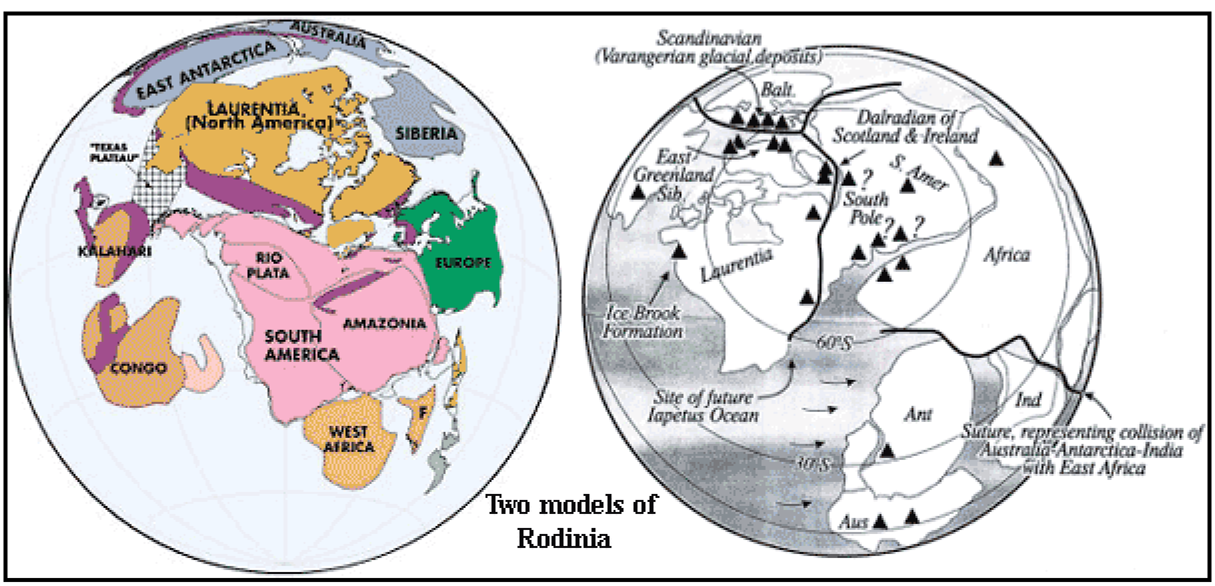
The Neoproterozoic

The Neoproterozoic Era of the Proterozoic Eon: 1000 to 542 million years ago

Introduction



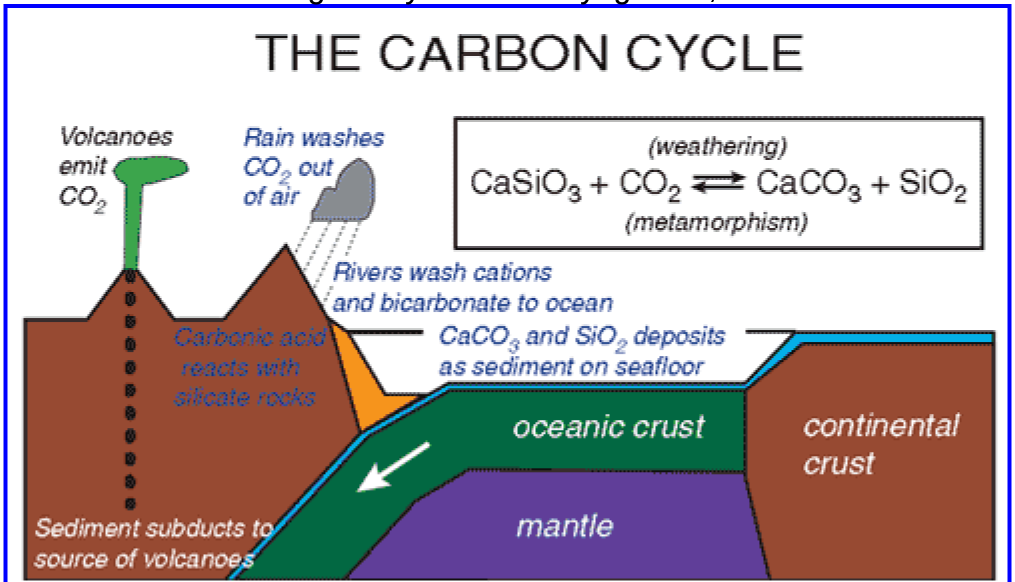
Two models of Rodinia

This is mostly a placeholder page at present. However, there is considerable specific coverage of the **Cryogenian** and **Ediacaran** Periods of the Neoproterozoic.

The Neoproterozoic is a vast stretch of time which science is just beginning to explore. It begins about the time that, according to the more conservative workers, eukaryotic cells were beginning to be a significant factor (some think that the Eukarya are at least twice as old). It ends, 458 million years later, at a time when animal life was beginning to become a major factor. It is comprised of three periods: the Tonian (1000-850 My), the Cryogenian (850 to ~630 My), and the Ediacaran (~630 to

542 My). Most of the evolutionary information we can currently access comes from the last 60 million years or so of the Neoproterozoic -- roughly the last two thirds of the Ediacaran, the last period of the Era. But this envelope is being pushed quite hard at present. It wouldn't be at all surprising if, ten years from now, we will be have pushed this curtain back to the Mesoproterozoic.

As usual, the geologists are leading the charge. Once they have sketched the outlines of the basic chronology, geochemistry and geography, the rest will probably fall, microfossil by microfossil. Currently, the front line is Snowball Earth, and we will have much to say on that topic. What seems certain is that there were between two and four intense ice ages during the Cryogenian and into the Early Ediacaran. The hot topic is just how cold did it get? How long did they last, and how did they end? What, if anything, is the relationship with the evolution of animals, which seem to first appear just after the last of the ice was retreating? Beyond the Cryogenian, advance elements are already beginning to take on the break-up of the supercontinent of Rodinia during the Tonian, an event which may have been at least as dramatic as the Ice Ages of the Cryogenian, and is even less well understood.



[Processes lettered in blue are absent in a snowball Earth]
From a lecture by Paul Hoffman & Daniel Schrag (1999)

Looming over the whole era is another, more diffuse, campaign to establish beachheads in geochemistry. We have remarkably little knowledge of the levels of oxygen and carbon dioxide during the Neoproterozoic, or of how the various chemical cycles worked. Yet without a handle on these parameters, it's hard to evaluate the competing theories about the ice ages of the Cryogenian, or say much about the environment in which the first metazoans evolved. We will run into a few of these brick walls in our discussions of the Snowball Earth. The carbon cycle is particularly critical, but has also proved particularly hard to pin down. Other important questions turn on worldwide budgets for magnesium, sulfur, and iron.

Despite these obstacles, the geologists are making progress; and, as mentioned, the last 50 My or so of the era are now open to the evolutionary biologists and paleontologists. Twenty years ago, we had only a few fossil forms from Australia and Russia. Now, various different Ediacaran communities are being explored in at least a dozen locations. At the moment, it's still hard to see any pattern in the data, but at least we're seeing lots of data. It seems likely that our lineage, the Bilateria, evolved quite early on. However, the ecosystems of the Ediacaran Period were dominated by large forms which are hard to identify. Many will probably turn out to be Cnidarians. Surprisingly few are likely to be Porifera. Many may not be metazoans at all, but a competing lineage of Fungi that became extinct in the Terreneuvian.

All things considered, the Neoproterozoic is likely to be the most exciting region of spacetime to be involved with over the next decade or two.

ATW059017.

Images: the images of Rodinia are from, respectively, (left) somewhere deep in the heart of the University of Texas computer system, and (right) an on-line paper by Toni Eerola (heading in Finnish, but paper mostly in Portuguese and English) titled **Fluxos de lama, erupções vulcânicas e/ou glaciação há 600 milhões de anos em Lavras do Sul, RS? Pesquisas geológicas no Sul do Brasil**.

The Cryogenian Period

The Cryogenian Period of the Neoproterozoic Era: 850 to about 630 million years ago

Neoproterozoic
Tonian
Cryogenian
Ediacaran

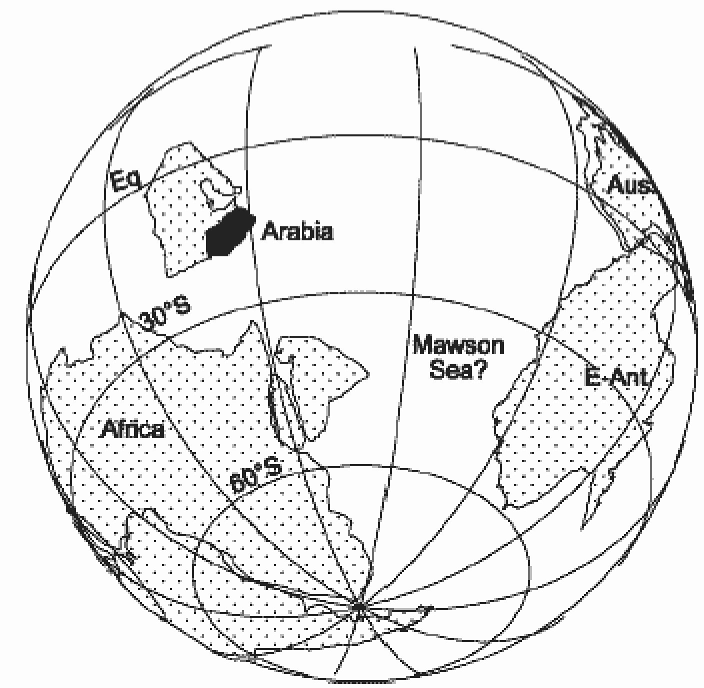
"Snowball" Scenarios of the Cryogenian
Weather Reports
References

The Cryogenian is, roughly speaking, the period of "Snowball Earth." During the Cryogenian, the world passed through at least two, and perhaps as many as four, "Ice Ages." At least one of these was so severe that it may have been briefly possible (if stupid) to ski from one pole to the other.

Weather Reports

The theory of Snowball Earth and its basic underpinnings are covered in a comprehensive page by Chris Clowes devoted to this subject. What follows here is, by contrast, a sort of mental ***tillite***. Our original thought was to update Chris's work. So, like a glacier, we plowed slowly through some of the massive recent literature on the subject, taking the path of least resistance, scooping up bits and pieces of ideas and scientific debris, pushing this ever-growing mound of random factoids before us. However, we realized at last that we weren't going to be able to improve on Chris's original. In fact, after writing over 3000 words on this topic, we discovered that we probably had no idea what this was all about. So, at that point, we simply melted away and dropped this enormous, unconsolidated mass of poorly-sorted data and erratic errata as a sloppy moraine, where you have been so unwise as to stumble across it. And that is also just about as far as we care to push this particular metaphor.

Since we admittedly have no idea how to fit the data together, we have simply organized our treatment around (a) particular phenomena that require explanation and (b) the reasons why we can't explain them. The fundamental background can be very quickly summarized as follows. Between the break-up of Rodinia (> 750 Ma) and the base of the Cambrian (544 Ma) the Earth passed through at least two severe episodes of deep freezing. The first is often called the Sturtian and is commonly dated at between 760 and 700 Ma. The second is called the Marinoan. The dates given for "the" Marinoan glaciation vary from about 650 to 550 Ma. There is some consensus (perhaps not based on evidence) that the Sturtian was a single, world-wide event. There is considerable suspicion (based mostly on a lack of evidence) that the Marinoan was not.



The Marinoan world according to Kilner *et al.* (2005).

The Snowball Earth theory, as articulated by Hoffman ***et al***. (1998), remains the best-articulated, most complete, and best reasoned explanation. That may not be saying a great deal. Hoffman is a really outstanding writer, and one reads his global explanations with a happy sense of revelation and full understanding. Sadly, this sensation is somewhat illusory, as we will see. Still, Snowball Earth is the leading contender. Briefly, Snowball Earth begins with the observation that, if ice sheets extend to 30º latitude or so, the ***albedo*** of all that ice reflects so much incoming solar radiation that the rest of the planet quickly freezes, becoming encased in an ice sheet about 1000 m thick. Over a period of time (2-20 Ma), carbon dioxide accumulates in the atmosphere from volcanic sources. When the carbon dioxide reaches a critical threshold, the greenhouse effect of this gas causes an equally extreme hothouse which rapidly melts the glaciers and raises temperatures to about 50º C for a short period before the excess carbonate is absorbed by weathering, and/or directly by the oceans, and precipitates out as carbonates. The strongest evidence for the model is the existence of "cap" carbonates **[2]** associated with all major glacial deposits of the era. These show extraordinary features, such as meter-long crystals of ***dolomite***, which suggest very rapid formation.

"So, what's the problem?" you say. That's just what we thought -- about 3000 wasted words ago. We have thrown out all those words, and we now begin again:

Why We Are Clueless

The Position of the Continents

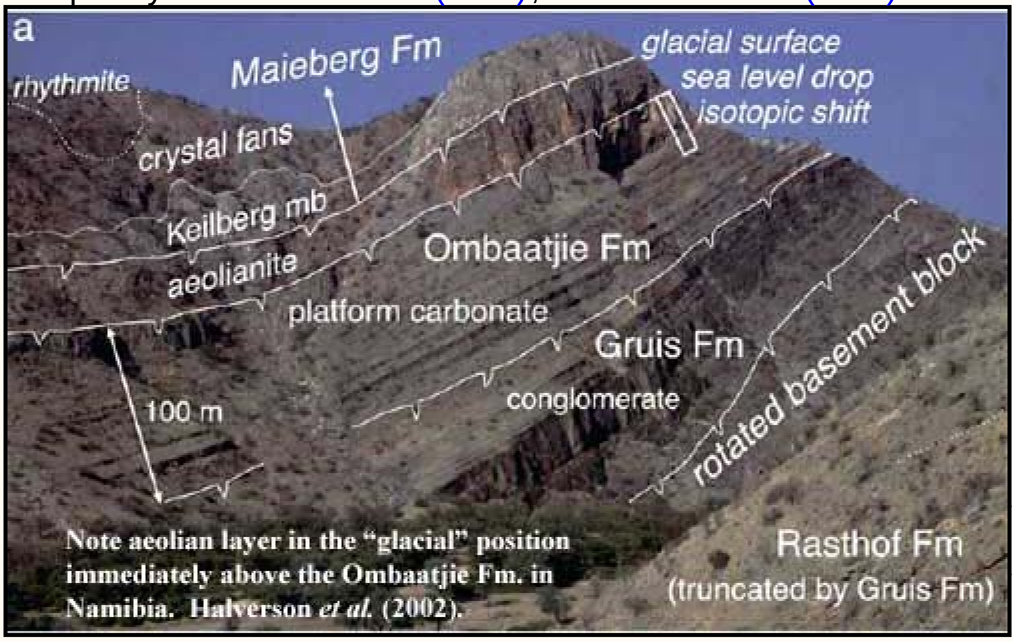
The Hoffman version of Snowball Earth grew out of extensive fieldwork in Southwest Africa, mostly on the coast of Namibia. One of the striking things about that region was the presence of glacial deposits on the Congo and Kalahari Cratons, which were said to be near the equator during the relevant parts of the Neoproterozoic. In fact, Hoffman ***et al***. have postulated that an unusual clustering of all major continents around the equator contributed strongly to the initiation of icehouse conditions -- an initiation they otherwise don't do much to explain. ***See*** Hoffman & Schrag (2000); Halverson ***et al***. (2002); Hoffman & Schrag (2002); and especially Schrag ***et al***. (2002).

As it turns out, that isn't likely to be the case. Until very recently, the only decent ***paleomagnetic*** data was from Australia, which ***was*** on the equator. However, recent information from Oman places it at 20º S latitude at about 600 Ma. Kilner ***et al***. (2005). Given the fact that Africa was more or less fully assembled and wedged into Gondwana at the time (Beyth ***et al.***, 2003; Frimmel & Fölling, 2004), and given that Arabia was also about to dock into that system, we can place Namibia fairly accurately – at about 75° S latitude. ***See*** image above. Thus, during the Marinoan, Namibia was emphatically not in the tropics, nor was most of the rest of Gondwana (Australia excepted).

If Kilner ***et al.*** are correct, this is a finding that ought to raise eyebrows about some of the other conclusions from Namibia. The Snowball theory demands that glaciation from 30º to the equator ought to be quick. It says nothing about glaciation at the poles. Thus, it is not clear exactly what the "Marinoan" event in Namibia was, or when it occurred.

Continental Ice Shelves

The Snowball Earth hypothesis concerns frozen seas. It does not demand frozen continents. Indeed, the lack of precipitation from the dry, extremely cold atmosphere requires that continental ice shelves be "thin and patchy." Hoffman ***et al.*** (1998); Kirschvink ***et al.*** (2000). This necessarily follows from the fact that the water cycle is shut down. Water cannot evaporate through ice cover. Thus, if continental ice sheets formed at all, they would have been ablated as the ice age got into high gear. If thick continental ice shelves were present, this would imply the existence of an active water cycle that should not exist under hard freeze conditions.



Note aeolian layer in the "glacial" position immediately above the Ombaatjie Fm. in Namibia. Halverson *et al.* (2002).

This conclusion seems to apply to Namibia, at least in the Marinoan, but plainly does not apply to Australia or Canada because "Neoproterozoic glacial deposits in Australia and North America are locally thick (>1 km), fill incised paleovalleys (<150 m deep), contain faceted and striated stones, have associated outwash deposits, and record as many as six magnetic polarity reversals. These features indicate that substantial amounts of flowing ice existed on land for time scales of 10^6 years." Hoffman & Schrag (1999). Accordingly, the authors modified their theory, but failed to state how continental ice could accumulate. They assert that c. 10^7 years is enough to build a continental ice cover, even at very modest rates of ice accumulation. However, we don't see how there could be any ***net*** accumulation, because of the supposed lack of direct connection between sea and atmosphere, and because of the loss of ice cover by gradual sublimation and seaward transport.

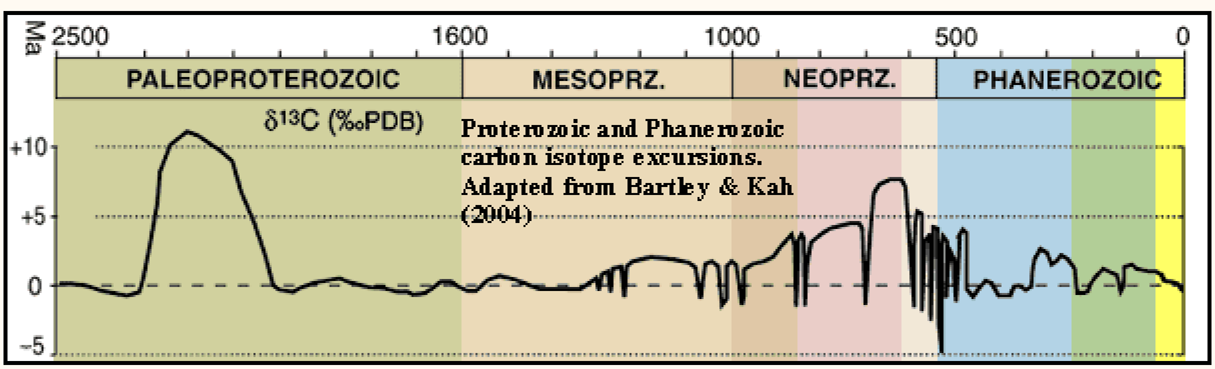
On the other hand, in the ***absence*** of continental ice masses, we would expect significant amounts of bare ground. This could have an important effect, in that large swathes of wind-borne dust and dirt would drastically reduce the albedo of the sea ice cover, which is needed to maintain the snowball state. Pierrehumbert (2004); Pollard & Kasting (2005).

"Alarums & Excursions," Part 1: ^{13}C and All That

Alarums, excursions: Enter Thersites

Thersites: ***Now they are clapper-clawing one another; I'll go look on.***

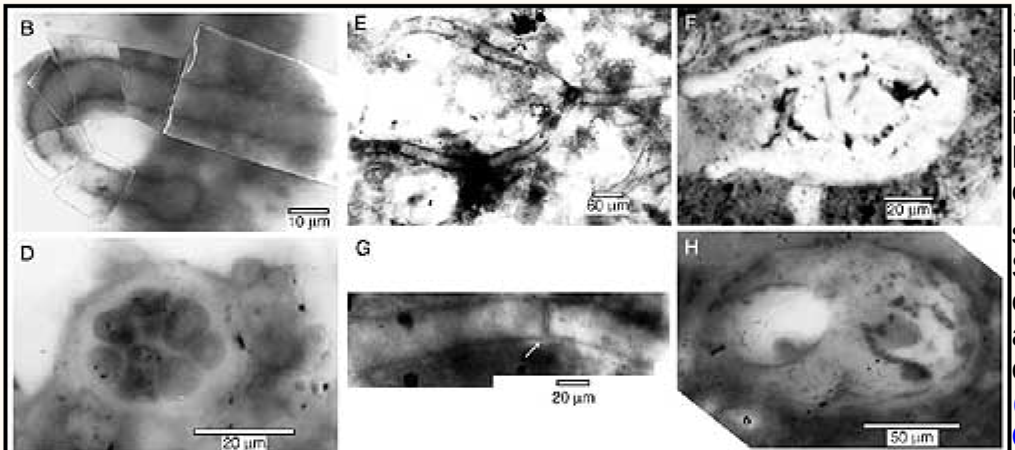
-- Shakespeare, **Troilus and Cressida**, Act V, Sc. 4



Here we enter the original heartland of the Snowball Earth debate. However, if the string "$\delta^{13}C$" leaves you looking vague and perplexed, we recommend reviewing this remedial footnote: **[1]**.

As the figure shows, the Proterozoic was characterized by a sustained, positive ^{13}C excursion, punctuated by relatively brief episodes of marked instability. The Snowball Earth mechanism purports to explain these instabilities by associating them with Snowball episodes. This association is bolstered by the fact that the "cap carbonate" deposits immediately above the glacial levels contain a distinctive ^{13}C signature, generally involving low ^{13}C values and a gradual return to normal (for the Proterozoic) highs. Parenthetically, we should note that the data points showing sudden negative $\delta^{13}C$ are probably all taken from cap carbonates. Thus, this is not really an explanation, but a tautology.

Nevertheless, post-glacial carbonates with low ^{13}C are a natural consequence of the Snowball Earth model, and are not adequately explained by any other model. AsHoffman & Schrag (2002) aptly, if smugly, state, "We are not burdened by an overabundance of explanations for cap carbonates." Damned right! The problem is that we're not entirely sure their explanation is complete, either. Here are two problems.



Fossils reported by Corsetti *et al.* (2003) from Cryogenian glacial carbonate.

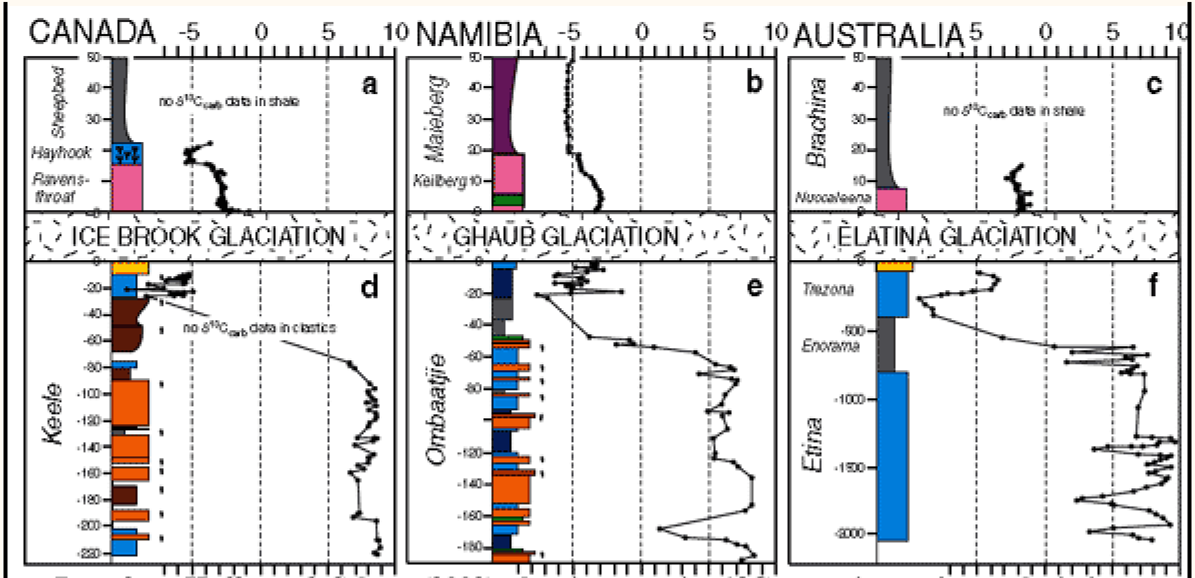
1. Hoffman & company explain the negative excursions with a complex, but plausible chain of reasoning involving global carbon burial rates. However, the fact remains that organic material is the primary source of ^{13}C-depleted carbonate. Stromatolitic carbonates and other organic remains are often found in association with the lower levels of cap carbonates. Allen & Hoffman (2005); Beyth ***et al***. (2001); Corsetti ***et al***. (2003); Frimmel (2004); Halverson ***et al***. (2002); Hoffman ***et al***. (1998). How confident can we be that the results are not being influenced by all this organic carbon? In fairness, we judge this to be a small point.

2. It isn't clear whether the cap carbonate $\delta^{13}C$s are local or global, and whether the origin of the carbon is terrestrial (via runoff), marine, or dissolved carbon dioxide from the atmosphere. Under more normal circumstances, this would make no difference. However, the Snowball Earth hypothesis calls for all kinds of partitioning. During a Snowball event, for example, deep sea, superficial sea, ice cover, land, and atmosphere are all somewhat (or entirely) separate compartments. Hoffman ***et al***. (1998) assumed that air, sea and ocean would all be in equilibrium with volcanic carbon dioxide (which has a negative $\delta^{13}C$). It is unclear why that would necessarily be the case for the oceans. In any case, Hoffman & Schrag (2002) invoke rapid weathering as the primary post-glacial source of carbonate. But this, as they state, involves weathering of ***pre***glacial carbonate shelves. So what are we measuring?

In addition, various authors have grumbled about effects of such factors as water depth on ^{13}C. Halverson ***et al***. (2002) (citing work of Holland); Frimmel (2004); Frimmel & Fölling (2004); ***c.f.*** Bartley & Kah (2004) (depth effect depends on productivity). Bear in mind, also, that the Snowball Earth model calls for a number of unusual changes of state for carbon: sublimation in intensely dry and cold conditions, possible CO_2 freezing at the poles, very rapid freezing, thawing, and crystallization, and unusual crystal forms. It is unsafe to assume that none of these processes would impact $\delta^{13}C$. For an interesting example of isotope fractionation under similar unusual conditions, see Eiler & Kitchen (1999); Rahn & Eiler (2000); Socki ***et al***. (2003) (simulated conditions on Mars).

"Alarums & Excursions," Part 2: An Early Decline

Alarums,
Excursions. Enter
Warwick.



Data from Hoffman & Schrag (2002), showing negative 13C excursions prior to glaciation.

Warwick: ***Forspent with toil, as runners with a race,***
I lay me down a little while to breathe;
For strokes receiv'd, and many blows repaid,
Have robb'd my strong-knit sinews of their strength,
And, spite of spite, needs must I rest awhile

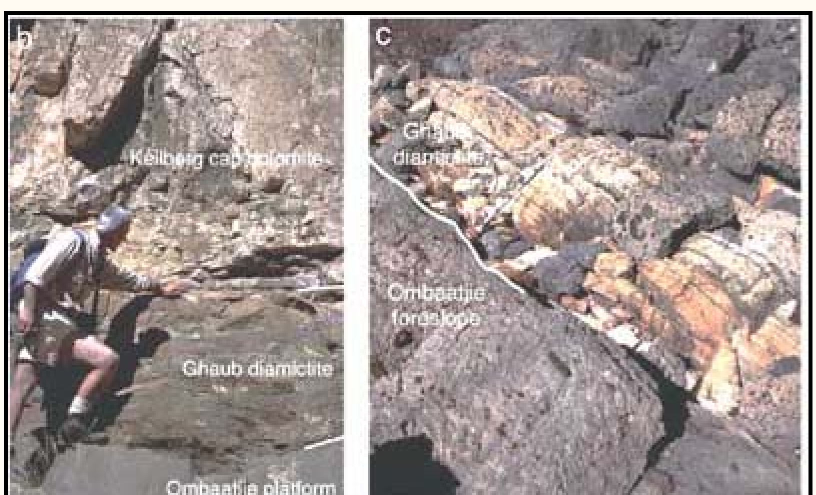
-- Shakespeare, **Henry VI, Part 3**, Act III, Sc. 3

Another anomalous carbon anomaly is discussed by Halverson ***et al***. (2002) and by Hoffman & Schrag (2002). As these authors note, the ^{13}C values, like Shakespeare's Warwick, withdraw a little earlier than honor would allow. That is, the low values found in the cap carbonates actually begin in levels ***below*** the glacial ice. In fact, to our untutored eye, it appears that the negative excursions peak somewhat before the glaciation and that the cap carbonates smoothly continue a generally ***upward*** trend line which began before the glaciations. Halverson's group estimates that the negative excursion in Namibia began about 600,000 years before the Marinoan glaciation.

As far as we are aware, no satisfactory explanation has been offered for these peculiar results. (Halverson & Co. offer a game, but ultimately unsatisfactory explanation discussed below.) From the viewpoint of the carbon isotope record, it almost appears that the glaciers were inserted into a previously continuous series of strata, or that the glaciation formed part of a recovery phase from some earlier perturbation.

Before leaving this interesting, but entirely speculative topic, we should point out that, in some cases, little or no geological record of the actual glaciation exists. Thus, as shown in the image, pre-glacial and post-glacial carbonates are almost in contact, and may even interpenetrate. This makes the pre- and post-glacial isotope continuity seems more natural, but still entirely inexplicable.

"Alarums & Excursions," Part 3: Methane



Images from Halverson *et al.* (2002) illustrating that the glacial Ghaub diamictite layer is thin (sometimes non-existent) and is interpenetrated by the underlying Ombaatje Limestone.

Alarums, excursions. Enter the Bastard, with Austria's head

Bastard: ***Now, by my life, this day grows wondrous hot;***
Some airy devil hovers in the sky
And pours down mischief ...

--Shakespeare. **King John**, Act III, Sc. 2.

Hoffman's group postulates a methane-related mechanism for the pre-glacial positive carbon isotope excursion. Perhaps we are simply jaded, but we are suspicious. Methane is currently a sort of compound ***de jour***. In some areas, it has almost eclipsed extraterrestrial impacts as the explanation for all that is inexplicable. We admit to invoking methane in that manner several times ourselves. Certainly it has been speculated that methane production and/or methane ***clathrate*** releases may have been responsible for ***escaping*** the deep freeze. ***See, e.g.***, Kennedy ***et al***. (2001). However, all of this appears to be erudite arm-waving at the moment.

With all that said, the explanation offered by Halverson ***et al***. (2002) is not entirely ***ad hoc***. The mechanism proposed by Halverson ***et al***. is that a sustained release of methane from some oceanic source caused greenhouse warming, which promoted continental weathering, which drew down atmospheric carbon dioxide. When the methane release ended, the atmosphere contained low levels of both greenhouse gasses, triggering an ice age.

The subject has been reviewed by Holland (2003). Without, getting deeper into geochemistry than this discussion warrants, Holland concludes that excess methane production is possible, although there is no particular evidence to show that it actually occurred. The amount of methane being released to the atmosphere depends critically on the state of the oxygen and sulfate cycles, both of which were evolving rapidly during the Neoproterozoic. It also depends on the state of the deep oceans (mixed or unmixed, anoxic or otherwise). It is clear that, by the very end of the Neoproterozoic, both oxygen and sulfate were at much higher levels than at any previous time. However, the pace and timing of the change are unclear. ***See also***, Kah ***et al***. (2004) (arguing that the transition was very late). Thus, the state of methane during the Cryogenian and Early Ediacaran is an unknown quantity in an unknown geochemical system, which was probably out of equilibrium at any given time. As for the oceans, as Holland observes, we can be reasonably sure the deep oceans were at least locally anoxic during snowball events, since we find banded iron. However, as Holland also notes, that cuts both ways. Neoproterozoic banded iron is ***only*** found in association with Snowball events. Perhaps the oceans were otherwise well mixed. Accordingly, we can neither rule out nor accept a methane explanation at this point.

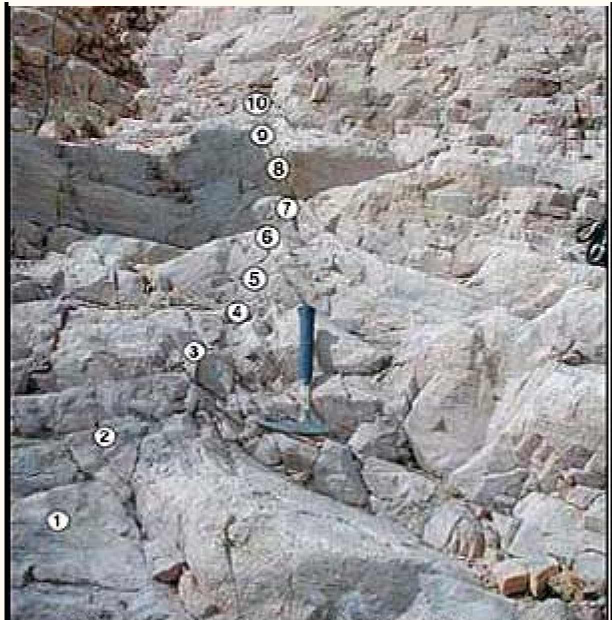
Ice-olated Cases?

As mentioned above, the dating of the Snowball events is not exactly well-constrained. To confuse matters further, ^{13}C excursions have frequently been used to date rock sequences with seeming confidence, when it is actually unclear whether they correspond to unique, world-wide events. Indeed, it seems that any poorly-sorted conglomerate overlaid by Proterozoic dolomite is assumed to be part of a "Snowball" event, even where no particular pattern of carbon excursions was found and dates were essentially unconstrained. ***See, e.g.,*** Beyth ***et al***. (2003). Such conclusions in the literature, like ice beyond 30º latitude, signal an unstoppable positive feed-back effect in which each "Snowball" finding increases the likelihood that the next study will also find one.

In fact, there is no reliable evidence that any of the Snowball events represent synchronous global phenomena. So far as we are aware, none of the (few) events with well-constrained dates are synchronous. The global nature of the events has generally been assumed from the ^{13}C excursions, the thought being that ^{13}C values will generally be in equilibrium with ocean values worldwide. Knoll ***et al***. (2000) (dissenting comments of Sokolov ***et al***.); Knoll (2000); Hoffman & Schrag (2002). However, most -- perhaps all -- of the well-documented Snowball carbonate sequences come from relatively restricted waters, a circumstance which is known to correlate with higher ^{13}C values. Frimmel (2004). Allen & Hoffman (2005) argue that the presence of what they believe to be giant wave ripples in the cap carbonates suggests access to open oceans with unlimited fetch. However, their calculations require a number of critical assumptions, and it is unclear whether or not these authors may have inadvertently assumed their conclusions.

Thaw or Meltdown?

The Snowball Earth theory requires a very quick deglaciation, driven by extraordinary levels of atmospheric carbon dioxide. The evidence for extremely fast deposition of carbonate caps is excellent in some areas. In addition to large dolomite crystals, calcite "fans" and similar structures are frequently observed. Allen & Hoffman (2005) have recently reported tented structures attributable to enormous



Giant wave ripples on the Namibian Otavi Platform. Allen & Hoffman (2005).

waves (not tsunamis, but ordinary gravity waves) in many different cap carbonates, consistent with the kind of brutal weather we would expect to see in a rapidly melting world.

The last-named study aroused our slumbering curiosity, since it cited evidence from exposures not commonly mentioned in the Snowball literature. One of them, the Stelfox Member of the Ice Brook Formation, looks to be a fairly typical Snowball facies, but it occurs ***above*** the first occurrence of Ediacaran fauna, and also above ***another*** Marinoan Snowball sequence. The same may apply to the Spitzbergen succession (Wilsonbreen Fm.) mentioned by the same authors. ***See***, Kaufman ***et al***. (1997).

But, the embarrassing surplus of Snowball events aside, is there evidence for slower deglaciation? Apparently this is the case. We say "apparently" because it is often asserted to be true. Christie-Blick ***et al***. (1999); Goodman & Pierrehumbert (2003). We have personally looked at only one such study. McMechan (2000). It is also unclear whether Christie-Blick and Hoffman's Snowball group are talking about the same thing when they discuss deglaciation. The former cites studies apparently dealing with continental ice masses, while Hoffman is mainly focused on sea ice. One could envision a case in which sea ice melted very rapidly, but continental ice sheets retreated much more slowly. Something similar may have occurred during the Pleistocene Ice Ages. However, unless continental ice also melted quickly, surface rock would not be available for the rapid weathering needed to draw down the excess carbon dioxide, thus prolonging the "hothouse" aftermath of the glaciers.

Cyberslush

Two examples of sea ice with clearly different albedos.

A number of workers have created computer models of greater or lesser sophistication in an attempt to understand the complex interactions involved in the Snowball phenomena. Poulson ***et al***. (2001); Goodman & Pierrehumbert (2003); Pierrehumbert (2004); Poulson & Jacob (2004); Pollard & Kasting (2005). These are fascinating papers, particularly Pollard & Kasting (2005) who go into great detail about the effects of various assumptions, including the albedo parameters assumed for sea ice (a critical and insufficiently examined parameter). Unfortunately, this type of modeling pushes the limits of available computing power and requires potentially unrealistic simplifying assumptions. Our personal favorite is from Goodman & Pierrehumbert (2003: 3): "We ignore the existence of continents ..." -- surely a remarkable statement for a geologist! In fact, this was a perfectly sensible assumption in the context of what those authors were doing, ***i.e.*** proving the importance of equatorwards ice flow from both poles in maintaining the Snowball steady state. However, it underlines the point that modeling results must be approached with a clear understanding of their assumptions and limitations.

A number of potentially relevant factors might be added to these models. One factor which does not seem to have been included in any of the models is tide. Since tides were both more frequent and stronger in the Neoproterozoic than in the present day, this is distinctly odd. Perhaps we are mistaken, but it would appear that tidal heating and deformation might have a considerable impact on a worldwide ice sheet. Another factor we would like to see is some degree of random variation in the parameters. So, for example, Pollard & Kasting assume that 2% of the ocean surface is exposed through cracks ("leads") in the ice. Pollard & Kasting find that this is a surprisingly important variable in the results. A more realistic and informative choice might be to allow this parameter to vary randomly in different computational cells between 1 and 3%. Finally, with apologies to Goodman & Pierrehumbert, we'd like to see more continents. One of the modelling groups includes one big continent straddling the equator, but this is not ideal. Polar continents might have strong effects in limiting thick ice production, and thus equatorward glacial flow. Smaller, mid-latitude continents might create large, thin- or no-ice refugia on their equatorward sides as the sea glacier split to flow around them.

Thus far, two conclusions seem to emerge from the modeling studies. First, as Goodman & Pierrehumbert pointed out, the Snowball model necessarily requires a "sea glacier" that continuously transports ice and cold, fresh water from poles to equator. Second, "thin ice" and "slushball" scenarios are possible. That is, a hard frozen ice-ball is not necessarily required. A hard freeze does emerge as the result of most modeling runs, but the result depends on assumptions about fine points such as ice albedo, cloud cover (and cloud thermal properties), winds, precipitation, and the amount of sea surface exposed by cracks in the ice. Beyond these results, as Poulson & Jacob (2004) state: "At this stage in the modeling of Neoproterozoic climate, model results should not be used to argue one way or another for the existence of a Neoproterozoic snowball Earth. Rather, climate models should be used to gain insights into the processes or mechanisms that might contribute to promoting or inhibiting global sea-ice cover."

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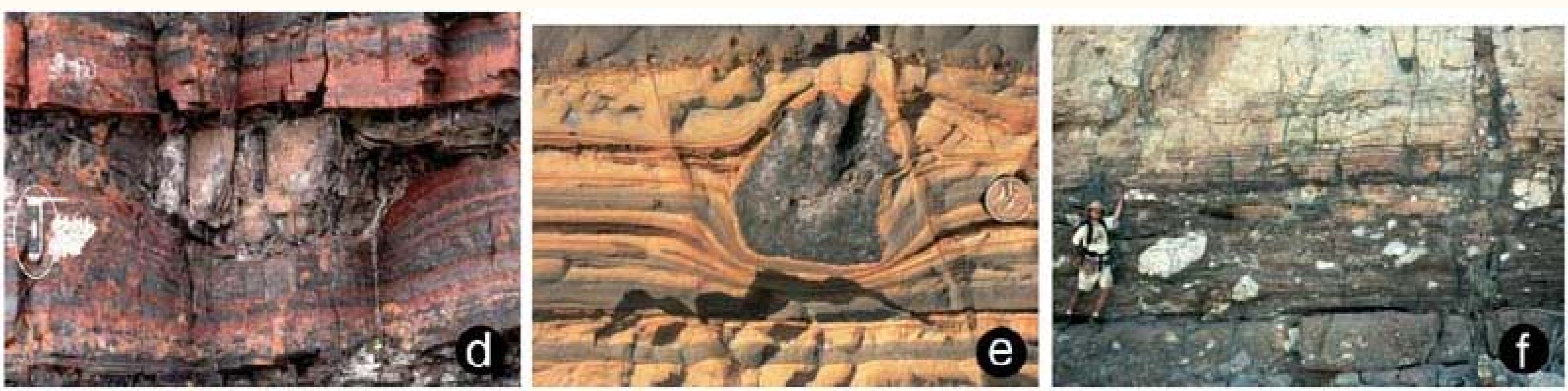
The Cryogenian Period - 2

Dropstones

At a glacial terminus in quiet water, floating ice melts slowly and often drops exotic rocks and sediment far out on a lake bottom. These isolated rocks are referred to as dropstones. In characterizing the Snowball events as involving glaciation, most writers point to the abundance of dropstones as determinative. After all, any mass wasting can lead to an unconsolidated ***gemisch*** of unsorted rock that might be mistaken for glacial ***diamictite*** after a few millennia. However, dropstones are almost unique to glaciers, and they are abundant around Snowball events. ***See*** the following dropstone images from Halverson ***et al***. (2002).



Sounds good, but why would we expect to see dropstones? Snowball events are supposed to be dominated by ***sea*** glaciers. Sea ice doesn't cut through mountains and there is little reason to expect it to contain stones to drop. Furthermore, the expectation is that a sea glacier would freeze additional water at the bottom, rather than melting. Hoffman & Schrag (1999); Pollard & Kasting (2005). Since a sea glacier is not melting, but growing, in open water, it would drop nothing which was encased in the ice. Sea glaciers would not be expected to drop much of anything until the very end, at the time of the global hothouse. But the Neoproterozoic dropstones are generally found in the middle of layered sedimentary deposits which clearly did not result from a sudden, chaotic thaw accompanied by giant waves, etc.

Workers in this area, without explicitly acknowledging this problem, generally assume that the dropstones are created by sea ice abrading the continental shelf at depth. Note that the sea glacier in most scenarios is expected to exceed 1000 m in height. Accordingly, the glacier would initially impact the continent in deep water, usually on the continental slope and at a considerable distance from shore, since most of the glacier would flow below the surface. If so, the location of the dropstones might be dispositive. However, even assuming erosion of the continental shelf (which ought to leave some ***very*** distinctive signs), and even assuming that rock would be incorporated into ("plucked" by) the glacier, a dropstone still has to be dropped, which normally requires the ice to melt. Under Snowball conditions, that shouldn't occur. In fact, Hoffman & Schrag (1999), while addressing another point, argued that material trapped in a Snowball glacier would generally be advected upward. The presence of numerous dropstones would appear to indicate either (a) that the glaciers were continental, not sea glaciers, or (b) that the sea glaciers were regularly melting at the base, suggesting a possible "slushball" scenario with thin or seasonal ice.

We are aware of only one study which attempts to work out the origin of the dropstones, although there are probably others. McMechan (2000) finds that the material transported by Neoproterozoic glaciers in British Columbia was of continental origin, ***i.e.*** that the ice sheets were continental, not sea glaciers. Since the material was dropped some distance from shore, it does not seem to have been constrained by massive sea ice and plainly was in water warm enough to cause melting.

Old Salts

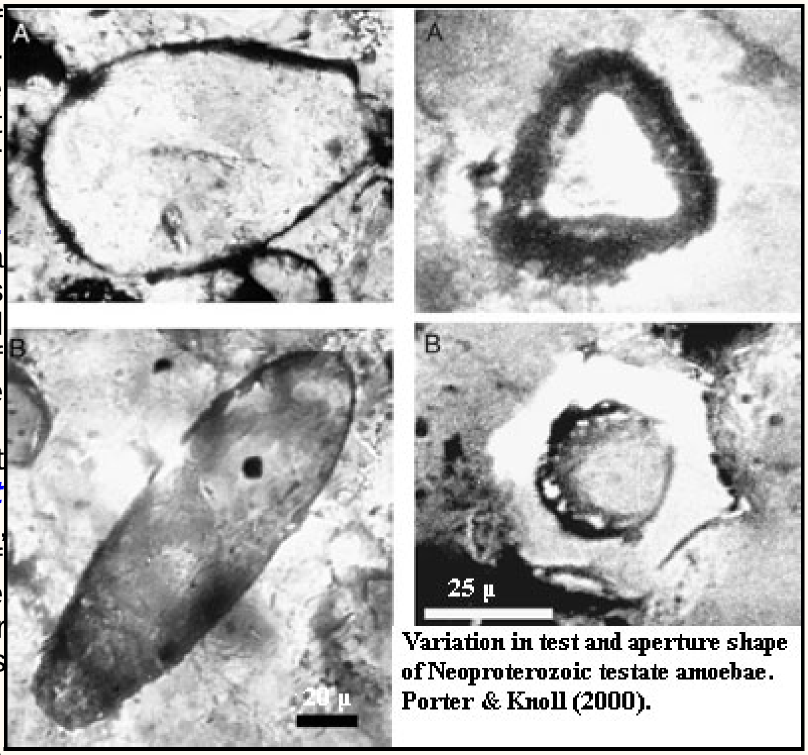
Just one more. Numerous authors have mentioned, usually without much comment, the presence of ***halites*** or ***evaporites*** in association with Snowball events. Chakraborty ***et al***. (2002); Holland (2003); Frimmel & Fölling (2004); Frimmel (2004); Schröder ***et al***. (2004); Sumner & Grotzinger (2004). Since we already have an embarrassing number of unexplained phenomena, no one seems to have had time for this one yet.

Conclusion

You must be kidding! Conclusions are for people who understand what's going on. ATW050926

Cryogenian Life

You might expect, with this frenetic cycle of freezing, thawing, steaming, crushing, and what-not, that life might have taken a considerable beating. Perhaps it did, but the evidence is, at best, equivocal. As discussed elsewhere, a number of studies have looked at this issue. Knoll (1994); Corsetti ***et al***. (2003); Porter (2004); Olcott ***et al***. (2005); Huntley ***et al***. (2006). The Tonian data seem to indicate a break from the billion-year stasis of the Mesoproterozoic. The Ediacaran included two (or even three) enormous bursts of diversification which we associate with the ediacaran fauna and the evolution of animals. What happened in between is less clear. The most sophisticated study currently is probably Huntley ***et al***. (2006). They, and a number of older papers, claim a dip in diversity and imply a loss of abundance during the Cryogenian. However, the data are perhaps not good enough to reach either conclusion; and no one's results indicate any mass extinction or significant evolutionary bottleneck.



Variation in test and aperture shape of Neoproterozoic testate amoebae. Porter & Knoll (2000).

Several important groups may even have first evolved, or undergone important development, during the Cryogenian, including the red and green algae, dinoflagellates, ciliates, stramenopiles, and testate amoebae. Porter & Knoll (2000). The amoebae are particularly important, as they represent the first fossil record of eukaryotic heterotrophs, the stem group of fungi and animals. All of this evolutionary novelty doesn't rule out slushball episodes, but it does seem inconsistent with the most extreme hard freeze scenarios.

Interestingly, testate amoebae are becoming important tools in Holocene paleoclimatology as extremely sensitive indicators of water level and environmental stability. ***See, e.g.***, Davis & Wilkinson (2004). The utility of this biomarker on the scale of megayears is unclear. However, given the scarcity of reliable climatic proxies in the Cryogenian, it might be worth looking into.

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"Snowball" Scenarios of the Cryogenian

Abstract

There is now good evidence that at least three Proterozoic ice ages culminated in glaciation extending to very low latitudes; possibly to the equator. Joseph Kirschvink (1992) coined the term 'snowball Earth' to describe these events, suggesting that if ice had also covered the oceans at these times, then the Earth might have resembled a highly reflective snowball (p. 52).

Evidence in support of the snowball hypothesis has been accumulating since the 1960s, although the two landmark papers on the subject, by Kirschvink and Hoffman ***et al.***, did not appear until the 1990s. Although these are powerful theories which potentially explain a number of disparate and otherwise problematic phenomena, none of the several versions of the snowball hypothesis yet provides a complete explanation of all field observations.

Keywords: Neoproterozoic, Precambrian, low-latitude glaciation, Sturtian, Marinoan, Varanger, Snowball Earth

Related Topics

Further Reading

- ***Snowball Earth*** - Gabrielle Walker

Related Pages

- Kirschvink's 1992 paper

Other Web Sites

- Paper by Hoffman & Schrag

Introduction

“In 1891 the Norwegian geologist Hans Henrik Reusch found an ancient deposit he interpreted as being a glacial moraine. The deposit, now believed to be a tillite, lay atop a striated rock surface beside Varanger Fjord in northern Norway. Both the tillite and the rock surface are demonstrably Pre-Cambrian" (Harland & Rudwick, 1964). A few years later, around 1900, Sir Douglas Mawson recognised the glaciogenic nature of the Sturt Tillite, a few kilometres south of Adelaide in South Australia. Since then, Late Proterozoic glaciogenic sequences have become known from almost all of the major cratonic areas, including North America, the Gondwana continents, and the Baltic Platform.

Although the earliest snowball event or events may have occurred as early as 2,300 to 2,200 Ma (Kirschvink, 2002), our reconstruction of these ancient times is still not clear. Far stronger evidence supports recognition of three Neoproterozoic events: Sturtian, Marinoan and Varanger. Corsetti & Kaufman (1999); Rice ***et al***. (2003). Some publications (***e.g***. Narbonne, 1998: fig. 2) suggest the possibility of multiple individual glaciations in the Sturtian, usually by means of cryptic indicator symbols on time charts; it is difficult to guess how to interpret such typography.

Evidence for Glaciation at Low Paleolatitudes

Whereas the Permian and Quaternary glacial deposits formed at relatively high latitudes, those of the Proterozoic are believed to have formed much closer to the equator. In 1992, Joseph Kirschvink (1992) coined the expression "snowball earth" to evoke his conjectured appearance of a fully glaciated planet.

Arguments in support of this contention have been repeatedly advanced since the 1960s (***e.g.*** Harland & Rudwick, 1964 [sidebar ®]; Harland, 1964; Hambrey & Harland, 1981; Kirschvink, 1992; Hoffman ***et al***., 1998), prompted by observations that some of the diamictites contain an unexpected abundance of carbonate debris, presumably derived from nearby carbonate platforms. Additionally, many of these units are bounded above and below by thick carbonate sequences which today are known to form only at tropical latitudes, within about 33° of the equator. Ziegler ***et al***. (1984); Kirschvink

> "The distribution of Infra-Cambrian water-deposited tillites is almost worldwide. Whether they are considered according to the present position of the continents or according to a possible Pre-Cambrian arrangement, ... it is difficult to confine them ... to a restricted portion of the globe. There are two alternative hypotheses to account for this fact. One states that the ice was widespread at all latitudes" (Harland & Rudwick 1964, p. 33).

(1992). Other anomalies include dropstones and varves in the carbonates, evaporites, and anomalous iron enrichment (iron-rich mudstones and even some BIFs). The iron deposits should have been able to form only if the contemporary Proterozoic oceans contained little or no dissolved oxygen, but by that time the atmosphere is believed to have had nearly the same composition as it has today.

Diamictite: massive, structureless unsorted rock. The sort of mess a really big glacier would leave.

Drop stone: stones carried along by glaciers and dropped when the bottom of the glacier melts over water.

Varve: A rhythmic sequence of sediments deposited in annual cycles in glacial lakes. Light-colored, coarse summer grains are deposited by rapid melting of the glacier. The summer layers grade upward to layers of finer, dark winter grains of clay minerals or organic material that are deposited slowly from suspension in quiet water while streams and lakes are icebound. Oilfield Glossary- Term 'varve'

Early paleomagnetic data presented in support of low-latitude interpretations were famously suspect, particularly in terms of constraining the time at which remanent magnetisation was acquired. (Two important exceptions to this were the reports of Embleton & Williams, 1986 and Sumner ***et al***. 1987, for the varved sediments of the Elatina Formation of South Australia.) However, subsequent studies have confirmed the equatorial placement of Rodinia. Kirschvink concludes that, "During the uppermost Marinoan glaciation in Australia, it now seems clear that these extensive, sea-level deposits (including varves and dropstones) were formed by widespread continental glaciers which were within a few degrees of the equator. The data are difficult to interpret in any fashion other than that of a widespread, equatorial glaciation" (Kirschvink 1992, p. 51).

Marinoan: Early Ediacaran (Vendian), about 580 Mya. This was the most recent of the putative three snowball events. The others occurred in the "**Varanger**" (~600 Mya, Cryogenian - Ediacaran boundary) and the **Sturtian** (~800 Mya, Early Cryogenian).

Initial Scepticism

Initial reluctance to accept that glaciations had extended to low latitudes was largely sustained by two theoretical difficulties:

- Firstly, nobody had advanced a reasonable causal mechanism which adequately explained the profundity of the glaciations ***per se***, and also why they were different from the subsequent Phanerozoic glaciations which were restricted to high latitudes.

- Secondly, there was a view that once the Earth had become fully iced-over, it would reflect so much of the Sun's energy that it would freeze even further, and never escape from the so-called "ice catastrophe." Thus a second mechanism, to permit thawing, was also required.

Joseph Kirschvink (1992) appears to have been first to offer both.

Possible Causal Mechanisms for Low-Latitude Glaciation

Early converts to the hypothesis offered a variety of causal explanations.

One suggestion, proposed in Williams 1975, was that the obliquity of the Earth's orbit may have been greater than its present value of around 20°. Were it to exceed about 54°, the Sun would heat the poles more than the equator. Glaciers might then form in the equatorial regions. This proposal, however, poses more difficulties than it resolves: Whereas the physical basis for the Milanković-scale changes (a few degrees with a period of a few tens of thousands of years) is fairly well understood, no mechanism has yet been proposed that would lead to the much larger oscillations required by the Williams hypothesis. Moreover, detailed studies of both modern and ancient heliotropic stromatolites (Vanyo & Awramik, 1982; Vanyo & Awramik, 1985; Awramik & Vanyo, 1986; and Vanyo ***et al***., 1986) argue convincingly that the obliquity at 800 Ma was in the range of the present values. Kirschvink, 1992: 51).

“[Another] possibility to consider is that the Neoproterozoic sun was weaker by approximately 6 percent, making the earth more susceptible to a global freeze. The slow warming of our sun as it ages might explain why no snowball event has occurred since that time. But convincing geologic evidence suggests that no such glaciations occurred in the billion or so years before the Neoproterozoic, when the sun was even cooler” Hoffman & Schrag (2000: 75).

Paleogeographic reconstructions for this time indicate that the bulk of the continental land mass probably lay in middle to low latitudes during the late Precambrian, a paleogeography which has not recurred subsequently. Kirschvink suggests, "[i]n a qualitative sense, this could have had a fundamental impact on global climate, as most of the solar energy adsorbed by the earth today is trapped in the tropical oceans (in contrast to the continents which are relatively good reflectors) and in high latitude oceans which often have fog or other cloud cover. Furthermore, if extensive areas of shallow, epicontinental seas were within the tropics, a slight drop in sea level would convert large areas of energy-absorbing oceanic surface to highly reflective land surface, perhaps enhancing the glacial tendency." Kirschvink (1992: 51-52).

When a significant proportion of the continental landmass lies near the poles, as it does today, carbon dioxide in the atmosphere remains in high enough concentrations to keep the planet warm. When global temperatures drop enough that glaciers cover the high-latitude continents, as they do in Antarctica and Greenland, the ice sheets prevent chemical erosion of the rocks beneath the ice. Moreover, ice-cover is inhospitable to most plant life, so photosynthesis is also inhibited. With the principal carbon sinks suppressed, the carbon dioxide in the atmosphere rises to a level high enough to fend off the advancing ice sheets, maintaining an equilibrium. If all the continents cluster in the tropics, on the other hand, they would remain ice-free even as the earth grew colder and approached the critical threshold for a runaway freeze. The carbon dioxide 'safety switch' would fail because carbon burial continues unchecked. (Partly after Hoffman & Schrag 2000: 75).

Note, however, that the onset of glaciation may have begun with the break-up of Rodinia, some 750 Ma (Walker, 2003: 241), an inconsistency which requires some accommodation from current hypotheses.

Mechanisms Permitting Thawing

Having found a plausible mechanism to permit low-latitude glaciation, there remains the opposite problem: although the snowball events appear to have lasted a very long time, obviously they did end, and more quickly than continental rafting away from the equator alone would permit.

Kirschvink appears to have been first to suggest that the reversal of ice house conditions could be effected, "through the gradual buildup of the greenhouse gas, CO_2, contributed to the air through volcanic emissions. The presence of ice on the continents and pack ice on the oceans would inhibit both silicate weathering and photosynthesis, which are the two major sinks for CO_2 at present. Hence, this would be a rather unstable situation with the potential for fluctuating rapidly between the 'ice house' and 'greenhouse' states." Kirschvink (1992: 52), the onset of the latter possibly occurring in as little as a few hundred years. Hoffman & Schrag (2000: 68).

An interesting constraint on this hypothesis is provided by relatively high the freezing point of CO_2: about -78° C. If the polar areas were consistently colder than this, they would form an additional CO_2 sink.

"With this greenhouse scenario in mind, climate modelers Kenneth Caldeira of Lawrence Livermore National Laboratory and James F. Kasting of Pennsylvania State University estimated in 1992 [Caldeira & Kasting (1992)] that overcoming the runaway freeze would require roughly 350 times the present-day concentration of carbon dioxide [~0.12 bar]. Assuming volcanoes of the Neoproterozoic belched out gases at the same rate as they do today, the planet would have remained locked in ice for up to tens of millions of years before enough carbon dioxide could accumulate to begin melting the sea ice. A snowball earth would be not only the most severe conceivable ice age, it would be the most prolonged." Hoffman & Schrag (2000: 72).

Phenomena Relating to the Global

Snowball Model

The test of any historical model lies in its consistency with observation – past and future – which is a form of prediction. The global snowball model is potentially very powerful, providing a unifying explanation for a number of diverse phenomena. Further, several implications may themselves be testable.

- Global Distribution

The model 'predicts' a global distribution of synchronous glacial units which is consistent with our understanding at present, although the dating of many of these units is still quite unclear and even the interpretation of some units as diamictites is far from straight forward. However, this problem is, at least in principle, amenable to attack by standard dating, paleogeographic and sedimentological methodologies.

- 'Late' Banded Iron Formations

Iron is virtually insoluble in the presence of oxygen. 'Normal' banded iron formations (BIFs) occur much earlier in earth history when the atmosphere (and hence the oceans) contained very little oxygen and iron could readily dissolve. "Kirschvink reasoned that millions of years of ice cover would deprive the oceans of oxygen, so that dissolved iron expelled from seafloor hot springs could accumulate in the water. Once a carbon dioxide induced greenhouse effect began melting the ice, oxygen would again mix with the seawater and force the iron to precipitate out with the debris once carried by the sea ice and glaciers." Hoffman & Schrag (2000: 72).

Banded Iron formations "occur in Proterozoic rocks, ranging in age from 1.8 to 2.5 billion years old. They are composed of alternating layers of iron-rich material (commonly magnetite) and silica (chert). Each layer is relatively thin, varying in thickness from a millimeter or so up to several centimeters. Here is one theory as to how they might have formed: It is theorized that the Earth's primitive atmosphere had little or no free oxygen. In addition, Proterozoic rocks exposed at the surface had a high level of iron, which was released at the surface by weathering. Since there wasn't any oxygen to combine with it at the surface ... the iron entered the ocean as iron ions. At the same time, primitive photosynthetic blue/green algae were beginning to proliferate in the near surface waters. As the algae would produce O_2 as a waste product of photosynthesis, the free oxygen would combine with the iron ions to form magnetite (Fe_3O_4), an iron oxide. This cleansed the algae's environment. As the biomass expanded beyond the capacity for the available iron to neutralize the waste O_2 the oxygen content of the sea water rose to toxic levels. This eventually resulted in large-scale extinction of the algae population, and led to the accumulation of an iron-poor layer of silica on the sea floor. As time passed and algae populations re-established themselves, a new iron-rich layer began to accumulate. Unfortunately, the algae were of relatively low intelligence and were unable to learn from their past excesses (this was also before the EPA), so they would again proliferate beyond the capacity of the iron ions to clean up their waste products, and the cycle would repeat. This went on for approximately 800,000,000 years!" GeoMan's Banded Iron Page.

“[T]he presence of floating pack ice should reduce evaporation, act to decouple oceanic currents from wind patterns and, by inhibiting oceanic to atmosphere exchange of O_2, would enable the oceanic bottom waters to stagnate and become anoxic. Over time, ferrous iron generated at the mid-oceanic ridges or leached from the bottom sediments would build up in solution and, when circulation became reestablished toward the end of the glacial period, the iron could oxidize to form a ‘last-gasp’ blanket of banded iron formation deposition in upwelling areas. Iron-rich deposits of this sort are known from several late Precambrian glacial units in Canada, Brazil, Australia, and South Africa. The banded iron-formations in the Rapitan Group of northern Canada are interbedded with tillites and contain occasional dropstones.” Kirschvink (1992: 52).

Associated sedimentary manganese deposits provide a parallel argument. Kirschvink (2002).

The BIFs and manganese deposits seem to require a hard-frozen ocean, and are currently difficult to reconcile with the softer, ‘slush-ball’ version of the global glaciation theory.

- Cap Carbonates

The snowball glacial units are almost universally overlaid by carbonate units, dubbed 'cap carbonates,' which today form only at tropical latitudes. The lithological transitions from diamictite to carbonate are abrupt and do not appear to correspond to lost time; thus it is assumed that they record a genuinely rapid change in depositional regime.

This information was unavailable to Kirschvink and has largely come to be understood through the work of Paul Hoffman and Daniel Schrag (***e.g.*** Hoffman ***et al***., 1998), who postulate thick sequences of carbonate rocks as the expected consequence of, “extreme greenhouse conditions unique to the transient aftermath of a snowball earth.” Once the Earth had frozen over, an extremely high carbon dioxide atmosphere would be needed to raise temperatures to melting point at the equator. Once melting began, however, low-albedo seawater would replace high-albedo ice, and the runaway freeze is reversed. The greenhouse atmosphere may have driven surface temperatures as high as almost 50 degrees C.

“Resumed evaporation also helps to warm the atmosphere because water vapor is a powerful greenhouse gas, and a swollen reservoir of moisture in the atmosphere would drive an enhanced water cycle. Torrential rain would scrub some of the carbon dioxide out of the air in the form of carbonic acid, which would rapidly erode the rock debris left bare as the glaciers subsided. Chemical erosion products would quickly build up in the ocean water, leading to the precipitation of carbonate sediment that would rapidly accumulate on the seafloor and later become rock. Structures preserved in the Namibian cap carbonates indicate that they accumulated extremely rapidly, perhaps in only a few thousand years. For example, crystals of the mineral aragonite, clusters of which are as tall as a person, could precipitate only from seawater highly saturated in calcium carbonate.” Hoffman & Schrag (2000: 73).

Current explanations for the formation of the cap carbonates seem to require a hard-frozen ocean, and are currently difficult to reconcile with the softer, 'slush-ball' version of the global glaciation theory.

- Carbon Isotope Composition

Cap carbonates also exhibit an unusual $^{12}C/^{13}C$ profile. The same patterns are observed in cap carbonates worldwide. Hoffman ***et al***. (1998) reported that the isotopic variation is consistent over many hundreds of kilometres of exposed rock in northern Namibia.

Immediately below the glaciogenic rocks, the carbon isotope ratio falls from normal biogenic values to abiotic, volcanic levels, presumably recording a profound drop in biogenic productivity as ice advanced over the high- to mid- latitude oceans. The 'hard' version of the snowball hypothesis posits ice cover extending all the way to the equator, when biogenic productivity would almost cease. In such a situation, however, calcium carbonate precipitation would also cease, so even if this event did occur, no carbon isotope data would exist.

In the cap carbonates above the glacial deposits, the abiotic carbon isotope ratio recurs immediately above the glaciogenic units, gradually climbing back to normal biogenic values over a few hundred metres of section, as the biosphere recovers and biogenic productivity rebounds.

Similarly sharp carbon isotope excursions are associated with documented mass extinctions, though the Neoproterozoic excursions are the most extreme and of the longest duration. Knoll & Carroll (1999);

Hoffman & Schrag (2000).

Snowball Events

Although there is some limited evidence for a profound global ice age at about 2,300 to 2,200 Ma (Kirschvink, 2002), the well-documented events are all Neoproterozoic.

~710 to 680 Ma: The Sturtian Glaciation(s)

Rice ***et al***. (2003) concludes that glacial deposits corresponding to the earliest (Sturtian) glaciation are absent in Norway, Svalbard, eastern Greenland, Scotland and Death Valley. "However, cap-carbonates to this glaciation can be recognized in many sequences, based on the isotopic and sedimentological characteristics of the Sturtian cap-carbonates in Namibia (Rasthof), NW Canada (Rapitan), and South Australia (Sturt). In all these cap-carbonates, $d^{13}C$ rises sharply from –4‰ to +5‰ in relatively organic-rich sediments. Probable Sturtian cap-carbonates, without underlying diamictites, include the lower Russøya Member from Svalbard and the lower Beck Springs Formation from Death Valley." Rice ***et al***. (2003).

605 to 585 Ma: The Varanger-Marinoan Ice Ages

The Marinoan glaciation is the most widespread and most easily recognised of the snowball events. Unlike the earlier Sturtian glaciation, the Marinoan was presaged by a large (up to 15‰) though gradual decline in $d^{13}C$. Unequivocal Marinoan deposits include the Ghaub (northern Namibia), Elatina (South Australia), and Ice Brook (north-western Canada) formations, all of which are the higher of two diamictites.

Marinoan glacial deposits are overlaid by a distinctive transgressive, laminated cap-dolostone, which variably contains isopachous cements, accretionary oscillation megaripples, tubestones, and peloids. The cap-dolostone is bounded above by a flooding surface that corresponds to an increase in the fraction of siliciclastic sediments and, commonly, a shift to from dolomite to calcite. In some successions, seafloor barite and aragonite cements occur at this transition.

Throughout the cap-dolostone, d^{13}C remains consistently in the range -2 to -4‰.

Applying these unique isotopic and sedimentological boundary conditions as correlation tools, Rice ***et al***. (2003) concluded that the diamictite pairs Petrovbreen + Wilsonbreen (northeast Svalbard), Ulvesø + Storeelv (eastern Greenland), and Surprise + Wildrose (Death Valley) are jointly Marinoan in age. These criteria also indicate that the thick Port Askaig (750m) and Smalfjord (420m) diamictites in Scotland and Norway, respectively, are Marinoan. These correlations are important because, in both cases, the Marinoan diamictite is the lower of two glacial horizons. Thus, it is concluded that the upper diamictites in Norway (Mortenses) and Scotland (Loch na Cille) correspond to a third glaciation: the Varangian.

Varangian glacial deposits are not widespread, but overlie and appear to be related to the largest Neoproterozoic negative d^{13}C anomaly (-8‰). This shows up globally between Marinoan and Ediacaran-aged strata (***e.g.*** the Wonoka Formation in South Australia and the Huqf Group in Oman).

(After Rice ***et al***. 2003.)

Biological Consequences

Extinctions

It has been suggested that the time of the Varanger-Marinoan glaciations, which lasted from approximately 605 to 585 Ma (Martin ***et al***., 2000), was an interval of widespread extinction, a contention based mainly on carbon isotopic profiles, which "display strong negative as well as positive excursions. Negative excursions are specifically associated with the major ice ages that mark immediately pre-Ediacaran time. Much research is currently focused on this unusual coupling of climate and biogeochemistry, and both paleoceanographic models and clustered phytoplankton extinctions suggest that these ice ages had a severe impact on the biota – potentially applying brakes to early animal evolution." Knoll & Carroll (1999: 2135).

Acritarchs are sometimes supposed to have been major victims of a mass extinction, around 610 Ma, perhaps associated with the glaciations, when some estimates suggest that up to 70% of taxa went extinct. Interestingly though, the late Gonzalo Vidal, perhaps the most widely quoted and respected of researchers into Precambrian acritarchs, while acknowledging the very low diversity of acritarchs reported from this interval, also points out the scarcity of rocks likely to yield good acritarch assemblages, and stops short of any causal speculation. Vidal (1981).

When considering a possible mass extinction at this time, it must be remembered that the Twitya fauna, ***Aspidella terranovica*** and ***Nimbia occlusa***, or at least forms which left behind indistinguishable fossils, passed through the Varanger-Marinoan.

Effects on Metazoan Evolution

The Sturtian snowball period is shortly succeeded by the earliest unambiguous record of metazoan animals and, after an additional 170 Ma and two more low-latitude glaciations, by the appearance of shelly Cambrian faunas. Thus, it was an interesting stage in the evolution of multicellular animals, posing not only the question of how early life survived under such environmental stress (Hyde ***et al***., 2000) but whether the glaciations actually acted to shape metazoan evolution in some way, as first proposed by Martin Rudwick in the 1960s. ***See, e.g.*** Harland & Rudwick (1964: 36): "[A]t the end of the ice age, the improvement in climate and the rise of the sea level would have re-created a variety of favourable but biologically empty environments, in which the opportunity would exist for radical evolutionary changes to take place."

This argument is rather compelling: "Explosive" radiations following mass extinction events are well-documented from the Phanerozoic so it is tempting to extend the snowball earth speculation to suggest that these evolutionary changes were actually driven by the glaciations – “the periodic removal of all life from higher latitudes would create a series of post-glacial sweepstakes, perhaps allowing novel forms to establish themselves, free from the competition of a preexisting biota.” Kirschvink (1992: 52).

With their usual flair for the dramatic, Hoffman & Schrag (2000: 74) observe (not quite accurately): “Eukaryotes … had emerged more than one billion years earlier, but the most complex organisms that had evolved when the first Neoproterozoic glaciation hit were filamentous algae and unicellular protozoa. It has always been a mystery why it took so long for these primitive organisms to diversify into the 11 animal body plans that show up suddenly in the fossil record during the Cambrian explosion. … A series of global freeze-fry events would have imposed an environmental filter on the evolution of life. All extant eukaryotes would thus stem from the survivors of the Neoproterozoic calamity.”

Some evidence for the extent of eukaryotic extinctions may be evident in the universal tree of life. Hoffman & Schrag (2000) propose that eukaryotic lineages may have been ‘pruned’ during the snowball earth episodes – a concept seemingly akin to Gould’s (1989) ‘decimation by lottery’ – which is certainly plausible. However, their supporting contention that universal trees “depict the eukaryotes’ phylogeny as a delayed radiation crowning a long, unbranched stem” (p. 74) is neither strong evidence for pruning ***per se***, nor is the claim consistent with any published molecular biology as far as I am aware. My own understanding of the literature is that this model of eukaryote phylogeny is unique to Hoffman & Schrag, and contradicted by the overwhelming bulk of published research [sidebar ®].

However, their view does find an echo in Ernst Mayr’s otherwise inexplicable comment that “diversity of the early eukaryotes seemingly remained rather low for the period from 1,700 to 900 million years ago, but then rose rapidly to experience a veritable explosion of protistan microfossils during the Cambrian.” Mayr (2001: 48-50).

More plausibly, Hoffman & Schrag suggest that, in the face of varying environmental stress, many organisms respond with wholesale genetic alterations. Severe stress encourages a great degree of genetic change in a short time, because organisms that can most quickly alter their genes will have the most opportunities to acquire traits that will help them adapt and proliferate.

Widely separated refuge communities could accumulate genetic diversity over millions of years. When two groups that start off the same are isolated from each other long enough under different conditions, chances are that independent mutation will produce new species. Repopulations occurring after each glaciation would come about under unusual and rapidly changing selective pressures quite different from those preceding the glaciation; such conditions would also favour the emergence of new life forms. After Hoffman & Schrag (2000: 75).

Refugia

Founder communities must have survived the snowball events, perhaps in a variety of habitats. Psychrophilic (cold-loving) representatives are today known from among the cyanobacteria, dinoflagellates, and some algae, which can live in snow and on the surfaces of rock particles in floating sea-ice. Less cold-tolerant organisms may have held out in locations where geothermal action preserved warm micro-climates – some perhaps from around deep-sea fumaroles, though photoautotrophs must clearly have 'over-wintered' elsewhere. Hoffman & Schrag (2000: 74) make the reasonable point that the steep and variable temperature and chemical gradients endemic to ephemeral hot springs would preselect for survival in the runaway greenhouse conditions which they postulate to succeed the snowball events.

However, we may not yet need to invoke the image of a few last bastions of life huddled around some deep-sea vent. It is not clear what fraction of the equatorial oceans in deep water would form pack ice, as these zones would still absorb large amounts of the incident solar radiation, perhaps enough to prevent ice formation. Hence, we might expect to find some warm tropical "puddles" in the sea of ice, shifting slightly from north to south with the seasons. In turn, this should produce extreme climatic shifts in some local areas. Kirschvink (1992: 52). A variant of this supposition finds support from the results of computer simulations with a coupled climate/ice-sheet model, reported in Hyde ***et al*.** (2000): "To simulate a snowball Earth, we use only a reduction in the solar constant compared to present-day conditions and we keep atmospheric CO_2 concentrations near present levels. We find rapid transitions into and out of full glaciation that are consistent with the geological evidence. When we combine these results with a general circulation model, some of the simulations result in an equatorial belt of open water that may have provided a refugium for multicellular animals."

"Although the extent of glaciation remains uncertain, if the protostome-deuterostome divergence occurred before these world-wide glaciations, they are likely to have imposed a severe ecological constraint on the forms that could have survived. Runnegar (2000) argued that conditions even within the refugia would have allowed survival only of small, simply constructed, pelagic bilaterian stem group forms (such as proposed for the remote ancestors of the Bilateria by Davidson ***et al***., 1995). Evolution of adult body plans in the bilaterian stem group would have had to await the more favorable late Neoproterozoic environments." Erwin & Davidson (2002: 3024).

Also see Runnegar (2000); Peterson & Davidson (2000).

Conclusion: Current Status of the Snowball Hypotheses

Overall, the various snowball earth hypotheses have potential to explain diverse observations of the Proterozoic geological record: synchronous low latitude diamictites associated with carbonate deposits, carbon isotope excursions, banded iron formations, and so on. Nevertheless, I feel Hoffman & Schrag (2000: 74) somewhat overstate their case with the claim that the "strength of the hypothesis is that it simultaneously explains all these salient features, none of which had satisfactory independent explanations." As Kirschvink (2002: table 1) makes clear, neither of the major variants – 'hard' snowball or slushball – is presently able to explain all observations, and "a more complex scenario may be closer to the actual truth than any of the discrete models" proposed to date.

The link with evolutionary phenomena, though tantalising, is at this time a less well-developed speculation.

Chris Clowes 0309xx

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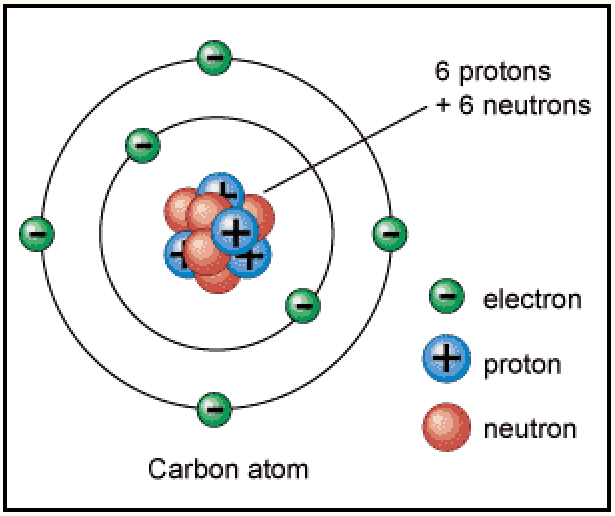
Notes

[1] We were embarrassed to find that there is no other full explanation of carbon isotopes in Palaeos, so here we go. We assume no background.

All ordinary materials are made up of atoms. Atoms contain a very small, very dense ***nucleus***. The nucleus is made up of two kinds of particles: ***protons***, which have a positive charge, and ***neutrons*** which are very similar, but have no charge. The electric charges in the nucleus do not cause the nucleus to fly apart because these ***nucleons*** (protons & neutrons) are held together by the ***strong nuclear force***, which is stronger than electrical repulsion at very short distances. The nucleus is surrounded by a very much larger, but more diffuse, cloud of negatively-charged ***electrons***. Each electron has exactly the same charge as a proton, although it is much less massive. This supplies overall electrical charge neutrality to the atom.



The chemical behavior of atoms is ***almost*** (remember the ***almost***!) completely determined by the electron cloud, and the number of electrons is controlled by the number of protons in the nucleus. So, any atom with 6 protons in the nucleus behaves about the same as any other atom with the same count. Thus ***elements*** are defined by reference to the number of protons in the nucleus, which is also the ***atomic number*** of the element. Any atom with 6 protons is an atom of ***carbon***.

Notice we have said nothing about neutrons. For chemical purposes, they don't matter. However, only nuclei with certain numbers of neutrons are stable for each element. Thus, we only find carbon atoms with 6, 7, or 8 neutrons. These different varieties of carbon atom are referred to as ***isotopes***. Isotopes are referred to by their total number of nucleons. Thus, the most common type of carbon has 6 protons (by definition) and 6 neutrons and is designated ^{12}C. The isotope ^{13}C is also common and is also stable. Carbon-14, or ^{14}C, is created in very small quantities by nuclear reactions in the upper atmosphere involving nitrogen (element 7) and cosmic rays. ^{14}C is not stable. One of the neutrons tends to flip back to being a proton, with the release of energy in the form of a very energetic electron. That energetic electron is one form of ***radioactivity***. There is a 50% chance that this ***radioactive decay*** will happen to any given atom of ^{14}C in 5730 years. Thus, we say that ^{14}C is a ***radioactive isotope*** with a ***half-life*** of 5730 years.

In the universe as a whole, ^{12}C makes up about 99% of all carbon, while ^{13}C is about 1%. ^{14}C makes up a vanishingly small fraction, which we can ignore. All atoms of carbon ought to behave in ***almost*** same way in chemical reactions. Do you still remember the "almost"? It becomes important here because it turns out that the enzymes involved in photosynthesis are a little biased. They are slightly more likely to fix CO_2 molecules with ^{12}C than we would expect by chance. Virtually all carbon in living things ultimately derives from photosynthesis. Thus almost all ***organic*** (or ***biogenic***) ***carbon,*** carbon which is or was part of a living creature, ***is isotopically light***, meaning it has slightly more than the usual 99% ^{12}C. When a great deal of carbon is tied up in organic sediments, the remaining carbon in atmospheric carbon dioxide becomes ***isotopically heavy***. This is called a ***positive excursion*** in ^{13}C, or, for those wishing to be particularly obscure, a ***positive*** $\boldsymbol{\delta^{13}C}$ ***anomaly***. Fortunately, it is remarkably easy to measure the ratios of carbon isotopes to very high precision using mass spectroscopy (= ***mass spec***). By examining ancient inorganic carbon, we can read the isotopic state of the atmosphere at any given time in the past. There can be great debate about the reasons for an excursion, but the existence, and usually the magnitude, of the excursion are easily determined and quite reproducible.

Footnote to footnote: We apologize for the stupid picture. ***Do not*** get the idea that electrons orbit about the nucleus like a planet circling a star. That is completely inaccurate. Explaining why would take too long, so we'll take it up another time.

[2] Chris's essay explains the cap carbonates **here**. These are calcium magnesium carbonates, or dolomite [$CaMg(CO_3)_2$], associated with the end of the major glaciations, and overlying the glacial tillite (unsorted terminal glacial rock) on all continents. The cap carbonates are sometimes found without tillite, presumably deposited in deep water not actually reached by the continental glaciers.

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The Ediacaran (Vendian) -1

The Ediacaran Period of the Neoproterozoic Era: 630 to 542 Mya

Abstract

This page describes the stratigraphy and fossil record of the Ediacaran (f/k/a Vendian) Period, including a brief introduction to the Ediacaran fauna. Some famous Ediacaran lagerstätten are briefly discussed, followed by a sketched outline of some of the major evolutionary events.

Keywords: Ediacaran, Vendian biota, fossil record, evolution, Varangian, Varanger-Marinoan, snowball earth, Ediacaran, Metazoan

Related Topics

Further Reading

- ***The Precambrian-Cambrian Boundary*** – Cowie, J.W. and Brasier, M.D. (eds.)

radiation

Introduction

The Ediacaran Period and System were first proposed by Sokolov 1952, from drill core sequences on the Siberian Platform. Sokolov & Fedonkin (1984). Although the Ediacaran was not embraced quickly, it is now recognised by the Subcommission on Precambrian Stratigraphy and has now come into almost universal usage -- although frequently still called the Vendian.

As with the better-known Cambrian Period, the absolute age constraints on the Ediacaran interval have ebbed and flowed over the past few years; the best current best guess is from 630 to 542 million years (Ma) ago.

The Precambrian era was a period in earth history before the evolution of hard-bodied and complex organisms. Throughout the extent of both periods, dominant Precambrian and Ediacaran organisms were simple, entirely marine, and for the most part soft-bodied: hard-bodied organisms did not occur until nearly the beginning of the Cambrian Period when the so-called "small shelly faunas" appeared.

Stratigraphy

The Lower Boundary

The Ediacaran Period and System were first proposed by Sokolov (1952), from drill core sequences on the Siberian Platform. It was officially adopted by the ICS in 2004. The base of the Ediacaran (the Global Standard Stratotype Section and Point, or **GSSP**) is defined by reference to the base of the Marinoan cap carbonate (Nuccaleena Formation), immediately above the Elatina diamictite in the Enorama Creek section, Flinders Ranges, South Australia. ***See*** discussion at The Ediacaran Period- A New Addition to the Geologic Time Scale.

While we follow the ICS designation, we agree with the dissenting opinion of the Russian members. This may not have been the best pick for a number of reasons:

1) The age of the GSSP is very poorly constrained.

2) At least one widespread "Ice Age" post-dates the GSSP.

3) There are no signs of metazoan life anywhere near the GSSP, much less any Ediacaran assemblage.

4) the name is confusing, since it suggests an

Related Pages

- Ediacaran Biota
- Cambrian Period
- Doushantuo Formation
- Ediacaran – Cambrian Geological Column

Other Web Sites

- Possible cnidarians from the Twitya Formation, Mackenzie Mountains

Ediacaran assemblage.

The Upper (Ediacaran–Cambrian) Boundary

Since 1947, when H.E. Wheeler initiated debate with the suggestion that the Precambrian-Cambrian boundary should be based upon the first appearance of trilobites, much has ensued. Progress has largely been facilitated by the International Geological Congress (IGC) and the establishment in 1960 of a Subcommission on Cambrian Stratigraphy. The classical idea of placing the boundary at an unconformity has been displaced by the search for monofacial, continuous deposition sequences across the boundary, with the view to selecting a stratotype.

The search itself produced a wealth of data from around the world – including the Palaeotethyan Belt, Siberian Platform, and England – eventually focusing upon south-east Newfoundland. In 1991 the International Subcommission on Cambrian Stratigraphy (through its Working Group on the Precambrian-Cambrian Boundary) made the official decision to draw the base on the Cambrian at the first appearance date (FAD) of ***Trichophycus pedum*** (fig. 1) in the reference section at Fortune Head.

Fig. 1: The horizontal burrow trace fossil, ***Trichophycus*** (formerly ***Phycodes***) ***pedum*** defines the lower boundary of the Cambrian in the reference section at Fortune Head, southeastern Newfoundland. [Image courtesy of Dr. Gerd Geyer, Institut für Paläontologie, Bayerische Julius-Maximilians-Universität, Würzburg, Germany.]

Current Chronology of the Ediacaran

The name

Era	Period	Epoch	Russian Stage	Approx. Base	Type of Unit
Paleozoic	Cambrian	Lower Cambrian	Toyonian Botomian Atdabanian	513.0 ±2.0	GSSP not designated
				undefined	undefined
			Tommotian Nemakit-Daldynian	542.0 ±1.0	
Neo-proterozoic	Ediacaran			~630	
	Cryogenian			850	
	Tonian			1000	

"Ediacaran," in its geochronologic sense, used to mean an upper subunit of the Vendian, approximately 565 to 543 Ma (Bowring & Erwin 1998), with a stratotype in South Australia. This was supposed to take the age of the Ediacaran fauna, while the Varangian sub-period took in the age of the Varangian glaciation – presumably the first half of the Vendian.

Unfortunately, both nomenclature and dating have changed considerably:

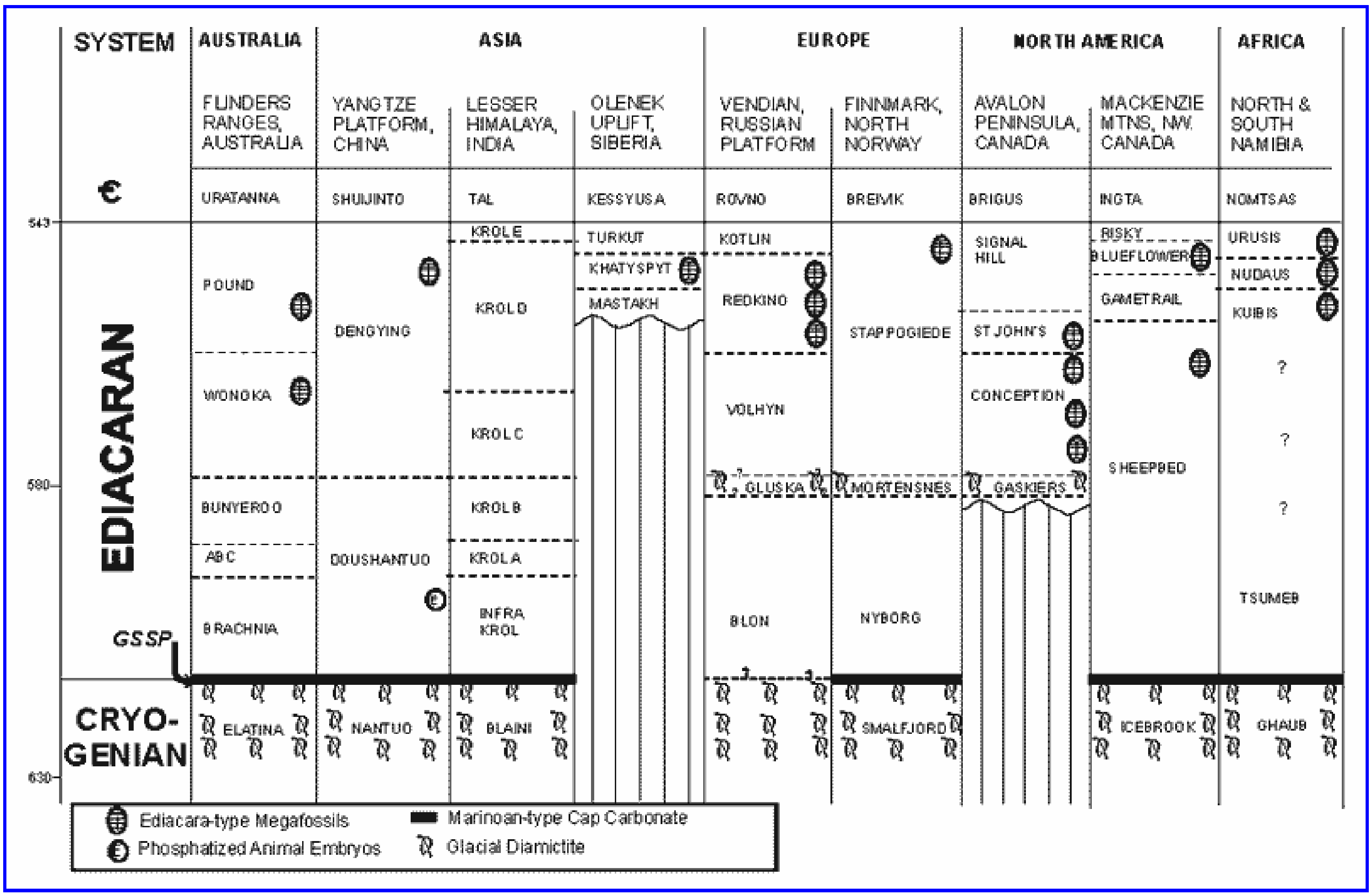
The Ediacaran is still the age of the Ediacaran fauna, sort of. We can conceive of the Ediacaran as a period during which the Ediacaran fauna presumably evolved and in which conditions were generally right for it to live, even if we have yet to establish its presence with certainty. The earliest signs of metazoan life at Chengjiang almost reach the 600 My mark, and the earliest Twitya trace fossils push 610 My. The GSSP lies somewhere between 600 and 635 Ma, with the most likely date being **630 Ma**. Thus the correspondence between the GSSP and metazoan life is not all that unreasonable. The Ediacaran-Cambrian boundary (***i.e.*** the base of the Cambrian, is still dated at **542 Ma** -- about the same as it has been for the last decade.

The Cryogenian is a chronostratigraphic unit. That is, its base is ***defined*** in terms of years. It cannot move, and it has no GSSP. Thus its base is fixed at **850 Ma** and its end is defined as the beginning of the Ediacaran, or about **630 Ma**.

The "Varangian" is not a recognized unit. Fortunately, the age of the Varanger glaciation has also been re-dated -- at **800 to 630 Ma**. Thus, the Cryogenian covers essentially the same turf. Despite the sanction of the ICS, the term "Varanginian" is used far more often than "Cryogenian." The broad (but short-lived) Ice Age which occurred about 600 or 580 My is a distinct event. The tendency in the recent literature has been to call it the **Marinoan** and to distinguish it from the world-wide **Varanger** (or Varanginian) Ice Age which ended about 630 My.

The "Vendian" no longer exists as a stratigraphic unit. This is a ***good thing***. Personally, we liked the name. It was easy for even Texans to pronounce **[1]**. It honored the important Russian contributions to Pre-Cambrian stratigraphy. It was more widely used than "Ediacaran," and less easily misspelled. However, it was always hopelessly ambiguous. We suspect the Russians will have their day when the Early and Middle Cambrian ages are finally agreed on.

The following more detailed look of the stratigraphy of the Ediacaran comes from the **Report of the Terminal Proterozoic Subcommission of the International Commission on Stratigraphy**, Knoll *et al*. (2000):



Paleogeography

Major Tectonic Events

The Precambrian supercontinent usually known as Rodinia (or, rarely, as Proto-Pangea or Ur-Pangea) formed ~1,000 Ma from the amalgamation of three or four pre-existing continents, in an event known as the Grenville Orogeny. Perhaps beginning ~700 Ma, but protracted over many millions of years, Rodinia began breaking up into three major blocks: West Gondwana, East Gondwana, and Laurasia. Subsequently - perhaps ~540 Ma - West and East Gondwana merged in the mountain-building event known as the Pan-African Orogeny. (After Rogers 1996.)

Climate

605 to 585 Ma: The Varanger-Marinoan Ice Ages

It has been suggested that the Varanger-Marinoan ice ages, which lasted from approximately 605 to 585 Ma (Martin et al. 2000), were "snowball" events in which glaciation extended to very low latitudes; possibly right to the equator. It may have been a time of widespread extinction, a contention based mainly on carbon isotopic profiles, which display large negative excursions. Anyone who thinks they understand the "snowball" phenomenon should consult the defense of our strongly held position of total confusion on this subject.

Post-Glacial Ediacaran

The post-glacial Ediacaran was warm to hot and relatively arid at low and most middle latitudes. Even at high latitudes in the south, there is evidence of a warm, humid climate. The latest Ediacaran and earliest Cambrian were marked by a return to colder conditions, with some glaciation at high latitudes. (mod. ATW060108)

Paleontology

General Characteristics

Trace fossils

Body fossils typically of cnidarian grade dating from as early as 600 or 610 Ma - ***e.g***. the Twitya fossils are simple cup-shaped animals, possibly similar to the sea anemones of today.

Doushantuo Phosphate

Mineralised skeletons of uncertain affinity - the 'small shelly fauna' - appear just before the beginning of the Cambrian, ~550 Ma, increasing in numbers and diversity towards the Tommotian. The most common skeletal materials are calcium carbonate (aragonite or calcite) and varieties of calcium phosphate. Many of the latter may originally have been carbonates, phosphatized during preservation. The oldest of these to occur abundantly are ***Cloudina*** and the allied genera comprising the family Cloudinidae: small, conical fossils made of calcium carbonate, first (?) appearing in the Ediacaran Stirling Quartzite of California (Langille, 1974) and persisting into the Cambrian. Anabarites and Cambrotubulus are other Ediacaran SSF taxa, known from Siberia and Mongolia.

Fossil Localities

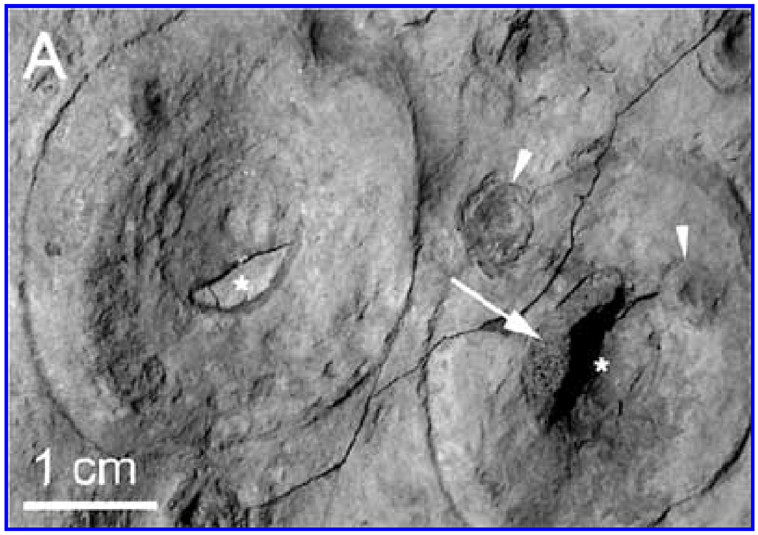
610 to 600 Ma: McKenzie Mountains

Simple disc-like impressions, interpreted as cnidarian-grade body fossils, have been reported from the inter-tillite beds of the 610 to 600 Ma Twitya Formation, in the Bluefish Creek area of the McKenzie Mountains, north-western Canada. Hofmann ***et al***. (1990). The Twitya Formation is a ~800 m thick succession of siliciclastic turbidites within the Windermere Supergroup. Fossils occur in the interval 170 to 200 m below the top of the formation.

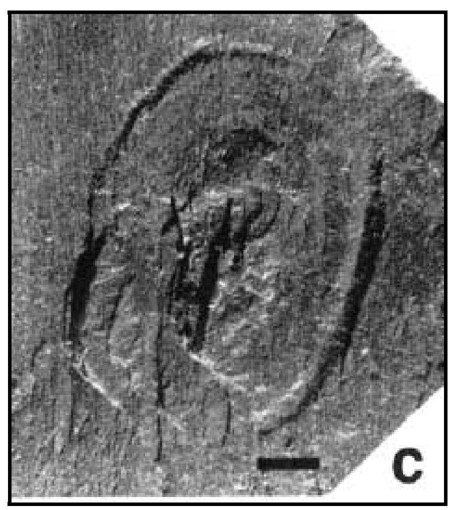
The age of the assemblage (approximately 610 Ma, Martin ***et al***. 2000: fig. 1), indicates deposition during the early part of the Varanger-Marinoan ice age. This placement is supported by overlying deep-water diamictite containing dropstones, rare striated clasts, and relict ice-cemented boulders.

The Twitya impressions are preserved as "very simple, convex discoidal and annular reliefs on the lower surfaces of thin sandstone beds, and as counterparts on the tops of the underlying shale beds." Hofmann ***et al***. (1990: 1199). This mode of preservation is quite characteristic of the Ediacaran fauna, which typically occurs in somewhat younger rocks. Inorganic sedimentary structures such as gas-evasion marks, load and dewatering structures, are common in the Twitya Formation. However, systematic differences between the presumed fossils and obviously inorganic structures, as well as a high degree of morphological consistency exhibited by the hundred or more specimens, argue strongly for a biogenic origin.

Hofmann ***et al***. provisionally assigned the fossils to three taxa: ***Nimbia occlusa***, ***Vendella***?, and ***Irridinitus***? The last two of these, however, are both probably junior synonyms of ***Aspidella terranovica*** (refer Gehling ***et al***., 2000: 448) so probably only two taxa are represented. Their occurrence at the bottom of turbidite beds suggests a sessile habit. They are



Several examples of ***Aspidella*** in the Fermeuse Fm. of Newfoundland, Canada, from Peterson ***et al***. (2003). These authors make a strong argument, based on mode of life and size distributions, that ***Aspidella*** was a fungal growth form. They expressly disclaim any assertion that ***all*** of the Ediacaran forms were fungi. However, one quite plausibly imagine a Late Neoproterozoic in which sponges, early cnidarians, and fungi contested for ecological dominance.



Possible ***Nimbia*** specimen from the Ediacaran of Norway. Farmer ***et al***. (1992). Note that both ***Nimbia*** and ***Aspidella*** may be holdfast marks left by some organism or colony with a stem and frond-like extensions, as in ***Spriggina***.

most widely interpreted as the basal impressions of cnidarians – either simple pedestal impressions or possibly the remains of a sand 'ballast' retained within the organisms during life – or at least as metazoans of cnidarian grade. "Interpretation as colonial aggregates of prokaryotes (e.g. ***Nostoc***-like balls) is possible but is difficult to reconcile with the morphology and relatively high relief of the remains, their occurrence at the bottom of turbidite beds, and the lack of a carbonaceous film outlining them, particularly in view of the of the fact that carbonaceous compressions are present in the formation." Hofmann ***et al***. (1990: 1202).

The principal significance of this occurrence of cnidarian-grade metazoans is their stratigraphic position below ?Varangian glaciomarine tillites (Aitken 1988, 1989) **[2]**. This is the only Ediacaran-like assemblage found below Varanger glacial deposits anywhere, and provides a useful test for those models positing metazoan evolution to have been arrested during one or more of the Neoproterozoic glaciations. See, ***e.g.,*** Runnegar (2000); Peterson & Davidson (2000).

In addition to the putative cnidarian impressions, the Twitya Formation contains the carbonaceous film taxa, ***Morania*** and ***Beltina***, and also some poorly preserved filamentous microfossils and leiosphaerids.

575 Ma: Ediacarans of the Drook Formation

An impoverished but characteristic Ediacaran assemblage occurs in the upper beds of the Drook Formation, south-eastern Newfoundland, 1500 m stratigraphically below the well-known Mistaken Point fossils; these are the oldest of the large, architecturally complex fossils found so far (Narbonne & Gehling, 2003). The published age constraints on these fossils are from 595 Ma (Varangian glacial diamictites of the Gaskiers Formation) to 565 Ma (well-dated Ediacaran fossils at Mistaken Point occurring 1.5 km stratigraphically higher). Unpublished data noted in Walker (2003: 220) indicates an age of 575 Ma.

Current-aligned fronds attributable to the cosmopolitan Ediacaran, ***Charnia masoni***, and those of a large (up to nearly 2 m in length) new species, ***Charnia wardi,*** occur on the shaly tops of turbidite beds under volcanic ashes. Their position above the glacial marine rocks of the Gaskiers Formation (595 Ma) provides our earliest window on life following the Varanger ice age.

Holotype of ***Charnia wardi*** from the Ediacaran of the Drook Formation, Newfoundland, Canada. From Narbonne & Gehling (2003).

>570 Ma: Weng'An (Doushantuo)

Soft-tissue fossils preserving cellular structures, notably including the earliest record of sponges (see below), occur in the Doushantuo Formation phosphates, exposed near Weng'an in Guizhou (south central China), providing evidence of a diverse biota.

Age constraints on the Doushantuo Formation are rather weak. Chemostratigraphic profiles suggest that Doushantuo fossils predate the last strongly positive carbon isotope excursion of the Proterozoic, dated as 549 ± 1 Ma in Namibia (Grotzinger et al. 1995). Similarly, Doushantuo microfossils provide biostratigraphic evidence that this formation predates the 555 ± 3 Ma sandstones of the Redkino Series, northern Russia, which contain diverse Ediacaran body and trace fossils. Bio- and chemostratigraphic correlations further suggest that Doushantuo fossils are older than diverse Ediacaran assemblages found in Australia, Ukraine, and northern Siberia. However, in the absence of direct radiometric constraints, it is uncertain whether Doushantuo fossils predate frondose Ediacaran remains from Newfoundland, dated at 565 ± 3 Ma, although even the age of 570 Ma for the Doushantuo fossils proposed by Martin ***et al***. (2000) (much less the c. 600 Ma found by Knoll ***et al***., 2000) places them some 5 Ma earlier. Knoll 2003, p. 141, suggests a range of 600 to 590 Ma. Whichever is correct, the deposit seems certain to be post-Varangian.

The reported biota now includes probable algae, cnidarians and bilaterians – the last two largely known from fossil embryos. Unfortunately, diagenetic effects are sometimes difficult to distinguish from genuine biological structures, and much of the evidence from this source, though widely accepted, remains equivocal.

Embryos from the Doushantuo Formation. Image from the website of **Prof. Shuhai Xiao**, Virginia Tech Univ.

565 Ma: Mistaken Point

The oldest of the diverse Ediacaran assemblages yet described is that from Mistaken Point, eastern Newfoundland, where fossils are spectacularly preserved on large bedding surfaces along the sea-cliffs of the Avalon Peninsula. Zircons from interbedded ash have been dated at 565 ± 3 Ma (Benus 1988).

The Mistaken Point assemblage contains a few cosmopolitan taxa such as ***Charnia*** and ***Aspidella***, but most are either endemic or shared only with the Charnwood Forest locality in central England.

555 Ma: Zimnie Gory

The The two most abundant and diverse Ediacaran trace and body fossil assemblages are those from the White Sea coast of Russia and from the Flinders Ranges in South Australia, which together account for 60% of the well-described Ediacaran taxa.

"Many exposures in the White Sea region contain known Ediacaran biotas; however, the best fossil occurrences are found along the shoreline cliffs at Zimnie Gory. These unmetamorphosed and nondeformed (except for present-day cliff-face slumping) siliciclastic rocks belong to the uppermost Ust-Pinega Formation and form the northern flank of the Mezen Basin along the southeast flank of the Baltic Shield." Martin ***et al***. (2000: 842). Zircons from a volcanic ash in the lower part of the sequence preserved between Medvezhiy and Yeloviy Creeks (***id***.) yielded a date of 555.3 ± 3 Ma, the minimum age for the "oldest definitive triploblastic bilaterian, ***Kimberella*** [***see*** sidebar], and the oldest well-developed trace fossils; and it documents that spectacularly diverse and preserved Ediacaran fossils formed more than 12 million years before the base of the Cambrian." ***Id***. at 843.

"The fossil ***Kimberella quadrata*** was originally described from late Precambrian rocks of southern Australia. Reconstructed as a jellyfish, it was later assigned to the cubozoans ('box jellies'), and has been cited as a clear instance of an extant animal lineage present before the Cambrian. Until recently, ***Kimberella*** was known only from Australia, with the exception of some questionable north Indian specimens. We now have over thirty-five specimens of this fossil from the Winter Coast of the White Sea in northern Russia. Our study of the new material does not support a cnidarian affinity. We reconstruct ***Kimberella*** as a bilaterally symmetrical, benthic animal with a non-mineralized, univalved shell, resembling a mollusc in many respects. This is important evidence for the existence of large triploblastic metazoans in the Precambrian and indicates that the origin of the higher groups of protostomes lies well back in the Precambrian." Fedonkin & Waggoner (1997).

Kimberella from the Winter Coast of the White Sea, Russia. Image from Erwin & Davidson (2002). These authors note the presence of certain "adjacent parallel lines [which] are trace fossils associated with ***Kimberella***, and are believed to represent infilled feeding scratches through a microbial mat. The presence of these feeding traces suggests that ***Kimberella*** possessed feeding structure similar to the molluscan radula." ***Id***.

The Ediacaran (Vendian) - 2

555 Ma: Ediacara Hills

Material from the Ediacara Hills (Flinders Ranges) has still not been precisely dated; it is assumed to be approximately coeval with the White Sea fossils, in the region of 555 Ma (see below), but it could be as young as the +1 to +2 d13C interval, dated at 549 to 543 Ma in southern Namibia. Martin ***et al***. (2000: 844). It is the assemblage from this site that is most widely associated with the base of the Ediacaran biota. Although best known for the 'classical' body fossils, the region also provides interesting traces. One ichnotaxon, similar to that from Zimnie Gory, has been interpreted as the radula scratchings of a mollusc (possibly Kimberella).

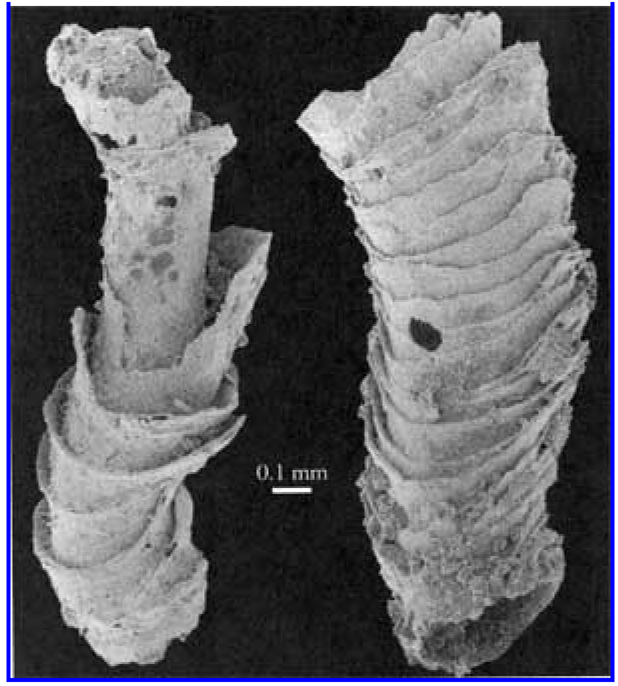
Trace fossil from the Flinders Range

549 to 543 Ma: Nama Group

The Nama Group is a thick (> 3 km) shallow marine and fluvial foreland basin succession, partitioned into northern and southern sub-basins by an intervening arch, across which most stratigraphic units thin, located in southern Namibia. The age range of the Ediacaran assemblages from the Nama Group is the interval 548.8 ± 1 to 543.3 ± 1 Ma. Grotzinger ***et al***. (1995).

In addition to typical Ediacaran taxa,

such as the cosmopolitan ***Pteridinium***, the shelly fossil ***Cloudina*** first appears slightly below the earliest Ediacaran fossils, extends throughout the Ediacaran range, and into the Cambrian. Moreover, a second, unnamed, shelly taxon ("goblet-shaped shelly fossils") coexists with ***Cloudina*** from at least 545 Ma through into the Cambrian. ***Id***.



Cloudina

Ediacaran Life

The following passage is from Benchley and Harper, ***Palaeoecology***, pp.121-123

> "The main and most conspicuous elements of the Vendian biota belong to the Ediacara fauna. The fauna is entirely soft-bodied and was probably adapted to relatively low oxygen conditions in a variety of usually nearshore marine environments. The apparently unique morphology and mode of preservation of the Ediacara fauna led to much debate bout the identity and origins of the assemblage. Are the Ediacarans one of the first true metazoans, or the impressions of an entire ecosystem populated by quite a different type of organism? Seilacher (1989) has reinterpreted the fauna in terms of its constructional and functional morphology. Apart from a distinctive mode of preservation, the fauna shares

the following features: quilted ***pneu*** (rigid, hollow, balloon-like) structures with sometimes additional struts and supports together with a significant flexibility. If the Ediacara animals are in fact divorced from the true metazoans and indeed may be grouped together as a separate grade of organization - termed by Seilacher and others, the ***Vendozoa*** or ***Vendobionta*** (Buss and Seilacher, 1994) - certain generalizations about their anatomy and behaviour, some speculative, may be made. Reproduction may have been by spores or gametes, and growth was achieved by both isometric and allometric modes. The skin or integument had to be flexible, although it could crease and fracture. Moreover the skin must have acted as an interface for diffusion processes, whilst providing a water-tight seal to the animal. This stimulating and original view of the fauna, however, remains controversial. A range of adaptive morphologies has been recognized in the fauna.

There is little doubt that the Ediacara biotas dominated the latest Precambrian marine ecosystem, occupying a range of ecological niches and pursuing varied life strategies probably within the photic zone. It is also possible that these flattened animals hosted photosymbiotic algae, maintaining an autotrophic existence in the tranquil 'Garden of Ediacara' (McMenamin, 1986). The ecosystem, however, was dominated by medusoid pelagic animals and attached, sessile benthos; infaunal animals were sparse; food chains were probably short and the trophic structure was apparently dominated by suspension- and deposit-feeders."

There can be little doubt, on the basis of

"Other Precambrian

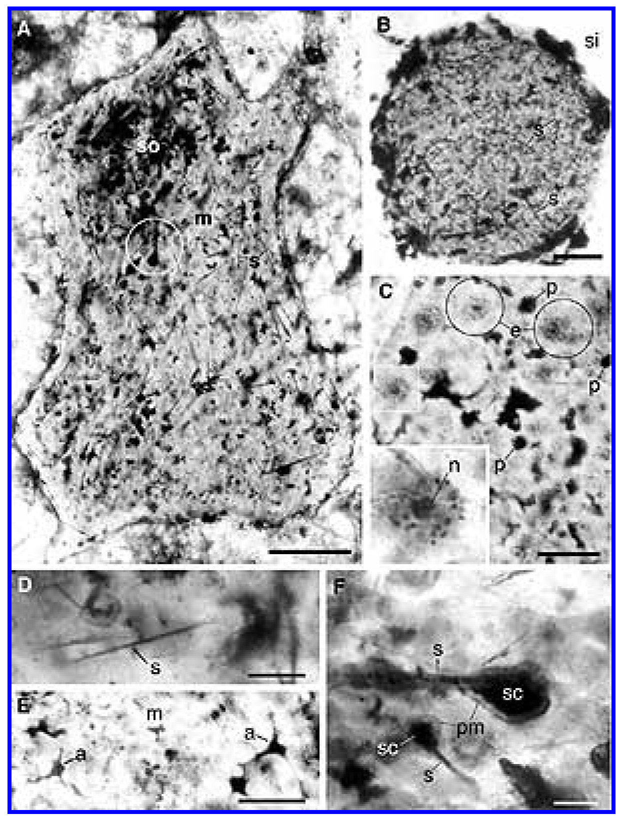
trace evidence alone, that bilaterian metazoans existed in the Ediacaran, and possibly early in the Ediacaran. Although some traces are simple, rather featureless, winding trails, "others display transverse rugae and contain pellets that can be interpreted as of fecal origin. The bilaterian nature of these traces is not in dispute. Furthermore, such traces must have been made by worms, some of which had lengths measured in centimetres, with through guts, which were capable of displacing sediment during some form of peristaltic locomotion, implying a system of body wall muscles antagonized by a hydrostatic skeleton. Such worms are more complex than flatworms, which cannot create such trails and do not leave fecal strings." Valentine (1995: 90). Sets of paired hypichnial ridges strongly hint at an arthropod ***s.l.*** presence.

Unfortunately, it is equally true that the relatively few body fossils known from the late Precambrian do not shed much light on the sequence of evolutionary advances that led to the famously diverse Cambrian taxa. There are a few sign-posts, however:

- Sponges are widely recognised (***e.g***. Nielsen, 2001: 30, 506-507) to be the most primitive of living metazoans, occupying a basal position in metazoan phylogeny, as a sister group to all other Metazoa. Thus their first occurrence in the fossil record is a metric of particular interest. However, only rare occurrences of Precambrian sponges have been reported. The earliest record is of presumed sponge remains from the Doushantuo phosphates, dated around 570 Ma (Li ***et al.,*** 1998), and the earliest described species is Paleophragmodictya reticulata from the ?555 Ma Ediacara locality. However, sponges could have occurred earlier and not been recognised;

fossils do appear to be from the ancestors of modern animals. It is generally agreed that simple burrows and trace-fossils (such as Helminthopsis pictured to the right) found in upper Precambrian rocks were made by primitive worms. These worms, and some other members of the Ediacara Biota, survived the extinction event and took part in the greatest evolutionary event in Earth's history: The Cambrian "Explosion" of Life. Within 35 million years of the end of the Precambrian, representatives of essentially all modern phyla were present in the Cambrian seas." Image and quote from **The Miller Museum of Geology** Queen's University, Kingston, Ontario, Canada.

Sponge sections from



Doushantuo, approximately 580 My. Image from Li ***et al.*** (1998). Note the characteristic randomly-oriented spicules, channels, and porocytes.

spicules are not necessarily diagnostic, even in living sponges (Dr. Allen Collins, pers. comm.)

- Fossils of the Twitya Formation are generally presumed to be cnidarians, or at least metazoans of cnidarian grade. "Interpretation as colonial aggregates of prokaryotes (e.g. ***Nostoc***-like balls) is possible but is difficult to reconcile with the morphology and relatively high relief of the remains, their occurrence at the bottom of turbidite beds, and the lack of a carbonaceous film outlining them, particularly in view of the of the fact that carbonaceous compressions are present in the formation." Hofmann ***et al***. (1990: 1202). Of principal significance is this occurrence of cnidarian-grade metazoans in pre-Varanger sediments, since the Varanger glaciation is sometimes cited as an evolutionary 'bottleneck' which arrested metazoan evolution.

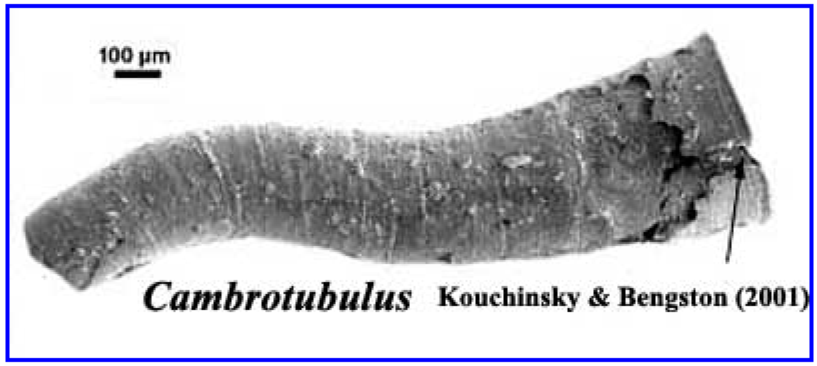
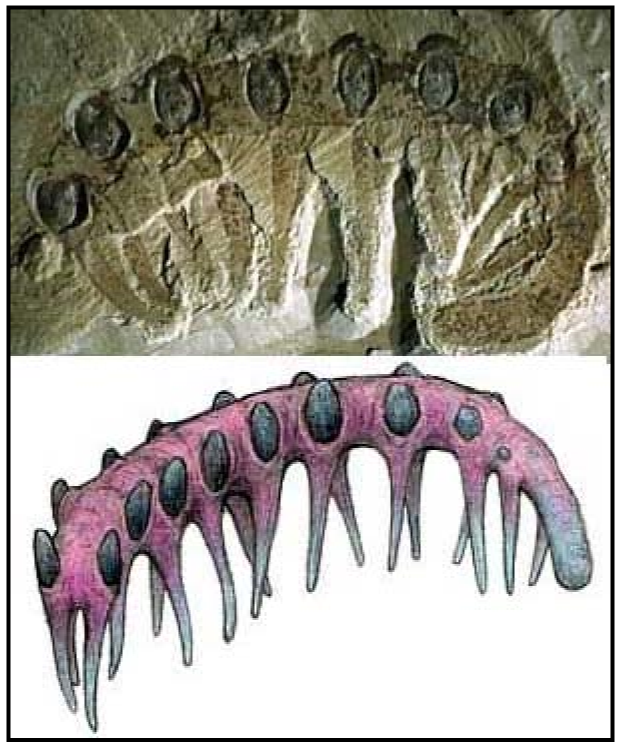


Image of fossil and life



reconstruction of ***Microdictyon***. Reconstruction from 川崎悟司イラスト集·ミクロディクティオン. Fossil image from **DinosaurWorld.cn**.

- In preserving evidence of bilaterians, the Ediacaran record provides constraints on the protostome-deuterostome split. If ***Kimberella*** is indeed a mollusc, as suggested by Fedonkin & Waggoner (1997), or the Ediacara/Zimnie Gory traces are correctly interpreted as radula scratches, we have evidence for derived protostomes at 555 Ma. Similarly, if ***Arkarua adami*** (from the Pound

Subgroup, South Australia; Gehling, 1987) is correctly interpreted as an echinoderm, we have evidence for a derived deuterostome of similar age [***but see***, Mooi (2001) and our discussion of ***Arkarua*** at **Ambulacraria**]. In either case, it follows that the P-D split must have occurred well before 555 Ma, which is in accordance with most 'molecular clock' studies.

Mineralised skeletons of uncertain affinity - the 'small shelly fauna' - appear just before the beginning of the Cambrian, ~550 Ma, increasing in numbers and diversity towards the Tommotian. The most common skeletal materials are calcium carbonate (aragonite or calcite) and varieties of calcium phosphate. Many of the latter may originally have been carbonates, phosphatized during preservation.

The oldest of these to occur abundantly are ***Cloudina*** and the allied genera comprising the family Cloudinidae: small, conical fossils made of calcium carbonate, first (?) appearing in the Ediacaran Stirling Quartzite of California (Langille, 1974) and persisting into the Cambrian. ***Anabarites*** and ***Cambrotubulus*** are other Ediacaran SSF taxa, known from Siberia and Mongolia.

While it is not known what kind of organism produced ***Cloudina***, and many other SSFs are equally problematic, some of the Cambrian representatives have been tied back to a firm systematic placement, such as ***Microdictyon***, which is now known to be an onychophoran.

Extinctions

Adapted from The Precambrian and Vendian Mass Extinctions:

Extinctions are proposed to have affected even life's earliest organisms. About 650 million years ago, seventy percent of the dominant Precambrian flora and fauna perished in the first great extinction. This extinction strongly affected stromatolites and acritarchs, and was also the predetermining factor that encouraged the diversification of the Ediacarans.

The first extinction of the Precambrian, which largely affected stromatolites and acritarchs, has been correlated with a large glaciation event that occurred about 600 million years ago. This event was of such severity that almost all micro-organisms were completely wiped out.

However, this distinct fauna may also have perished in a second extinction event at the close of the Ediacaran. This event may have been responsible for the ensuing diversification of the Cambrian shelly fauna.

The Ediacaran extinction, occurring near the close of the Ediacaran period, is currently under debate as to whether an extinction event occurred or not. Many paleontologists believe that the Ediacaran fauna were the progenitors of the Cambrian fauna. However, others believe that the Ediacaran fauna have no living representatives. Under this latter hypothesis, the Ediacaran fauna is believed to have an undergone an extinction, after which the Cambrian fauna evolved. Until more information can be collected, details on the Ediacaran extinction event will remain open to debate.

Although some taxa are now known to have persisted, and others may have evolved into different forms, most of the Ediacarans simply vanish from the fossil record near the beginning of the Cambrian. Some believe this is evidence of a mass extinction.

Moreover, in "the past few years, evidence has accumulated for a remarkable perturbation in the carbon cycle close to the Proterozoic-Cambrian boundary. Globally distributed sedimentary successions document a strong (7 to 9 per mil) but short-lived negative excursion in the carbon-isotopic composition of surface seawater at the stratigraphic breakpoint between Ediacaran-rich fossil assemblages and those that document the beginning of true Cambrian diversification. The causes of this event remain uncertain, but the only comparable events in the more recent Earth history coincide with widespread extinction – for example, the Permo-Triassic crisis, when some 90% of marine species disappeared, is marked by an excursion similar to but smaller than the Proterozoic-Cambrian boundary event. An earliest Cambrian increase in bioturbation shuttered the taphonomic window on Ediacaran biology. Thus, while Chengjiang and Sirius Passet fossils indicate that Ediacaran-grade organisms were not ecologically important by the late Early Cambrian, biostratigraphy admits the possibility that Ediacarans were eaten or outcompeted by Cambrian animals. It is biogeochemistry that lends substance to the hypothesis that Ediacaran and Cambrian faunas are separated by mass extinction." Knoll & Carroll (1999).

One school of thought holds that Ediacarans may have been largely wiped out by a supposed nutrient crisis – 'Kotlin Crisis,' ***see*** Brasier (1992) – immediately prior to the Ediacaran-Cambrian boundary.

However, other researchers observe that a mass extinction event is not necessary to explain the disappearance of the Ediacarans from the fossil record; conditions may simply have ceased to be favorable to their preservation with the arrival of more numerous and more diverse scavenging and bioturbating organisms. Indeed, the lower boundary of the Cambrian is now defined by the occurrence of a distinctive horizontal burrow trace fossil, ***Trichophycus*** (formerly ***Phycodes***) ***pedum*** in the reference section at Fortune Head, southeastern Newfoundland.

> "We cannot tell how abruptly the Ediacaran Faunas became extinct, but only a very small number are represented by possible survivors... ."

Briggs ***et al***. (1994: 46)

> "Although most Ediacaran fossils have no post-Proterozoic record, they were not immediately succeeded in lowermost Cambrian rocks by diverse crown group bilaterians. Earliest Cambrian assemblages contain few taxa, and

the diversity of trace and body fossils grew only over a protracted interval. Hyoliths and halkieriids (extinct forms thought to be related to mollusks), true conchiferan mollusks and, perhaps, chaetognaths enter the record during the first 10 to 12 million years of the Cambrian, but crown-group fossils of most other bilaterian phyla appear later: the earliest body fossils of brachiopods, arthropods, chordates, and echinoderms all post-date the beginning of the period by 10 to 25 million years. Trace fossils suggest earlier appearances for some groups, notably arthropods, but the observation remains that the Early Cambrian contains considerable time for the assembly and diversification of crown group morphologies" .

Knoll & Carroll (1999)

The Ediacaran (Vendian) - 3

The Ediacaran Biota ("Vendobiota")

Introduction

This section deals with the unique Ediacaran biota. The material, in small measure, repeats some of the earlier text on localities. We could invent some important didactic for doing this. However, the truth of the matter is that the repetition simply results from our haphazard editing of different materials which were subsequently combined.

The name 'Ediacaran' has a geochronologic meaning, providing an upper subunit of the Vendian, approximately 565 to 543 Ma (Bowring & Erwin 1998), with a stratotype in South Australia. Confusingly, the same term is also used in a biogenic sense, and in two different ways: Many authors apply the term 'Ediacaran' in a broad sense to any Vendian (or Ediacaran) age macrofossil, whereas others restrict the term narrowly to the unique and distinctive assemblage of enigmatic organisms best known from the Ediacara Hills of South Australia, and characterised by problematic oval, frondose, and spindle-shaped forms of unknown affinity.

Ediacaran fossils were described from the Fermeuse Formation on the Avalon Peninsula – specifically, ***Aspidella terranovica*** was named – by E. Billings in 1872. A second assemblage was described from Namibia sixty years later (Gürich 1933). Nevertheless, the assemblage acquired its name from a third and even later

Related Topics

Further Reading

- Crucible of Creation, The – Simon Conway Morris
- Fossils of the Burgess Shale, The – Derek Briggs ***et al***.
- Snowball Earth - Gabrielle Walker
- Garden of Ediacara, The – Mark McMenamin

Related Pages

- Vendian Period
- Vendian-Cambrian geological column
- Ediacaran Taxa
- Ediacaran Localities
- Ediacaran Survivors
- Cambrian Explosion

Other Web Sites

- Pictures and brief descriptions from Berkeley
- Ediacarans of Canda (incl. Mistaken Point) from Queen's University
- A few more articles about

discovery, made by Reginald Sprigg in March 1946, at an abandoned copper/lead/zinc mine in the Ediacara Hills, Flinders Range, north of Adelaide in South Australia. Since then, occurrences have been located on most continents.

The assemblage comprises marine life forms first appearing in Vendian (latest Precambrian, 620 to ~543 Ma) times – placing them among the oldest multicellular fossils known – and persisting into the basal Cambrian. The Ediacaran hey-day predates by a distinct interval of perhaps 20 Ma or more, the so-called 'Cambrian Explosion' when 'modern' multicellular life began to diversify rapidly.

For some years a number of authors (***e.g.*** Seilacher 1984, McMenamin 1986) have argued that the Ediacarans were unrelated to any living group of organisms; that they represented a new kingdom (Vendobionta Seilacher 1992) which disappeared around the Vendian-Cambrian boundary, perhaps wiped out by a mass extinction event. However, this view has always encountered opposition and now appears to have lost much of its support.

Ediacarans from Bellarmine University

Geological Setting

Occurrences are scattered at low paleolatitudes on every continent except (so far) Antarctica. Additionally, the South American Mato Grosso occurrence from southwestern Brazil (Hahn ***et al***. 1982) is questionable. The best known are the 'classic' localities in southern Namibia, the Flinders Range locality in Australia, Mistaken Point in south east Newfoundland, and on the White Sea coast of northern Russia, but there are also reported occurrences in Mexico, England, Ireland, Scandinavia, Ukraine, and the Ural Mountains (read more).

Habitat and Habit

Among the first comprehensive treatments of the Ediacarans were those of Martin Glaessner, in the 1960s. However, although we may now agree with many of his conclusions, his ideas were predicated on an incorrect interpretation of the paleoenvironment: Glaessner (1961; also Glaessner & Wade 1966; Jenkins 1981) believed the Rawnsley depositional sequence to have been semi-emergent ("sandy shoals ... [with] areas of temporary quiescent conditions between the shifting current tracks, where fine particles could settle until they were covered again by sand waves" – Glaessner & Wade

The Australian fossils occur in preservational windows in the Ediacara Member of the Rawnsley Quartzite, a formation of the Pound

1966, pp. 599-600) and the body fossil assemblage transported. Glaessner envisaged the assemblage as a mass stranding, thereby predisposing himself to accept the radial forms as 'medusoids.' More recently, however, Gehling (1991, 2001) has demonstrated that the South Australian fossils occur above a valley fill facies, on sandstone partings within upward-shoaling, delta-front environments between storm- and fair-weather wave base (Gehling 2001). Other occurrences are now widely understood to be ***in situ*** marine assemblages, also.

Lithology

"The sand is of unusual texture; rather like foundry sand, which is a factor in this uncommon mode of preservation" (Clarkson 1993, p. 59).

"The clay lenses were subsequently highly compacted and altered and are now mostly only thin, lenticular partings between the quartzite flags. Most of these partings can be opened only by natural weathering. They reveal fossils mostly on the lower surfaces of the quartzite flags" (Glaessner & Wade 1966, pp. 599-600).

Chronology

The oldest characteristic Ediacaran fossils are those of the Drook Formation from south-eastern Newfoundland, believed to date from around 575 Ma, but the oldest of the 'classical' localities is the 565 Ma occurrence at Mistaken Point, Newfoundland. Youngest of the classical localities is in Namibia, where Ediacarans co-occur with small shelly faunas and range up to the Vendian-Cambrian boundary (543 Ma; see Grotzinger ***et al***. 1995, Martin ***et al.*** 2000). Thus, paleontologists have had to come to terms with a "relatively short time frame of Ediacaran biology. Diverse Ediacaran assemblages from Australia, northern Russia, and Namibia were all deposited within the last 15 to 20 million years of the Proterozoic Eon" (Knoll & Carroll 1999).

However, there are contenders to push these boundaries in both directions. The stratigraphic range of the Ediacarans ***sensu lato*** essentially equates to the ~100 Ma range of ***Nimbia occlusa***. The Twitya fossils (pre-Varanger) are the oldest fauna which have been termed 'Ediacaran,' and Booley Bay (Furongian) the youngest: both include forms assigned to ***Nimbia occlusa***. With the single exception of

Subgroup, bounded above by the Early Cambrian Uratanna sequence. The Rawnsley depositional sequence is developed over an erosional surface having some 250 m of relief, where southeasterly directed paleovalleys are filled with sequences of massive sandstone and laminated siltstones, passing up into up into well-bedded sandstone. The fossils occur above the valley fill facies, on sandstone partings within upward-shoaling, delta-front environments between storm- and fair-weather wave base (Gehling 2001).

the Twitya Formation occurrence, all appear to post-date the last Varangian glaciation.

First Appearance

Simple disc-like impressions, interpreted as cnidarian-grade body fossils, from the intertillite beds of the 610 to 600 Ma Twitya Formation in the Mackenzie Mountains, north-western Canada (Hofmann ***et al***. 1990), include the "Ediacaran taxon" ***Nimbia occlusa*** and are sometimes described as "Ediacarans." They are simple, circular impressions and, while it is true that many taxa from the 'classic' Ediacaran localities are little more, the Twitya assemblage as a whole does not exhibit the morphological diversity nor the complexity of the classical Ediacaran assemblages. Unless one regards the Ediacaran assemblage as simply a 'hold-all' for any Vendian macrofossil of probable metazoan origin, the Twitya fossils do not belong here.

In a report of Ediacaran taxa and associated trace fossils from the Clemente Formation of north-western Sonora, Mexico, Mark McMenamin (1996) rejects the authenticity of the Twitya assemblage and explicitly lays claim to having found "the oldest known remains of the Ediacaran biota" himself (see fig. 1A). McMenamin appears committed to this interpretation (***e.g***. 1998, pp. 204-207) though neither his assertions for the age of the material ("600 million years or more") nor the biological affinities of his putative fossils have been embraced with any enthusiasm by others. The proposed age, in particular, is based upon an extremely tenuous chain of reasoning, all under-pinned by the supposed stratigraphic range of a single, poorly-documented, 'ichnotaxon,' ***Vermiforma antiqua*** (1996, p. 4993), which may, in fact, turn out to be a tectonic artefact (Seilacher ***et al***. 2000). Thus the Sonora material cannot be seriously considered without additional corroboration and is not further discussed here.

Claims of 600 Ma plus require these fossils to pre-date the Varanger-Marinoan ice age, approximately 600 to 590 Ma, which may have been a time of widespread extinction. "Late Proterozoic carbon isotopic profiles display strong negative as well as positive excursions. Negative excursions are specifically associated with the major ice ages that mark immediately pre-Ediacaran time. Much research is currently focused on this unusual coupling of climate and biogeochemistry, and both paleoceanographic models and clustered phytoplankton extinctions suggest that these ice

(A)

(B)

Fig 1: ***Cyclomedusa*** is probably the most common and widespread Vendian fossil. It also has one of the largest size ranges, ranging from a few millimetres to about a meter in diameter. Formerly thought to represent a planktonic (floating) jellyfish of some sort, ***Cyclomedusa*** is now considered by some to have been a benthic (bottom-dwelling) polyp, somewhat like a sea anemone, and by others to be the anchoring holdfasts of colonial, soft octocorals. The latter hypothesis may also explain why they are so common as fossils – because they were already buried – and posits that most of the 'species' are artefacts of differing preservation.

(A) McMenamin's form "cf. ***Cyclomedusa plana*** Glaessner and Wade" (= ***Aspidella terranovica*** Billings 1872) from Sonora, Mexico: "A discoid fossil preserved in hyporelief. Note annular ridge occurrence at the margin (arrowhead) of the central cone. Greatest dimension of rock specimen is 6.0 cm. Sample 1 of 3/17/95; fossil occurrence is approximately 75 meters below the Clemente Formation oolite, in unit 1 of the Clemente Formation" (McMenamin 1996, fig. 2A).

(B) ***Cyclomedusa sp***. from the Winter Coast of the White Sea. This specimen is about 5 cm across. [Image courtesy of University of California Museum of Paleontology.]

ages had a severe impact on the biota – potentially applying brakes to early animal evolution" (Knoll & Carroll 1999). Although presumed body fossils, such as the Twitya assemblage occur earlier, all of the ***diverse*** Ediacaran fossil assemblages post-date the Varanger-Marinoan ice ages.

Acme

Oldest occurrences, such as those from the Twitya and Drook Formations, are taxonomically impoverished. The assemblage becomes rich around 565 Ma (***e.g.*** at the Mistaken Point locality) but does not achieve full diversity until about 555 Ma. From then it continues in full bloom until the Vendian-Cambrian boundary after which, although some taxa linger on, the characteristic assemblage as a whole abruptly disappears. It is uncertain whether a mass extinction event struck at this time, or if we are simply observing the closure of some form of 'taphonomic window.' It has been suggested that more widely spread and deeper bioturbation, evidence for which increases sharply at the base of the Cambrian, is incompatible with the unique 'Ediacaran preservation.' Somehow, I find this view unconvincing.

A number of 'Ediacarans' are reported from the Cambrian. The youngest of them all is an impoverished Furongian assemblage of just two taxa, one of which is ***Nimbia occlusa***, from Booley Bay in Co. Wexford, Ireland.

Last Appearance

At the younger end of their range, "Ediacara type" fossils have been increasingly reported from Cambrian sediments (see below). Youngest and most exciting of these are the Upper Cambrian Ediacarans from a turbidite sequence exposed at Booley Bay, near Duncannon in Co. Wexford, Ireland, which includes two taxa: '***Ediacaria booleyi***' (possibly yet another variant of ***Aspidella terranovica***) and the cosmopolitan ***Nimbia occlusa*** (Crimes, Insole and Williams 1995). The Booley Bay occurrence is dated by acritarchs of sufficient "diversity and quantity to constrain biostratigraphically the relative age of this succession ... to the upper part of the Upper Cambrian" (Moczydlowska & Crimes 1995), indicating that at least some Ediacarans co-existed with 'modern' taxa for perhaps 20 or 30 Ma – and certainly throughout the Cambrian Explosion.

Morphology

More than 30 different genera have been named. Ediacarans are a diverse group and earlier attempts to pigeon-hole them into a limited number of phylogenetic types appear now to have been misguided. However, for a quick overview it may be useful to consider four broad morphological categories (after Briggs ***et al***., 1994, p. 44), bearing in mind that these do not indicate evolutionary relationship.

1. Most abundant are circular impressions, some of which plausibly recall jellyfish and similar medusoid cnidarians, although many are so simple that convergence rather than affinity cannot be ruled out (fig. 1). Others of this form are believed to be the holdfasts of the frond-like Ediacarans (see below, also fig. 4A).

2. Next are the trace fossils of various tracks and burrows made, at least in part, by bilaterian animals. Although there is evidence of burrowing, the traces are simple and more or less horizontal; conspicuously absent is any evidence for wide-scale churning up of the sea bed by animals living in the sediment (infauna) (Conway Morris 1998, p. 30).

3. Third most abundant are a number of problematic benthic forms. Whereas some of these seem familiar enough to suggest affinities with extant groups such as annelids (***e.g.*** ***Dickinsonia*** and ***Spriggina***, ***see*** fig. 2; but ***see*** Dzik & Ivantsov (1999) for a contrary view), echinoderms (***e.g.*** ***Arkarua***), or arthropods (***e.g.*** ***Diplichnites*** and ***Parvancorina***, fig. 3A), others such as ***Praecambridium***, ***Vendia*** and ***Tribrachidium*** (fig. 3B) are more problematic.

4. Least abundant, though perhaps most characteristic of the assemblage as a whole, are the attached, frond-like organisms

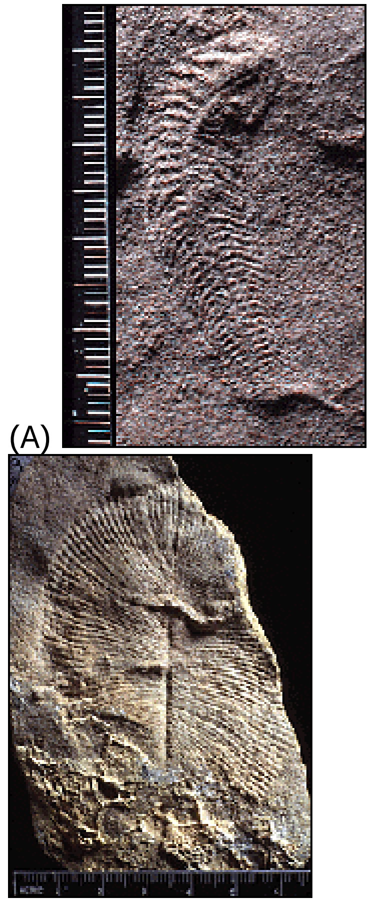


Fig. 2: (A) ***Spriggina floundersi*** Glaessner – From the Vendian Pound Quartzite of the type locality, Ediacara, South Australia. Overall length about 10 cm. Specimen from the Yale collection (YPM 63257).

(B) ***Dickinsonia costata*** Sprigg – Vendian, from the Brachina Gorge, Flinders Ranges, South Australia. Specimen from the Yale collection (YPM 35467). ***Dickinsonia*** has been known to reach dimensions of up to a metre.
[Images courtesy of the Peabody Museum of Natural History, Yale University.]

(A) (B)

(fig. 4A), which some propose have affinities with the sea pens and other soft corals.

Leaving aside the trace fossils, a typical Ediacaran of any form had a soft body – there is no evidence of any skeletal hard parts except, possibly, for the head-shield of ***Spriggina*** (fig. 2A) – yet they most commonly occur in silt- and sandstones which typically form in quite turbulent conditions: not the sort of sediments where one would ordinarily expect to find good soft tissue preservation.

Many of the forms display a morphology which has been described as "quilted." Some researchers consider this to be a real characteristic, which indicates a phylogenetic relationship between otherwise dissimilar forms: that all the "Ediacara fossils" are members of the same high-level taxon; that they form a single clade with a single bauplan (see below).

Interestingly, it appears that Ediacaran communities were largely free of large predators; no species appears to have possessed a jaw apparatus suitable for seizing and tearing prey, and few fossils show clear evidence of predatory damage. A possible exception, however, are some Chinese ***Cloudina*** fossils with tiny boreholes, which may simply be a diagenetic effect or may truly be indicative of predation.

Fig. 3: (A) ***Parvancorina minchami*** – A candidate arthropod, possibly a trilobite (see Fortey ***et al***. 1996). In this scenario, the central axial ridge and the strongly arched anterior 'lobes' may be analogous to the midgut and gastric diverticulae. The scale bar is in centimetres. [Image and interpretation courtesy of Chris Nedin, Department of Industry, Science and Resources, Canberra.]

(B) ***Tribrachidium heraldicum*** – Few fossils of Ediacaran animals are so compellingly bizarre as this unusual disc-shaped form with three-part (triradial) symmetry. Affinities have been proposed with either the Cnidaria (corals and anemones) or Echinodermata (urchins and starfish); nor can the possibility that it is a holdfast be entirely eliminated. [Image and interpretation courtesy of University of California Museum of Paleontology.]

Antecedents

Genetic evidence has been used to suggest significant metazoan diversity far pre-dating the Ediacaran fossils (***e.g***. Wray, Levinton & Shapiro 1996: "Calibrated rates of molecular sequence divergence were used to test this hypothesis. Seven independent data sets suggest that invertebrates diverged from chordates about a billion years ago, about twice as long ago as the Cambrian. Protostomes apparently diverged from chordates well before echinoderms, which suggests a prolonged radiation of animal phyla.")

Other estimates (***e.g.*** see Conway Morris 1998, Ayala ***et al.*** 1998, Knoll & Carroll 1999) are lower, but still require the existence of some animal diversity as early as 750 Ma ago, implying that for the first 150 Ma or more they left no fossil record. (Inexplicably, Ayala ***et al.*** claim that their results are "consistent with paleontological estimates.") The general rarity of soft-part preservation may explain this in part, but one would still expect to find some trace fossils – tracks and burrows – of any animals large enough to disturb sea-floor sediments. "Thus, if they really were present, we can be fairly sure that any pre-Cambrian animals would have been tiny, only a few millimetres long.... What later triggered their initial emergence as the Ediacaran faunas, and subsequently the even more spectacular Cambrian explosion, remains a significant topic for debate" (Conway Morris 1998, p. 144).

At approximately 610 to 600 Ma, circular impressions from the Twitya Formation of the Mackenzie Mountains provide evidence for the earliest metazoans, simple cup-shaped organisms, possibly cnidarians. Somewhat later, perhaps 590 to 565 Ma, but still predating any known Ediacaran assemblage, the Doushantuo phosphate deposit in China is slowly yielding a surprisingly diverse biota, including probable algae, sponges, cnidarians and bilaterians (read more).

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The Ediacaran (Vendian) - 4

Affinities

Until now we have considered the ‘Ediacaran fauna’ in abstract terms, without any attempt to delimit the concept. Real difficulties stand in our way – it is genuinely difficult to map the characters of most Ediacaran fossils onto the body plans of living invertebrates; certainly there are similarities, but they are "worryingly imprecise" (Conway Morris 1998, p. 28). Nevertheless, failure to make the attempt is no less reprehensible for having a long pedigree.

Initially, Ediacarans were interpreted in terms of extant phyla, such as cnidarians, annelids, ***etc***. Much of this early work was completed by Martin Glaessner. Fellow Australian, Jim Gehling (1991), reports that Glaessner left many Ediacaran forms unassigned, and in some cases undescribed, because he "refused to include new taxa in extant phyla without considered taxonomic evidence, stating that from a 'historical perspective, failures are not phyla.'" The German paleontologist, Hans Pflug was clearly unconvinced, however, and in 1972 erected the new phylum Petalonamae to accommodate some of the frondose Ediacaran taxa (Pflug 1972).

Vendozoa

Through the mid-1980s to mid-1990s, Adolf Seilacher and some others further questioned assignments of Ediacaran taxa to living phyla, and even the metazoan affinities of many Ediacarans. Seilacher 1992 recognises three groups: cryptic bilaterians which left only trace fossils, the Psammocorallia – coelenterates which utilised sand for an internal skeleton – and the 'quilted' Vendobionta, a concept roughly comparable to Pflug's Petalonamae. The last of these groupings has attracted some vigorous criticism: "In proposing the separation of Ediacaran organisms from the Metazoa, Seilacher (1989) has attempted to unify them with a common constructional model. ... By emphasising the untested generalisation that all [of the 'quilted'] Ediacaran organisms were flat and constructed of tubular elements, and uncomplicated by internal organs, Seilacher (1989, fig. 2) was able to argue that the observed variation between taxa was solely based on modes of growth, involving the addition of tubular elements. ... Only with a very broad brush could all Ediacaran organisms be represented as fractal growth variations based on the same units of construction" (Gehling, 1991). Gehling's last point is supported by observation of considerable variation between taxa, in the style of preservation, indicating that there were "different classes of organic construction involved in the Ediacara fauna" (Gehling & Rigby 1996, p. 185).

However, Seilacher's argument must be seen in the context of its time; it was predicated on knowledge of far fewer Ediacarans (in general, the larger taxa) than are known today, and underpinned by the beliefs – prevalent at the time – that:

1. the Ediacarans died out completely well before the Ediacaran-Cambrian boundary (the Kotlin crisis);

2. a considerable age separated the disappearance of the Ediacarans and the appearance of the first calcareous 'skeletons' (the so-called 'small shelly fauna,' see

below);

3. the assemblages represented mass strandings rather than ***in situ*** associations; and perhaps stemming from this,

4. that coeval trace fossils could not be attributed to the Ediacaran taxa.

However, none of these beliefs except, arguably, the last can be sustained today, and even that contention is less tenable than it was in the 1980s, when the Ediacarans were thought to be mostly large taxa. We now know that small taxa make up a large part of the assemblage; the small bilaterian forms are potentially the missing trace-makers.

Seilacher's original constructional analysis is not debated a great deal today, and though it still claims adherents (***e.g***. see McMenamin 1998), the majority of authors speak of 'Ediacaran metazoans' and 'the Ediacaran fauna.'

Recent Views

Bruce Runnegar and Mikhail Fedonkin (***in*** Schopf & Klein 1992, p. 373) were next to tackle the taxonomy of the assemblage. Their approach – by far the most convincing to date – combines the conservative reference of taxa to modern phyla, where such assignments are not obviously forced, with a pragmatic recognition of the large number of undeniably enigmatic forms. Probably the most significant message evident in Runnegar & Fedonkin's classification – obvious today, but enlightening in 1992 – is that the Ediacaran fauna is not a single, monolithic, taxonomic group. Rather, different Ediacaran taxa represent a variety of metazoan (and possibly other) lineages. Even today, some authors (***e.g***. McMenamin 1998) appear uncommitted to this view. Table 1 is an updated version of Runnegar & Fedonkin's work.

Traces

Although some traces are simple, rather featureless, winding trails, "others display transverse rugae and contain pellets that can be interpreted as of fecal origin. The bilaterian nature of these traces is not in dispute. Furthermore, such traces must have been made by worms, some of which had lengths measured in centimetres, with through guts, which were capable of displacing sediment during some form of peristaltic locomotion, implying a system

Phylum Cnidaria Hatschek 1888
  Class Cyclozoa Fedonkin 1983
    Order unknown
      Family Cyclomedusidae Gureev 1987
        Aspidella (incl. ***Cyclomedusa, Ediacaria, Spriggia, Tateana, Tirasiana,*** etc.)
  Class Hydrozoa Owen 1843
    Order unknown
      Families unknown
        Eoporpita, Ovatoscutum, Wigwamiella
  Class Anthozoa Ehrenberg 1834
    Order Pennatulacea ??? (Subclass Octocorallia)
      ?Family Pteridiniidae Richter 1955 [though maybe this family belongs with the Petaliform problematica or with the Trilobozoa?]
        Pteridinium (but not ***Charniodiscus***, in my view)
    Orders unknown
      Families unknown
        Beltanelliformis, Hiemalora, Inaria
  Class unknown
    Order unknown
      Family unknown
        Nimbia
Phylum Mollusca Linnaeus 1758
  Class unknown

of body wall muscles antagonized by a hydrostatic skeleton. Such worms are more complex than flatworms, which cannot create such trails and do not leave fecal strings" (Valentine 1995, p. 90).

Sets of paired hypichnial ridges further hint at an arthropod ***s.l.*** presence.

A trace fossil presumed to represent the radula scratches of a mollusc is found at Zimnie Gory and in the Ediacara Hills (Martin et al. 2000, p. 844).

'Metameric' (Segmented) Forms

Whereas there may be a general acceptance that the majority of Ediacarans are stem metazoans of some sort, most are still notoriously problematic. One large and important group of these, arguably the most crucial to our understanding of the overall pattern of metazoan evolution, are those exhibiting real or apparent metamerism. Most are small, though some of the dickinsonids can be enormous: up to about a metre.

Some authors, notably M.A. Fedonkin and A. Yu. Ivantsov, argue that many of these organisms are pseudosegmented, with segments alternating on either side of the mid line, thereby casting doubt on their bilaterian affinities. However, their published photographs (***e.g***. of ***'Archaeaspis'*** and ***Yorgia***) are often based upon relatively few specimens and the asymmetry is not always clear (Jim Gehling, ***pers. comm***.)

In some specimens of ***Dickinsonia***, the segments do not appear to correspond across the mid-line on the dorsal surface. However, as noted in Gehling 1991 (though the original observation is attributed to Bruce Runnegar), in all specimens where the ventral side is preferentially preserved, segments clearly continue across the mid-line, so offset on the dorsal side must be a product of flattening. It is only in rare specimens of ***Dickinsonia elongata*** that the alternate insertion and overlap of segments along the mid line is difficult to explain.

"Fedonkin (1983, 1984, 1985a, 1986) has not only attempted to assess the phyletic relationships of Ediacaran taxa, but has tackled the problem of comparative morphology. However, his approach has been strongly dependent on a two dimensional body plan

Order unknown
Family unknown
Kimberella

Phylum Arthropoda von Siebold & Stannius 1845
Class unknown
Orders unknown
Families unknown
?'Archaeaspis', Onega, Parvancorina, Praecambridium, Redkinia
Family Sprigginidae Glaessner 1958
Spriggina

Phylum Echinodermata
Class ?Edrioasteroidea
Order unknown
Family unknown
Arkarua

Insertae sedis

1. Triradially Symmetric Taxa (= Phylum Trilobozoa Fedonkin 1985)
Classes unknown
Orders unknown
Family unknown
Triforillonia
Family Albumaresidae Fedonkin 1985
Ablumares, Anafesta, Skinnera
Family Anabaritidae Glaessner 1979
Anabarites
Family Tribrachididae Runnegar 1992
Tribrachidium

2. 'Metameric' Taxa
Classes unknown
Orders unknown
Family Dickinsonidae Harrington & Moore 1955
Dickinsonia
Family Vendomiidae Keller 1976
?Vendia, Vendomia
Family Yorgiidae Ivantsov 2001
Yorgia

3. Petaliform Taxa (= Phylum Petalonamae Pflug 1972; Kingdom Vendobionta Seilacher 1992 ????)
Class Erniettamorpha Pflug 1972
Order(s) unknown
Family Erniettidae Pflug 1972
Ernietta, ?Swarpuntia
Family Pteridiniidae Richter 1955 [though maybe this family belongs with the Anthozoa or even the Trilobozoa?]
?Phyllozoan, Pteridinium
Class Rangeomorpha Pflug 1972
Order(s) unknown
Family Rangeidae
Rangea
Family Charniidae
Charnia, ?Charniodiscus, Paracharnia

4. 'Vermiform' Taxa (= Phylum "Vermes" of Runnegar 1992)
?Archaeichnum, ?Cloudina, Cochlichnus, ?Didymaulichnus,

analysis of symmetry. This concept of "promorphology" almost entirely disregards the original three dimensional architecture, palaeobiology, and ontogeny of the organisms. Bergström (1990, figure 2) illustrated four taxa with apparent alternation of regular elements on each side of the axis; but in each case the sketches represent unrestored images of flattened animals. Order within symmetry groups may be useful in classification of minerals, but in organisms, the superficial symmetry of body plans may be a secondary product of adaptation to different life styles" (Gehling 1991, p. 203.)

Gordia, Harlaniella, Helminthoidichnites, Planolites, Sellaulichnus

5. Serial Growth Forms

Neonereites, Palaeopascichnus, Yelovichnus

6. Others

Ausia, Bomakiella, Bonata, Lorenzinites, ?Wigwamiella

Table 1: Taxonomic outline of some Ediacaran forms. Blue = form-taxa; red = trace fossils (ichnotaxa).

Old text (no longer needed?):

Some, such as the German paleontologist Adolph (Dolf) Seilacher, have expressed doubts that the ‘quilted’ Ediacarans were animals at all; suggesting instead that they represent a quite separate evolutionary lineage. In spite of their apparent diversity, nearly all of the genera share a striking basic uniformity: they are thin and flattened, round or leaf-like, possess a ridged or ‘quilted’ upper surface, and lack clear indications of a mouth or gut. Seilacher believes that the Ediacaran body plan comprises tough organic walls surrounding fluid-filled internal cavities.

However, most workers reject this idea. "It’s clearly not true for, say, the Burgess Shale. Why should it apply to the Ediacarans?" (Waggoner 1999).

Initially, Ediacarans were interpreted in terms of extant phyla, such as cnidarians, annelids, etc. Through the mid-1980s to mid-1990s, however, Adolf Seilacher has questioned these assignments and even the metazoan affinities of many Ediacarans. Seilacher 1992 recognises three groups: cryptic bilaterians which left only trace fossils, the Psammocorallia - coelenterates which utilised sand for an internal skeleton - and the 'quilted' Vendobionta. It is the last of these groups which has attracted the most criticism: "In proposing the separation of Ediacaran organisms from the Metazoa, Seilacher (1989) has attempted to unify them with a common constructional model. ... By emphasising the untested generalisation that all [of the 'quilted'] Ediacaran organisms were flat and constructed of tubular elements, and uncomplicated by internal organs, Seilacher (1989, fig. 2) was able to argue that the observed variation between taxa was solely based on modes of growth, involving the addition of tubular elements. ... Only with a very broad brush could all Ediacaran organisms be represented as fractal growth variations based on the same units of construction" (Gehling

1991, pp. 192-193, 202). Gehling's last point is supported by observation of considerable variation between taxa, in the style of preservation, indicating that there were "different classes of organic construction involved in the Ediacara fauna" (Gehling & Rigby 1996, p. 185).

However, Seilacher's argument must be seen in the context of its time; it was predicated on far fewer Ediacarans (in general, the larger taxa) than are known today, and underpinned by the beliefs (justifiable at the time) that:

1. the Ediacarans died out completely at or before the Ediacaran-Cambrian boundary (the Kotlin interval);
2. a considerable age separated the disappearance of the Ediacarans and the appearance of the small shelly faunas;
3. the assemblages represented mass strandings rather than in situ associations; and perhaps stemming from this,
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None of these beliefs except, arguably, the last, can be sustained today, and even that contention is less tenable than it was in the 1980s, when the Ediacarans were thought to be mostly large taxa. We now know that small taxa make up a large part of the assemblage; the small bilaterian forms are potentially the missing trace-makers.

Seilacher's original constructional analysis is not debated a great deal today, and though it still claims adherents, the majority of authors speak of 'Ediacaran metazoans' and 'the Ediacaran fauna.'

Metazoan Origins

Some similar organisms – which post-date the major Ediacaran biotas and are generally better preserved – have been identified with conventional zoological taxa. Conway Morris 1998 cites as examples ***Thaumaptilon*** (fig. 4B), which he believes is a conventional pennatulacean (pp. 28-29), ***Mackenzia*** (pp. 83-84), and ***Emmonsaspis*** (p. 134, note

7). Advocates of this viewpoint explain the unusual 'Ediacaran preservation' by suggesting a paucity of burrowing and scavenging organisms to disturb the remains, once buried.

However, it remains true that the differences between the Ediacaran and overlying Cambrian faunas are far more striking than any similarities.

In view of the fauna's supposed primitive metazoan affinities, the virtual absence of sponges (phylum Porifera) is intriguing. However, rare occurrences of sponges ***have*** been reported: Gehling & Rigby 1996 describes a probable sponge, ***Paleophragmodictya*** from the Ediacaran of South Australia (read more) and Li et al. 1998 reports sponge remains from the extremely ancient Doushantuo phosphate deposit in China, which predates any known Ediacaran assemblage (read more).

There can be little doubt, on the basis of trace evidence alone, that bilaterian metazoans existed in the Ediacaran. Unfortunately, it is equally true that the relatively few body fossils known from the late Precambrian do not shed much light on the sequence of evolutionary advances that led to the famously diverse Cambrian taxa. There are a few sign-posts, however:

- Sponges are widely recognised (***e.g***. Nielsen 2001, pp. 30, 506-507) to be the most primitive of living metazoans, occupying a basal position in metazoan phylogeny, as a sister group to all other Metazoa. Thus their first occurrence in the fossil record is a metric of particular interest. However, only rare occurrences of Precambrian sponges have been reported. The earliest record is of presumed sponge remains from the Doushantuo phosphates, dated around 570 Ma (Li ***et al***. 1998), and the earliest described species is Paleophragmodictya reticulata from the ?555 Ma Ediacara locality. However, sponges could have occurred earlier and not been recognised; spicules are not necessarily

(A)

(B)

Fig. 4: (A) ***Charniodiscus arboreus*** – One of the frond-like Ediacaran fossils considered by some to be a 'conventional' cnidarian, possibly a pennatulacean. Collected from the Ediacaran Member, Rawnsley Quartzite, Bunyeroo Gorge, Flinders Ranges, South Australia. Specimen from the South Australian Museum Collection (SAM P19690). Overall length 40cm. [Image courtesy of the South Australian Museum.]

(B) ***Thaumaptilon walcotti*** Conway Morris 1993 – From the Middle Cambrian Stephens Formation Burgess Shale. Proposed by Conway Morris as a possible pennatulacean (sea pen). However, this view is by no means universally accepted; for example, Nielsen 2001 notes (p. 59) that the branches of both ***Charniodiscus*** and ***Thaumaptilon*** "were united with a membrane which makes the interpretation dubious on functional grounds, and the structures tentatively interpreted as polyps are very small and show no tentacles." Specimen from the US National Museum collection (USNM 468028). Overall length about 20 cm. If this animal is a descendant of ***Charniodiscus*** and its Ediacaran allies, as proposed by Conway Morris, the holdfast has been modified from the original bulky disc, possibly to facilitate withdrawal into a burrow. [Reproduction of fig.

diagnostic, even in living sponges (Dr. Allen Collins, ***pers. comm***.)

- Fossils of the Twitya Formation are generally presumed to be cnidarians, or at least as metazoans of cnidarian grade. "Interpretation as colonial aggregates of prokaryotes (***e.g***. ***Nostoc***-like balls) is possible but is difficult to reconcile with the morphology and relatively high relief of the remains, their occurrence at the bottom of turbidite beds, and the lack of a carbonaceous film outlining them, particularly in view of the of the fact that carbonaceous compressions are present in the formation" (Hofmann ***et al***. 1990, p. 1202). Of principal significance is this occurrence of cnidarian-grade metazoans in pre-Varanger sediments, since the Varanger glaciation is sometimes cited as an evolutionary 'bottleneck' which arrested metazoan evolution.

- In preserving evidence of bilaterians, the Ediacaran record provides constraints on the protostome-deuterostome split. If ***Kimberella*** is indeed a mollusc, as suggested by Fedonkin & Waggoner 1997, or the Ediacara/Zimnie Gory traces are correctly interpreted as radula scratches, we have evidence for derived protostomes at 555 Ma. Similarly, if ***Arkarua adami*** (from the Pound Subgroup, South Australia; Gehling 1987) is correctly interpreted as an echinoderm, we have evidence for a derived deuterostome of similar age. In either case, it follows that the P-D split must have occurred well before 555 Ma, which is in accordance with most 'molecular clock' studies.

Nutritional Hypotheses

Most Ediacarans appear to have been very thin. Some researchers, particularly those from

2E from Conway Morris 2000.]

the Seilacher camp, propose that their tissues may have housed symbiotic algae. Mark McMenamin (1986, 1998) coined the phrase 'garden of Ediacara' to encapsulate the concept and he has largely championed this theory. However, other workers such as Bruce Runnegar (1992, p. 83) point out that the hypothesis is both difficult to test and unlikely anyway, because some of the fossils appear to have been deposited below storm wave base – about 100 m – where the intensity of sunlight is very much diminished, perhaps below useful limits for such organisms.

Major Ediacaran Occurences

575 Ma: The Drook Formation

An impoverished but characteristic Ediacaran assemblage occurs in the upper beds of the Drook Formation, south-eastern Newfoundland, 1,500 m stratigraphically below the well-known Mistaken Point fossils. These are the oldest of the large, architecturally complex fossils found so far (Anderson 1978; Hofmann ***et al***. 1979; King 1980; Narbonne & Gehling 2003). The published age constraints on these fossils are from 595 Ma (Varangian glacial diamictites of the Gaskiers Formation) to 565 Ma (well-dated Ediacaran fossils at Mistaken Point occurring 1.5 km stratigraphically higher). Unpublished data noted in Walker 2003, p. 220, indicates an age of 575 Ma.

Current-aligned fronds attributable to the cosmopolitan Ediacaran, ***Charnia masoni***, and those of a large (up to nearly 2 m in length) new species, ***Charnia wardi***, occur on the shaley tops of turbidite beds under volcanic ashes. Their position above the glacial marine rocks of the Gaskiers Formation (595 Ma) provides our earliest window on life following the Varanger ice age.

~570 to 560 Ma: 'Old' Trace Fossils

Crimes ***in*** Cowie & Brasier 1989, p. 167, lists the earliest occurring trace fossils as

Planolites, ***Didymaulichnus***, ***Arenicolites***, ***Neonereites*** and ***Gordia***.

The lower Elkera Formation in the Georgina Basin, central Australia, contains the ichnofossil ***Planolites ballandus***, pre-dating the Australian Ediacaran fauna (Walter ***et al***. 1989, p. 218) though the genus is elsewhere known to range up into the Phanerozoic (Crimes ***in*** Cowie & Brasier 1989, p. 169). ***Planolites ballandus*** is a sub-horizontal, simple, straight to gently curved, unbranched, smooth, cylindrical burrow-fill, sometimes with fine longitudinal striations, approximately 1 mm wide (Walter ***et al***. 1989, p. 239).

Didymaulichnus is another horizontal burrow-fill, comprising a double-lobed, slightly sinuous to tightly curved, convex hyporelief, ~10 mm wide by ~3 mm deep, the lobes separated centrally by a distinct, shallow furrow, and ranging up into the Atdabanian. ***Arenicolites*** is highly unusual – possibly unique among Ediacaran traces – insofar as it is not confined to the horizontal plane. It comprises a U-shaped tube, approximately 10 mm deep. It, too, ranges up into the Phanerozoic.

565 Ma: Mistaken Point – Oldest of the 'Classic' Ediacaran Assemblages

The oldest of the diverse Ediacaran assemblages yet described is that from Mistaken Point, eastern Newfoundland, where fossils are spectacularly preserved on large bedding surfaces along the sea-cliffs of the Avalon Peninsula. Zircons from interbedded ash have been dated at 565 ± 3 Ma (Benus 1988).

The Mistaken Point assemblage contains a few cosmopolitan taxa such as ***Charnia*** and ***Aspidella***, but most are either endemic or shared only with the Charnwood Forest locality in central England (King 1980).

?565 Ma: Charnwood Forest

The volcaniclastic turbidites of the Charnian Supergroup contain an Ediacaran fauna comprising frondose forms, either as simple fronds or multi-fronded balls, discs which are usually ovoid and contain variable numbers of concentric rings, worm burrows, and other forms which do not fit into these groups. Worm burrow traces occur in the lower Brand Group of Charnwood Forest. The discovery of ***Charnia masoni*** in 1957 has become an essential part of Ediacaran folk lore; ***Aspidella*** (as ***Cyclomedusa***) and ***Pseudovendia*** have also been reported from this site (Brasier ***in*** Cowie & Brasier 1989, p. 85).

Age constraints on the Charnwood Forest assemblage are poor. Taxonomic similarities with Mistaken Point suggest an age around 565 Ma; a K-Ar determination from a nearby porphyroid emplacement yielded a date of 583 ± 25 Ma.

555 Ma: White Sea

The two most abundant and diverse Ediacaran trace and body fossil assemblages are those from the White Sea coast of Russia and from the Flinders Ranges in South Australia, which together account for 60% of the well-described Ediacaran taxa.

"Many exposures in the White Sea region contain known Ediacaran biotas; however, the best fossil occurrences are found along the shoreline cliffs at Zimnie Gory. These unmetamorphosed and nondeformed (except for present-day cliff-face slumping) siliciclastic rocks belong to the uppermost Ust' Pinega Formation and form the northern flank of the Mezen Basin along the southeast flank of the Baltic Shield" (Martin ***et al***. 2000, p. 842). Zircons from a volcanic ash in the lower part of the sequence preserved between Medvezhiy and Yeloviy Creeks (***ibid***., fig. 2) yielded a date of 555.3 ± 3 Ma, the minimum age for the "oldest definitive triploblastic bilaterian, ***Kimberella***, and the oldest well-developed trace fossils; and it documents that spectacularly diverse and preserved Ediacaran fossils formed more than 12 million years before the base of the Cambrian" (***ibid***., p. 843).

The fossil ***Kimberella***, originally described from southern Australia but subsequently found elsewhere, including from the White Sea in northern Russia, has been persuasively reconstructed as a benthic bilaterian animal with a non-mineralised, univalved shell, resembling a mollusc (Fedonkin & Waggoner 1997). This interpretation provides evidence for the existence of large triploblastic metazoans in the Precambrian, and requires the origin of the higher groups of protostomes to have occurred deep in the Precambrian, at least prior to ~560

Ma.

Presumed radula scratchings are found at Zimnie Gory, as is ***Hiemalora***, another problematic form which cannot with certainty be categorised as either a body fossil or a feeding trace (Martin ***et al***. 2000, p. 844). Irrespective, this evidence establishes the existence of actively crawling organisms, almost certainly bilaterians, and almost certainly above the grade of planarians because of the implied hydrostatic skeleton.

Most provocative of all the Ediacaran forms are those exhibiting real or apparent metamerism (***e.g***. ***Dickinsonia*** and ***Spriggina***). Most are small, though some of the dickinsonids can be enormous: up to ~1 metre. Several authors – notably M.A. Fedonkin (***e.g***. 1986) and A. Yu. Ivantsov (***e.g***. 2001) – argue that many of these organisms are pseudosegmented, with segments alternating on either side of the mid line, thereby casting doubt on their bilaterian affinities. However, their approach has been strongly dependent on a two dimensional body plan analysis of symmetry, with little regard for the original three dimensional architecture of the organisms. Similarly, Bergström (1990, figure 2) illustrates four taxa with apparent alternation of regular elements on each side of the axis; but in each case the sketches represent unrestored images of flattened animals. James Gehling leaves little doubt where he stands on the matter: "To reconstruct the small Ediacaran segmented taxa as other than vagile metazoans requires an appeal to the absurd" (Gehling 1991, p. 205; also see pp. 199 and 203.)

?555 Ma: South Australia

Material from the Ediacara Hills (Flinders Ranges) has still not been precisely dated; it is assumed to be approximately coeval with the White Sea fossils, in the region of 555 Ma (see below), but it could be as young as the +1 to +2‰ d ^{13}C interval, dated at 549 to 543 Ma in southern Namibia (Martin ***et al***. 2000, p. 844). It is the assemblage from this site that is most widely associated with the Ediacaran biota.

The Ediacara Hills locality is also the provenance of the earliest taxonomically-resolved poriferan, ***Paleophragmodictya reticulata***, and the possible echinoderm, ***Arkarua adami***.

Although best known for the ‘classical’ body fossils, the region also provides interesting traces. One ichnotaxon has been interpreted as the radula scratchings of a mollusc (possibly

Kimberella).

549 to 543 Ma: The Nama Group

The Nama Group is a thick (> 3 km) shallow marine and fluvial foreland basin succession, partitioned into northern and southern sub-basins by an intervening arch, across which most stratigraphic units thin, located in southern Namibia. The age range of the Ediacaran assemblages from the Nama Group is the interval 548.8 ± 1 to 543.3 ± 1 Ma (Grotzinger ***et al***. 1995).

In addition to typical Ediacaran taxa, such as the cosmopolitan ***Pteridinium***, the shelly fossil ***Cloudina*** first appears slightly below the earliest Ediacaran fossils, extends throughout the Ediacaran range, and into the Cambrian. A second shelly taxon, ***Namacalathus*** (the "goblet-shaped shelly fossils" of Grotzinger ***et al***. 1995) coexists with ***Cloudina*** from at least 545 Ma through into the Cambrian.

549 to 543 Ma: Southwestern Mongolia

Ediacaran faunas and, notably, unquestionable hexactinellid (glass sponge) spicules, have been reported from limestones just above a phosphorite-chert-black shale marker bed in the upper Tsagaan Gol Formation of southwestern Mongolia (Brasier ***et al***. 1997). The dates have been established chemostratigraphically, based on carbon and $^{87}Sr/^{86}Sr$ isotope correlations.

Disappearance of the Ediacaran Assemblage

Decline

Although some taxa are now known to have persisted, and others may have evolved into different forms, most of the Ediacarans simply vanish from the fossil record near the beginning of the Cambrian. The characteristic assemblage persists in full bloom – at least in Namibia – right up until the Ediacaran-Cambrian boundary after which the assemblage, as a whole, abruptly disappears. It is uncertain whether a mass extinction event struck at this time, or if we are simply observing the closure of some form of "taphonomic window" – both have been suggested.

- One school of thought holds that Ediacarans may have been largely wiped out – possibly by the supposed Kotlin nutrient crisis, see Brasier 1992 – immediately prior to the Ediacaran-Cambrian boundary.

"In the past few years, evidence has accumulated for a remarkable perturbation in the carbon cycle close to the Proterozoic-Cambrian boundary. Globally distributed sedimentary successions document a strong (7 to 9 per mil) but short-lived negative excursion in the carbon-isotopic composition of surface seawater at the stratigraphic breakpoint between Ediacaran-rich fossil assemblages and those that document the beginning of true Cambrian diversification. The causes of this event remain uncertain, but the only comparable events in the more recent Earth history coincide with widespread extinction – for example, the Permo-Triassic crisis, when some 90% of marine species disappeared, is marked by an excursion similar to but smaller than the Proterozoic-Cambrian boundary event. An earliest Cambrian increase in bioturbation shuttered the taphonomic window on Ediacaran biology. Thus, while Chengjiang and Sirius Passet fossils indicate that Ediacaran-grade organisms were not ecologically important by the late Early Cambrian, biostratigraphy admits the possibility that Ediacarans were eaten or outcompeted by Cambrian animals. It is biogeochemistry that lends substance to the hypothesis that Ediacaran and Cambrian faunas are separated by mass extinction" (Knoll & Carroll 1999, p. 2135).

In Oman, the 'early' SSFs, ***Cloudina*** and ***Namacalathus***, are reported to go extinct very shortly after the Ediacaran-Cambrian boundary, at 542.0 ± 0.5 Ma (Kerr 2002).

- Other researchers observe that a

mass extinction event is not necessary to explain the disappearance of the Ediacarans from the fossil record; conditions may simply have ceased to be favourable to the unique 'Ediacaran preservation' with the arrival of more numerous and more diverse scavenging and bioturbating organisms.

The preservational characteristics of typical Ediacaran assemblages are undeniably unusual ('characteristic' might be a better word), and evidence for more widely spread and deeper bioturbation certainly does increase sharply at the base of the Cambrian. Indeed, as we have seen, the lower boundary of the Cambrian is now defined by the occurrence of the burrow trace fossil, ***Trichophycus pedum***. However, to offer this as a complete explanation for the abrupt disappearance of a distinctive, cosmopolitan fauna simply feels a little too convenient for my taste; I believe something ***did*** happen to the Ediacarans near the end of the Ediacaran or in the earliest Cambrian. If not, then another explanation must be found for the pronounced carbon isotope excursions.

Occasionally the idea of predation is raised. However, it should be noted that the only evidence of predation of Ediacaran organisms is confined to a few possibly bored ***Cloudina*** tubes.

Cambrian Occurences

For many years, Ediacarans were believed to have been confined to the Ediacaran. Indeed, prior to accurate dating of the Nama occurrences in the mid-1990s, they were widely conceived to have disappeared perhaps 10 Ma before the end of the period. A variant of this view is speculation (***e.g***. Seilacher 1984; Knoll & Carroll 1999) that a mass extinction terminated the Ediacaran and eliminated the Ediacaran biota. But although the Ediacarans were certainly no longer ecologically important by Chengjiang times, since about 1990 there has been a steadily accumulating body of Cambrian age discoveries, including the following.

Lower Cambrian

A South Australian discovery, including frond-like forms very similar to those found in the White Sea coast, and the disc-like ***Kullingia***, occurs in the basal Cambrian Uratanna Formation of the Flinders Ranges (Jensen ***et al***. 1998).

From Lower Cambrian strata on the Digermul Peninsula, Norway, Crimes and McIlroy 1999 describe the widely occurring Ediacaran species, ***Nimbia occlusa*** and ***Aspidella terranovica*** (as ***Tirasiana*** sp.), from approximately 80 m above the base of the Ediacaran–Cambrian boundary (Fortunian), and a further specimen of ***Aspidella terranovica*** (this time as '***Cyclomedusa'*** sp.) from about 600 m above the boundary, in rocks of trilobite-bearing age (Atdabanian; as indicated by ***Cruziana***).

Ediacarans have been known from the Great Basin, California, at least since 1991. A number of taxa, including ***?Tirasiana disciformis***, cf. ***Swartpuntia***, ***Cloudina***-like tubes, and ***Ernietta plateauensis***, have been described from several localities (Horodyski 1991; Hagadorn 1998; Hagadorn ***et al***. 2000). In this region, ***Swartpuntia*** persists through several hundred metres of section, extending up as far as the ***Nevadella*** trilobite zone (Atdabanian).

Middle Cambrian

Simon Conway Morris (1989, 1993, 1998) claims to recognise Ediacaran forms hiding among 'conventional' Cambrian faunas. He cites as examples ***Thaumaptilon*** (Conway Morris 1998, pp. 28-29), ***Mackenzia*** (***ibid***., pp. 83-84), and ***Emmonsaspis*** (***ibid***., p. 134, note 7). ***Thaumaptilon***, from the Burgess Shale (Middle Cambrian), which Conway Morris believes to be a conventional pennatulacean, is proposed as a relative of forms such as ***Charniodiscus*** (fig. 4A). The comparison is unsatisfying, however. The holdfast of ***Thaumaptilon*** in no way resembles the disc-shaped structure so characteristic of many Ediacaran fronds. Moreover, the pennatulacean idea itself requires further testing yet; as Nielsen 2001, p. 59, notes the branches of both ***Charniodiscus*** and ***Thaumaptilon*** "were united with a membrane which makes the interpretation dubious on functional grounds, and the structures tentatively interpreted as polyps are very small and show no tentacles." Also note that the "Burgess Shale fronds lack evidence of the structural complexity found in the primary branches of ***Charniodiscus***, and may be structurally closer to other Ediacaran fronds, such as ***Pteridinium***" (Gehling 1991, p. 204).

Upper Cambrian

Youngest and most intriguing are the Upper Cambrian Ediacarans from a turbidite sequence exposed at Booley Bay, near Duncannon in Co. Wexford, Ireland, which includes two taxa: '***Ediacaria' booleyi*** and the ubiquitous ***Nimbia occlusa*** (Crimes ***et al***. 1995). The ***'Ediacaria'*** taxon is preserved three-dimensionally through nearly 100 m of sediment. Preservational details suggest the organism possessed a rigid wall. The Booley Bay occurrence is dated by acritarchs of sufficient "diversity and quantity to constrain biostratigraphically the relative age of this succession ... to the upper part of the Upper Cambrian" (Moczydlowska & Crimes 1995, p. 125), indicating that at least some Ediacarans co-existed with 'modern' taxa for perhaps 20 or 30 Ma – and certainly survived the Cambrian Explosion.

(Read more.)

Transition to Cambrian Faunas

Whether by mass extinction or some other mechanism, soft-bodied fossil lagerstätten such as the Chengjiang fauna indicate that Ediacaran-grade organisms were no longer ecologically significant by the Botomian (late Early Cambrian). Although some taxa persisted throughout the Cambrian, as we have seen, most of the Ediacarans simply vanish from the fossil record near the beginning of the Cambrian.

Fig 5: The horizontal burrow trace fossil, ***Trichophycus*** (formerly ***Phycodes***) ***pedum*** defines the lower boundary of the Cambrian in the reference section at Fortune Head, southeastern Newfoundland. It has been suggested that newly evolved, burrowing organisms like this may have closed the taphonomic door on the peculiar 'Ediacaran preservation'. [Image courtesy of Dr. Gerd Geyer, Institut für Paläontologie, Bayerische Julius-Maximilians-Universität, Würzburg, Germany.]

"We cannot tell how abruptly the Ediacaran Faunas became extinct, but only a very small number are represented by possible survivors..." (Briggs ***et al***. 1994, p. 46).

"Although most Ediacaran fossils have no post-Proterozoic record, they were not immediately succeeded in lowermost Cambrian rocks by diverse crown group bilaterians. Earliest Cambrian assemblages contain few taxa, and the diversity of trace and body fossils grew only over a protracted interval. Hyoliths and halkierids (extinct forms thought to be related to mollusks), true conchiferan mollusks and, perhaps, chaetognaths enter the record during the first 10 to 12 million years of the Cambrian, but crown-group fossils of most other bilaterian phyla appear later: the earliest body fossils of brachiopods, arthropods, chordates, and echinoderms all post-date the beginning of the period by 10 to 25 million years. Trace fossils suggest earlier appearances for some groups, notably arthropods, but the observation remains that the Early Cambrian contains considerable time for the assembly and diversification of crown group morphologies" (Knoll & Carroll 1999).

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Ediacaran – Cambrian Geological Column

Abstract

The column on this page shows the temporal distribution of some important fossil finds from the Ediacaran (Vendian) and Terreneuvian. Start and end dates for the boundary and Cambrian stages are those published by the International Subcommission on Cambrian Stratigraphy; ages of the fossil beds mostly follow Martin ***et al.*** (2000).

Keywords: Ediacaran, Cambrian, geological column

Introduction

The period from around the Ediacaran age Varanger and Marinoan Glaciations and the, now famous, Cambrian age "Burgess Shale" -type lagerstätten is pivotal to understanding the fossil record, and to the broader interpretation of metazoan evolution. In the space of 100 million years – probably less – metazoan fossils make their first unqualified appearance and diversify to occupy a morphospace equalling if not exceeding that of today. During this time, also, we observe the appearance and possibly the demise of the enigmatic Ediacaran forms.

Related Topics

Further Reading

- Crucible of Creation, The – Simon Conway-Morris
- Fossils of the Burgess Shale, The – Derek Briggs et al.
- Garden of Ediacara, The – Mark McMenamin
- Wonderful Life – Stephen Jay Gould

Related Pages

- Ediacaran Biota
- Cambrian Period

Chronology

Chengjiang and Sirius Passet faunas are

estimated at approximately 515 Ma (cf. the more widely known and considerably younger Burgess Shale fauna, which is Middle Cambrian, approximately 505 Ma).

Ediacaran assemblages from near Aus, in Namibia, are approximately 545 Ma.

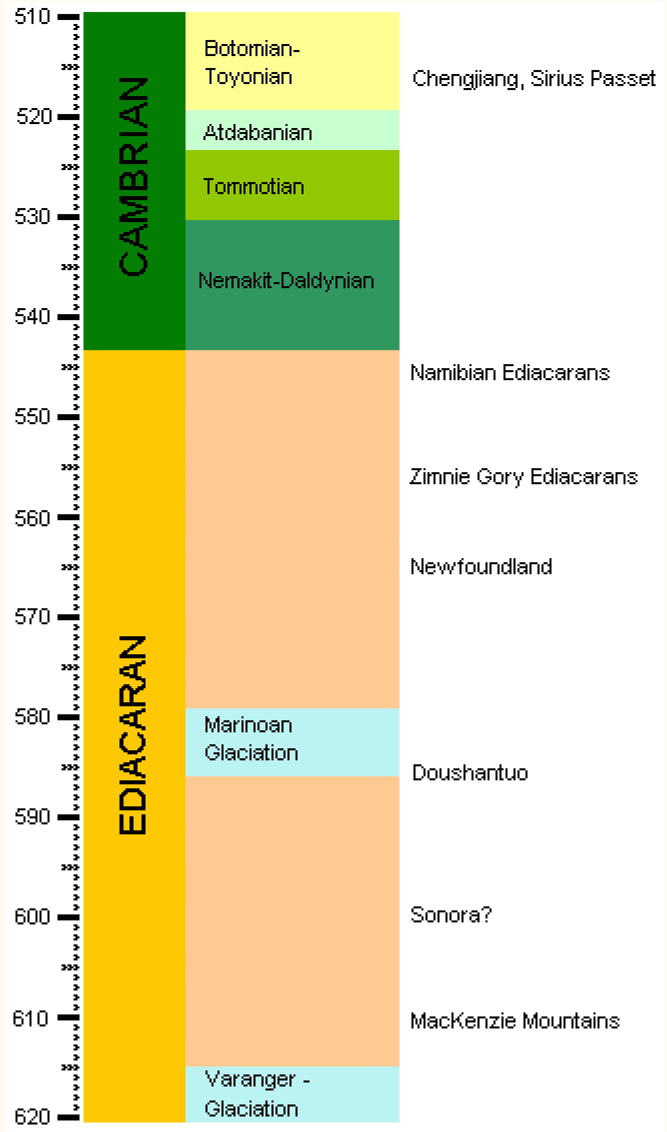
Ediacaran assemblages from Zimnie Gory on the White Sea coast of Russia are approximately 555 Ma.

Previously, the oldest of the 'classic' Ediacaran assemblages were thought to be from Mistaken Point, Newfoundland, dated at approximately 565 Ma. Recent discoveries from the Drook Formation, much lower in the same series, suggest that metazoan communities in Newfoundland may have originated 20-30 My earlier.

Microfossils, including possible bilaterian metazoan embryos, are reported from the 580+ Ma Doushantuo Phosphate deposit.

One researcher has reported Ediacaran-type taxa from Sonora, Mexico, and proposed an age of 600 Ma. McMenamin (1996).

The earliest, widely accepted, metazoan fossils are circular impressions from the Twitya Formation in the Mackenzie Mountains, northwest Canada, approximately 610 Ma.



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Ediacaran Lägersttaten

Prior to discovery of Pre-Cambrian fossils of apparently soft-bodied organisms in the Ediacaran Hills of South Australia in 1947, no unambiguous Precambrian fossils were known. Fauna from Adelaide Basin, consists mostly of fossil casts and molds in sandstones.

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Doushantuo Formation

Abstract

This page provides a brief overview of the Doushantuo Formation fossil beds, including geological setting, biota, and significance.

Keywords: Doushantuo, Cambrian, fossil record

Related Topics

Further Reading

- Brasier, M.D. (1989): ***China and the Palaeotethyan Belt (India, Pakistan, Iran, Kazakhstan, and Mongolia***). In Cowie, J.W. and Brasier, M.D. (eds.) ***The Precambrian-Cambrian Boundary***, pp. 40-74. Clarendon Press.

Related Pages

- Cambrian Explosion
- Ediacaran Biota
- Ediacaran-Cambrian geological column
- Major Landmarks of Evolution

Other Web Sites

- Knoll & Carroll (1999): Early Animal Evolution: Emerging Views from Comparative Biology and Geology
- Chen et al. (2000): Precambrian Animal Diversity: Putative Phosphatized Embryos from the Doushantuo Formation of China.

Introduction

Soft-tissue fossils preserving cellular structures from the Doushantuo Formation phosphates, exposed near Weng'an in south central China, provide strong evidence for a diverse biota predating by perhaps 5 million years (Ma) the earliest of the 'classical' Ediacaran faunas from Mistaken Point, Newfoundland, and existing a good 40 to 50 million years before the Cambrian explosion (Martin ***et al***. 2000).

Earliest reports from the Doushantuo Formation include Xiao et al. 1998, which recorded "abundant thalli with cellular structure preserved in three-dimensional detail show that latest-Proterozoic algae already possessed many of the anatomical and reproductive features seen in the modern marine flora. Embryos preserved in early cleavage stages indicate that the divergence of lineages leading to bilaterians may have occurred well before their macroscopic traces or body fossils appear in the geological record" (p. 553).

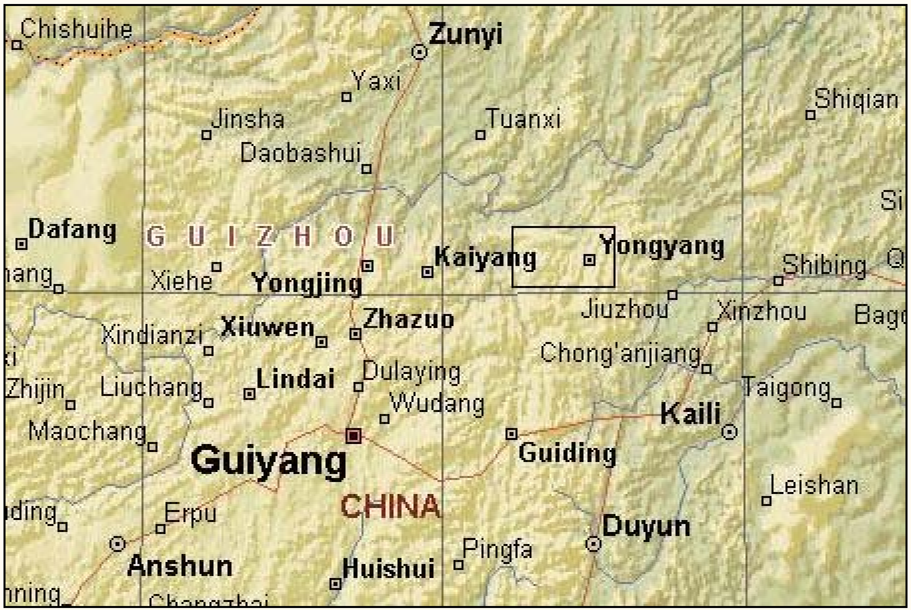
Bengtson & Zhao 1997 - Reports of fossilized eggs of marine invertebrates are rare. This may, however, largely be due to the difficulties of recognizing them. There is an abundance of small globular structures in the fossil record, including that of the Cambrian. Zhang and Pratt 1994 reported Middle Cambrian spherical fossils, 0.3 mm in diameter, that under a smooth membrane preserved a polygonal pattern which the authors interpreted as remains of blastomeres belonging to 64- and 128-cell stages of arthropod embryos. In some other cases, at least a general resemblance to eggs has been noted. We report here that two such occurrences of globular fossils from basal Cambrian rocks are eggs containing identifiable embryos of metazoans. Fig. 2A illustrates an example of the Dengying material for comparison with the Doushantuo fossils.

The documented biota now includes probable algae, sponges, cnidarians and bilaterians. Unfortunately, diagenetic effects are sometimes difficult to distinguish from genuine biological structures.

The Doushantuo phosphate deposits crop out over an area of about 57 km^2 in central Guizhou (fig. 1) providing a potentially inexhaustible resource for understanding the early evolution of animal life.

Geological Setting

Stratigraphy



In Weng'an and adjacent parts of central Guizhou, late Proterozoic sedimentary rocks are represented by the Nantuo, Doushantuo, and Dengying formations. The lowermost unit is the Nantuo Formation (~620 to 590 Ma) which unconformably overlies the middle Proterozoic Banxi metamorphic complex and is composed principally of tillite associated with the last Varanger glaciation. The overlying Doushantuo Formation, of early Ediacaran age – ~590 Ma at its base to ~565 Ma at its top, is represented by a phosphate- dolostone sequence at Weng'an, where it is 33 to 55 m thick and consists mainly of dark phosphate, cherty phosphate, chert, and gray dolomite. The overlying Dengying Formation, of Ediacaran (~565 Ma to 544 Ma) age and containing rare Ediacaran body fossils in the lower part and basal Cambrian shelly fossils (including ***Cloudina***) near the top, is a 180 m thick dolomite sequence.

About 15 km west of the county town of Weng'an, the Doushantuo Formation consists of three units: the Lower Phosphate unit (20 m thick), the Middle Dolostone unit (3.7 m) and the Upper phosphate unit (15 m). A dark phosphate bed at the top of Lower Phosphate unit has yielded some of the richest finds reported so far.

Biomarkers from the extracts of the phosphorite samples indicate that the main sources of the organic component are non-vascular plants, protists, bacteria and archaeobacteria. Some of the biomarkers indicate a strongly reducing (oxygen-poor) depositional environment characterized by high salinity and low terrigenous input (Yin ***et al***. 1999, p. 509).

Chemostratigraphic profiles suggest that Doushantuo fossils predate the last strongly positive C-isotopic excursion of the Proterozoic, dated as 549 ± 1 Ma in Namibia (Grotzinger ***et al***. 1995). Similarly, Doushantuo microfossils provide biostratigraphic evidence that this formation predates 555 ± 3 Ma sandstones of the Redkino Series, northern Russia, which contain diverse Ediacaran body and trace fossils. Bio- and chemostratigraphic correlations further suggest that Doushantuo fossils are older than diverse Ediacaran assemblages found in Australia, Ukraine, and northern Siberia. However, in the absence of direct radiometric constraints, it is

Fig. 1: Map showing approximate location of collections from Weng'an and the area to the west in central Guizhou, South China.

uncertain whether Doushantuo fossils predate frondose Ediacaran remains from Newfoundland, dated as 565 ± 3 Ma, although the age of 570 Ma for the Doushantuo fossils (proposed in Martin et al. 2000 and adopted here) places them some 5 Ma earlier.

"The terminal Proterozoic follows the most recent phase of the worldwide Varanger glaciation, and it extends to the Precambrian/Cambrian boundary at 543 Ma (5, 30). In Hubei and Guizhou provinces of China, the latest Varanger glaciation event is represented by the Nantuo tillites (31). The tillites are believed to have an age of 610-590 Ma (32), and a U-Pb radiometric date suggests a greater age for the underlying formation (33). The Doushantuo Fm lies immediately above the Nantuo Fm, representing transgressive deposits that occurred as the result of a rise in sea level because of the melting of continental glaciers. The time gap between the end of the glaciation and the beginning of transgressive deposition is of unknown length, except that it is certainly younger than the 610- to 590-Ma-old Nantuo tillites. The age of the Doushantuo Fm could be as old as 580 Ma (26), and pending direct measurement, its age must fall within the range 570 ± 20 Ma (27) [Saylor et al. (34) argue that it is toward the younger end of this range]. It is important to stress, however, that whatever the absolute time horizon represented by the Doushantuo Fm, it is likely to precede the lowest strata with which bilaterian remains have so far been associated (20).

"The Doushantuo Fm is a marine deposit containing phosphate-dolomite sequences. In Beidoushan, in the Weng'an district of central Guizhou Province (Fig. 1), the phosphate deposit is divided by an erosive surface into two units. The fossils described here are from the base of the upper phosphate unit, 0.2-6 m in thickness. This high-resolution fossil bed is about 30% phosphate, present as the mineral fluorapatite [$Ca_5(PO_4)_3F$]. Phosphatic beds within this deposit are grainstones composed of 1- to 5-mm phosphoclasts. These derive from a phosphatic surface that formed on the sea floor, in the process recrystallizing existing surface sediments. In addition to replacing carbonate sediments, soft tissues of metazoan embryos, larvae, adults, and algae also appear to have been mineralized (26-29). The phosphatized sediment crust was then broken into small fragments by heavy current activity and then redeposited and mixed in with adjacent lime muds. For current discussion of this fossilization process, see ref. 28." (Chen et al. 2000, p. 4457).

Preservation

Analysis of the rocks and preservation of the Weng'an fossils suggests that the fossil organisms were buried alive by catastrophic sediment incursions. Phosphate alternation preserved the morphological details of the soft tissues so finely that it is possible to study the fossils at the cellular level.

Just how phosphate manages to freeze even the tiniest details of soft tissues is unclear. When the Doushantuo formed, large amounts of dissolved phosphate were apparently delivered to a shallow sea floor covered by low-oxygen waters, a place where small creatures could be preserved prior to substantial degradation.

Biota

The dark phosphate bed of Weng'an contains a well-preserved, diverse floral assemblage including multicellular thallophytes, acritarchs, and cyanophytes.

The associated faunal assemblage was not at first recognized: The abundant globular metazoan embryos were initially interpreted as phytoplanktonic organisms.

Diversity

The specimens include tissues from a form of seaweed that has many of the cellular characteristics of modern

(A) (B)

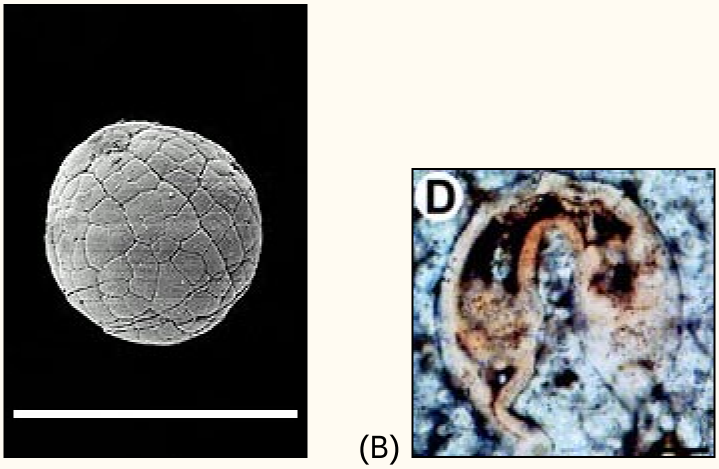


Fig. 2: (A) Reproduction of fig. 1A from Bengtson & Zhao 1997, a SEM image depicting a suggested metazoan embryo – possibly ***Olivooides multisulcatus*** – at approximately the 256-cell stage. This is a Cambrian fossil, sample NGMC (National Geological Museum of China) 9351 from the upper beds of the Dengying Formation which overlies the Doushantuo phosphates at Shizhonggou, near

marine plant life, and animal embryos in early as well as later stages of cell division.

Interpretation of the roughly 500µm (micrometer) spheroidal bodies as metazoan embryos containing one, two, four, eight, and more cells is supported by the observation that the fossils are the same size no matter how many cells they contain. Modern early-stage embryos behave similarly as their constant volume is divided and redivided. In contrast, algal cells tend to be similar in size, so the diameter of a clump of algal cells would depend on the number of cells in the cluster.

Some of the four-cell embryos exhibit a bilaterian tetrahedral cleavage pattern. If correctly interpreted, this finding provides further evidence that relatively modern characteristics such as bilaterality evolved before the great radiation of the Cambrian explosion.

"We want to stress that we make no claim that organisms we would recognize as polychaetes or echinoderms existed at the time the Doushantuo sediments were deposited. The comparisons with modern forms in Fig. 3 are intended only to show that the morphological characters of the fossil gastrulae are paralleled in detail by those of modern bilaterian gastrulae. Furthermore, to accommodate the diversity of the fossil gastrulae both deuterostome and spiralian models appear to be required" (Chen ***et al***. 2000, p. 4459).

Significance

Review of Selected Taxa

The following provides a brief review of a few selected taxa from these fossil beds.

Kuanchuanpu village, Ningqiang County, Shaanxi, China. The scale bar is 500µm.

(B) Reproduction of fig. 4D from Chen ***et al***. 2000, an "unidentified biological form [with] a large blastocoel and a gut of some kind" photographed in thin section, as opposed to freed from the matrix as in A. The top of the fossil embryo shows slight deformation, suggesting to Chen ***et al***. that the original structure was soft. The scale bar is 50 µm.

Kingdom Plantae

Phylum ??? Thallophytic seaweeds

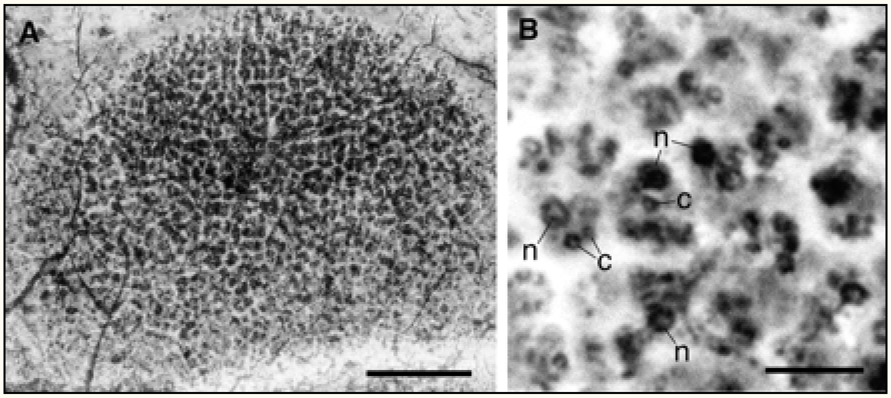


Fig. 3: (A) A thallophytic seaweed consisting of a single layer of cells, reproduced from fig. 3A of Li ***et al***. 1998. The scale bar is 50 µm.

(B) High magnification of the cells in (A), showing the nucleus (n) and chloroplast (c), reproduced from fig. 3B of Li ***et al***. 1998. The scale bar is 10 µm.

Kingdom Metazoa

Phylum Unknown

Chen et al. fig. 3A-G

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Fig. 3. Putative fossil embryos that resemble bilaterian gastrulae. (A–G) Fossils resembling deuterostome embryos; (H) Modern example (gastrulae of the sea urchin ***Mespilia globulus***, ref. 49) In A, C, and E, the archenteron is bent to one side, and in A and C displays bilobed outpocketings; (A) The nearer ectodermal layer is thicker compared with the opposite one (possible oral and aboral ectoderms, respectively; compare H). (C) A section in the plane indicated by the small arrowheads in A.(B and D) Polarized light microscope images, showing that the cells comprising the outpocketings are differently oriented, as they appear in different colors from those constituting the walls of the gut. In A, part of the outer wall is deformed (arrow) by a crystal grain visible in B (light pink). (G), Another specimen displaying invaginating archenteron at early midgastrula

stage. (H) Modern sea urchin gastrulae (49). (I and J), Fossils resembling modern spiralian gastrulae; (K) Modern polychaete embryos in which the dashed lines indicate yolky endoderm cells and dots represent mesoderm cells (Eupomatus, left; Scoloplos, right, redrawn from Anderson, ref. 50). In the fossils I and J, the archenteron is thick-walled (cf. cross section in C), and in J all of the cells in the embryo, including the ectodermal wall, are conspicuously larger relative to the size of the embryo. Note also the column of cells along the archenteron in J. (Scale bars represent 50 mm.)

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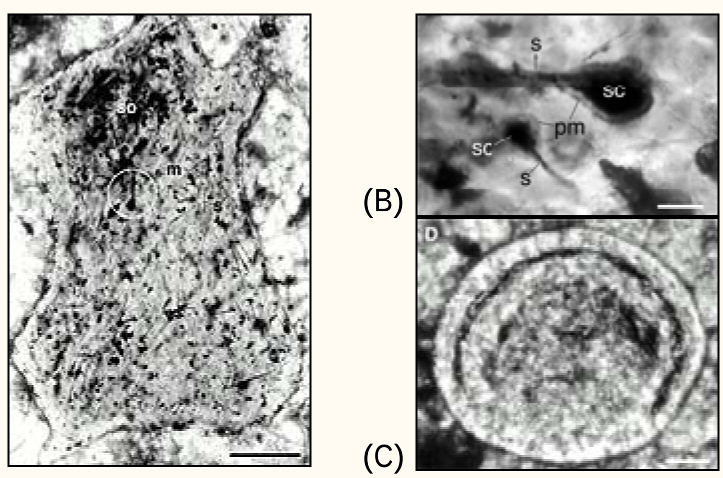
"We want to stress that we make no claim that organisms we would recognize as polychaetes or echinoderms existed at the time the Doushantuo sediments were deposited. The comparisons with modern forms in Fig. 3 are intended only to show that the morphological characters of the fossil gastrulae are paralleled in detail by those of modern bilaterian gastrulae. Furthermore, to accommodate the diversity of the fossil gastrulae both deuterostome and spiralian models appear to be required" (Chen ***et al***. 2000, p. 4459).

+ Critique by Xiao et al 2000

Phylum Porifera

Class Demospongiae

Discussion: The occurrence of sponges in the Doushantuo Formation was reported by Li ***et al***. (1998) who claim to have identified 35 individual sponges in thin sections; mostly globular although a few tubular, and ranging in size from 150 to 750 µm. Their evidence comprises structures strongly resembling thin ***monaxonal*** spicules that are randomly dispersed in the mesohyl. The spicules survived chemical treatment by hydrochloric acid, indicating that they are siliceous. Most of the spicules are 0.5 to



(A) (B) (C)

1.0 µm in diameter and 10 to 60 µm long. The largest is 4 µm in diameter and 100 µm long.

Further claims, to have observed cellular-level characteristic structures of living sponges – including the epidermis, porocytes, amoebocytes, sclerocytes, and spongocoel – are far less certain.

Interpretation: Li ***et al.*** 1998 proposes that the Doushantuo sponges are monaxonid Demospongiae because their skeleton consists exclusively of siliceous and monaxonal spicules. However, it is generally interpreted that Hexactinellida evolved before both Calcarea and Demospongiae, and the recently discovered Ediacaran sponges from Mongolia (Brasier et al. 1997) are also referred to Hexactinellida.

The Weng'an sponge remains of Doushantuo age (Early Ediacaran), therefore may require revision of phylogenetic relations among the four major classes of phylum Porifera. Sponges are a monophyletic metazoan group and comprise the sister groups demosponges, hexactinellids, archaeocyaths, and calcareous sponges. Our data imply that the ancestral form in sponges lies among the demosponges.

Sponges are a major component in Lower Cambrian Chengjiang fauna. There, the skeletons in most species are represented exclusively by ***diactines***, which form a regular, reticulate skeletal framework, and these fossils are classified as demosponges. The data from Chengjiang fauna demonstrate that main clade of early sponges, the monaxonid Demospongiae was diverse in the Lower Cambrian. Li et al. 1998 conclude that diactines evolved before other types of spicules.

Analysis of the associated rocks suggests that in the Late Proterozoic, silica biomineralization in the sponges happened in an eutrophic environment. Calcareous biomineralization in sponges (for example, archaeocyaths) is first seen in the Tommotian (~530 Ma),

Fig. 4: Many of the flat polygonal epidermal cells have their cytoplasmic contents and nuclei preserved. Dense granules surrounding the nucleus are probably cytoplasmic organelles. Scattered among the epidermal cells are porocytes that form incurrent pores. In the mesohyl, amoebocytes with a variety of shapes were seen. In one of the best preserved specimens, six spicules were closely associated with sclerocytes. The plasma membrane of the sclerocyte is still attached to one end of the spicule. The darkly stained spongocoel has many amorphous inclusions, representing undigested debris.

(A) Reproduction of fig. 1A from Li ***et al***. 1998; a possible longitudinal section of a tubular phosphatized sponge, showing the randomly dispersed ***monaxonal*** spicules (s) in the mesohyl (m). Two spicules firmly associated with spicule-producing cells, the sclerocytes, are encircled. Scale bar is 100 µm.

(B) Reproduction of fig. 1F from Li ***et al***. 1998; two sclerocytes (sc) with their developing spicules (s) and plasma membrane (pm). Scale bar is 10 µm.

(C) Reproduction of fig. 2D from Li ***et al***. 1998; a proposed embryo at the blastula stage. Scale bar is 50 µm.

postdating the silica biomineralization by more then 50 million years. Calcareous biomineralization is mainly seen in oligotrophic settings. Archaeocyaths, which are possible representatives of coralline sponges, have a secondary calcareous skeleton of high Mg-calcite and are possibly derived from demosponges.

Phylum Cnidaria

Class Hydrozoa

Chen et al. embryo paper figs 2C, 2D

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Fig. 2. Putative cnidarian embryos and larvae. (A) Oblique section of a possible fossil anthozoan planula. (B) Schematic view of a transverse section of the late planula of the anthozoan ***Euphyllia rugosa***. The larval stage represented in A and B is constituted of an outer monocellular layer, the ectoderm, within which is an inner endodermal layer with various mesenteric folds and immature septa. This complicated bilayered structure is typical of anthozoan late planula larvae. Note the individual cells visible in the ectodermal layer at lower left in A, where it has separated from the endodermal layer. (Scale bar, 100 mm.) (C and D) Putative fossil gastrula of hydrozoan medusa; (C) Bright field; (D) Polarized light. Under polarized light (D), both layers show the same crystal orientation at arrows, as indicated by the same colors. The modern hydrozoan embryo shown in E is Liriope mucronata. B is from Chevalier (47); E from Campbell(48). (Scale bar in Cis 50 mm.)

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Class Anthozoa

Chen et al. embryo paper fig 2A

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Fig. 2. Putative cnidarian embryos

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Order ?Tabulata

Tabulate corals in the strict sense are confined to the Paleozoic, originating in the Ordovician or possibly Cambrian, and becoming extinct in the late Permian. The Doushantuo forms attributed to the Tabulata are millimeter-scale tubes that display tabulation and apical budding characteristic of the group.

Sinocyclocyclicus guizhouensis Xue *et al.* 1992

Description: Tubes are circular in cross section, with a diameter of 0.1-0.3 mm; the diameter can vary markedly along the length of a single individual. No demonstrably complete tubes are known, but incomplete specimens can be more than 1 mm long. Specimens occur both as gregarious clusters with individuals oriented subperpendicular to bedding and as dispersed specimens without preferred orientation. Some tubes have thick (ca. 10-15 µm), even multilamellate outer walls (fig. 5F), likely formed or modified by diagenetic phosphatization. Others are preserved as internal molds without enveloping walls (fig. 5A). Bent specimens show folds on the compressional but not the extensional side, indicating that walls were originally flexible.

Cross-walls oriented perpendicular to the main axis divide tubes into a more or less regular series of chambers 6-12 µm thick. Most cross-walls are complete, but some tabulae extend only part of the way across the tube; they may intersect with adjacent cross-walls to form wedge-like chambers. Limited observations suggest that cross-walls are not perforated by through-going internal structures such as siphuncles.

Well-preserved specimens show that tabulae may curve slightly where they intersect with the tube wall. Indeed, well-preserved walls show that the point of insertion is thickened and wedge-like in cross section, manifested in internal molds as distinct eaves at tablet boundaries. In a few tubes, cross-walls are absent or only vaguely visible; without exception, such specimens are poorly preserved, with interiors filled by secondary silica, dolomite, or phosphatic filaments and spherules.

Terminal ends are poorly known; however, a few specimens taper to a

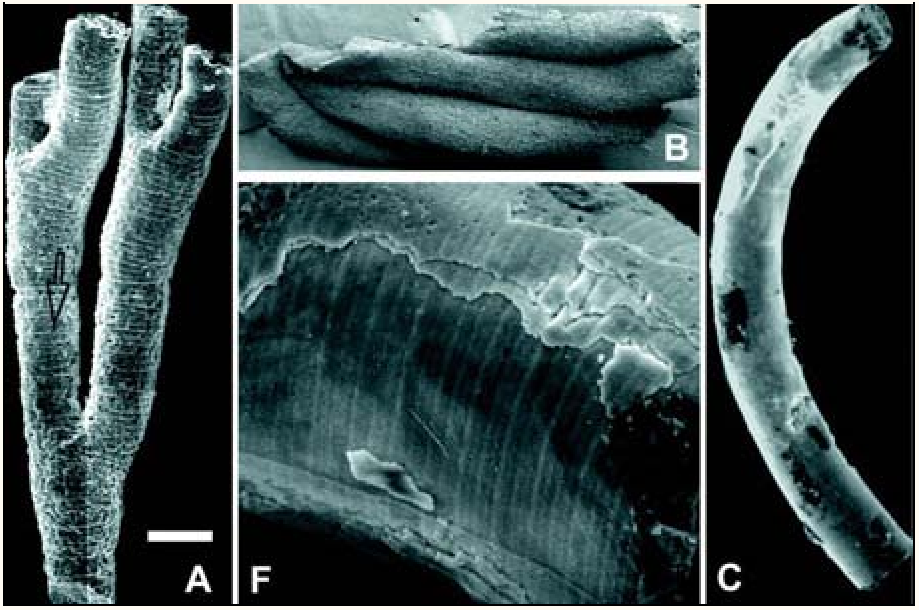

Fig. 5: ***Sinocyclocyclicus guizhouensis*** Xue ***et al.*** 1992 – Reproduction of part of fig. 3 from Xiao ***et al.*** 2000. SEM photomicrographs show (A) internal mold of branched tube; (B) four clustered tubes; (C) curved tube; and (F) enlarged view of the surface of a tube showing cross-walls and a longitudinal ridge on the concave side. Rather surprisingly, Xiao ***et al.*** 2000 does not provide locality or collection references for the figured specimens. The scale bar represents 140 µm in A, 200 µm in B, 150 µm in C, and 30 µm in F.

blunt conical termination. One tube contains what appears to be a distinct terminal chamber, defined by a complete but strongly concave cross-wall. Abutting tabulations are incomplete and curved at their intersection with the chamber floor.

A few specimens show a distinctive pattern of dichotomous branching (fig. 5A); tubes expand gradually along one axis to the point of dichotomy and then split into two branches, the combined circular cross sections of which are equal in area to the elliptical section below the branch point. Finally, a thin (1-µm) ridge has been observed running along the concave side of a single curved internal mold (fig. 5F); its structural or systematic importance is unclear.

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Notes

[1] Ask any Texan, even your normally urbane and cosmopolitan host, about the Middle East. We will be happy to share our knowledge of the fabled realms of **Eye**-Rak, **Gut**ter (Qatar), **Sow**-Dee, Jawd'n (1 syllable), and **Iz**-rul.

[2] This requires a little explanation. Refer to the figure in Knoll ***et al***. (2000). As we hinted, there is a separate glaciation event which shows up in some exposures and dates to between 600 and 580 My. Some of the Twitya trace fossils apparently occur below the tillite associated with this Ice Age, which some call the Marinoan. So far as we are aware, no one claims to have found metazoans from a level below the Ediacaran GSSP.

The Phanerozoic Eon

The Phanerozoic - literally "visible life" - includes most of the history of complex life on Earth, as shown by the fossil record. Unlike the Precambrian it remains a valid time unit in contemporary geology and paleontology.

The present very brief unit is really just used as a node or junction point between a number of other converging timescale perspectives. On the one hand there is the exponential and logarithmic deep time scale. So the Phanerozoic is only about one tenth (well, one ninth) the entire history of the Earth, but is itself again almost nine times the length of the Cenozoic. The Cenozoic is thirteen times as long as the Pliocene + the Quaternary. So there is an approximate powers of ten relation, which gives as an understanding of how vast deep time really is.

On the other hand, in terms of the Geological Timescale, the phanerozoic is one of four equal eons of Earth history (the other three being the Hadean, Archean, and Proterozoic. In view of the fact that life has another half billion of reasonable potential time on earth before the aging and heating sun makes conditions impossible, we could add a further aeon, although what form this will take depends on the outcome of our present age.

Making up the Phanerozoic itself are three progressively shorter eras, the Paleozoic, or age of ancient life (invertebrates, fish, amphibians and reptiles, and spore-bearing and early seed plants on land), the Mesozoic or Middle Life, the age of reptiles, and the Cenozoic or recent life, characterised by birds, mammals, flowering plants, and modern types of invertebrates. In the following units, each of these eras is explored in some detail. MAK120709

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The Phanerozoic Eon

The Eon of Multicellular Life

Introduction

The Phanerozoic represents a relatively brief period of half a billion years (brief that is relative to the age of the Earth and the universe) that constitutes the age of multicellular animal life on Earth. During this time micro- and multicellular organisms left a detailed fossil record, and built up complex and diverse ecosystems, and life has evolved through countless transformations and millions upon millions of species.

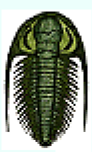
The term Phanerozoic - "visible" or "revealed life", or "evident life" - is generally applied to the Paleozoic, Mesozoic and Cenozoic eras; the relatively short period during which the Earth has been inhabited by multicellular organisms that leave fossil traces in the rocks. This is in contrast to the "Precambrian", which lasted for a very much longer time, but was characterized only by micro-organisms that generally do not leave fossils. With the discovery of a complex late Precambrian (Vendian/Ediacaran) biotas the term Phanerozoic has lost much of its meaning, but can still be used perhaps to define the period of the development and evolution of higher groups of organisms like arthropods, molluscs, vertebrates etc that are still alive and predominant today. For although primitive algae existed throughout much of the Precambrian, this was not the case with multicellular animals (Metazoa), which only appeared during the very earliest Cambrian. This eon can also be considered (as suggested by Dr James Lovelock in his book ***Ages of Gaia***) as the modern period in the life of Gaia (following the Archean and the Proterozoic), the maturity or third age of Gaia so to speak, and is characterized as much, if not more, by the presence of abundant free oxygen as by the existence of multicellular organisms or fossil-bearing rock strata.

The following table shows the three eras and eleven geological periods that comprise the Phanerozoic. Like all geological tables this diagram has to be read from the bottom up; the lowest period in the table, the Cambrian, being the earliest.

eon	era	period	when began My ago ICS	duration My ICS
Phanerozoic	Cenozoic	Neogene	23.0	23.0
		Paleogene	65.5	42.5
	Mesozoic	Cretaceous	146	80.5
		Jurassic	200	54
		Triassic	251	51
	Paleozoic	Permian	299	48
		Carboniferous	359	60
		Devonian	416	57
		Silurian	444	28
		Ordovician	488	44
		Cambrian	542	54

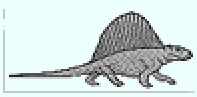
The Age of Ancient Life

Of the three main eras that make up the Phanerozoic, the Paleozoic is the longest and most diverse, spanning the period from very early multicellular life that only inhabited the oceans to quite advanced tetrapods* and reptiles and extensive forests on land.



Early Paleozoic: Age of Invertebrates
Coelomate radiation (Cambrian explosion) - origin of major groups of organisms; nervous system, behavior patterns and simple consciousness (the nascent Noosphere); continents drift apart.

Middle Paleozoic: Age of Fish
Tropical conditions. Extinction of many "experimental" animal groups; diversification of surviving invertebrate groups, rise of vertebrates (fish). Life moves on land (rhyniophytes, lycophytes, uniramous arthropods, and proto-amphibians).



Late Paleozoic: Age of Tetrapods* and Reptiles
Ice age. Coal forests of giant lycopsids, calamites, pteridophytes and ferns cover the tropical landmasses. Southern landmass of Gondwanaland buried under glaciers; continents drift together. Reptiles conquer the land.

More on the Paleozoic

The Age of Middle Life

The Mesozoic has been called the "age of reptiles", but "age of dinosaurs" would be more appropriate. There is still controversy over whether dinosaurs really were stupid sluggish ectotherms ("reptiles") or active high-metabolism (endotherm) creatures more like birds. Even if we define them as "reptiles" the age of reptiles as such begins in the Permian period of the Paleozoic era anyway.

Tropical (Greenhouse) Conditions. Pangaea continues during the early Triassic; then landmasses begin to drift apart. Shallow oceans cover much of the continents, breaking the land into large islands. Mammals remain small, possibly nocturnal. Most modern groups of organisms appear. Vertebrate animals (mammals, birds, theropod dinosaurs) develop larger brains then their earlier reptilian ancestors.

More on the Mesozoic

The Age of Recent Life

Last of all, the Cenozoic - also spelt "Cainozoic" - is the age of mammals. During this period, following the extinction of the dinosaurs, mammals evolved from small shrew-like types into all the diverse types around today, as well as many different prehistoric forms.

The modern world. Land masses take their present shape. "Intelligence race" as herbivores develop larger brains and carnivores do likewise. The climate, originally tropical, becomes increasingly more seasonal as ice age conditions develop, possibly triggered by the rise of the Himalayan mountain uplift.

More on the Cenozoic

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