# History of the Earth and Life

Shigenori MARUYAMA,[1] Yukio ISOZAKI,[2,3] Satoru NAKASHIMA,[3] and Brian, F. WINDLEY[3,4]

*1: Department of Earth & Planetary Sciences, Tokyo Institute of Technology, O-okayama 2-12-1, Muguro, Tokyo 152-8551 Japan; smaruyam@geo.titech.ac.jp*

*2: Department of Earth Science and Astronomy, The University of Tokyo, Komaba, Meguro, Tokyo 153-8902 Japan; isozaki@chianti.c.u-tokyo.ac.jp*

*3: Interactive Research Center of Science, Graduate School of Science and Engineering, Tokyo Institute of Technology, O-okayama 2-12-1, Tokyo 152-8551 Japan; satoru@geo.titech.ac.jp*

*4: Department of Geology, University of Leicester, Leicester LE1 7RH, UK, bfw@le.ac.uk*

**Abstract**

We summarize the thermo-chemical structure of the Earth in terms of the two layers of the core and of the mantle, and of the thermal-material boundaries between the inner and outer core, the core and lower mantle, the lower and upper mantle, and the layer of ocean/atmosphere/biosphere above the lithosphere. Conduction and convection release heat from the Earth, and convection patterns in the mantle, illustrated by whole-mantle seismic tomography, are interpreted as hot upwellings of superplumes and cold downwellings of subducted slabs. We outline the four ranks of the Earth's orogenesis, namely: normal period, pulse period, the time of birth of a superplume, and mantle overturn.

A major purpose of this paper is to present a working hypothesis for the history of the Earth and life, covering the whole Earth from the central core through the mantle, ocean-atmosphere and biosphere, to the magnetosphere. The following seven biggest events are proposed.

**(1) Birth of the Earth (4.56 Ga)**

The Earth was born by the collision-amalgamation of planetesimals and subsequent heavy extra-terrestrial bombardment at 4.55–4.56 Ga.

### (2) Initiation of plate tectonics (4.0 Ga)

The oldest rock, the Acasta TTG gneiss (Canada), has an andesitic protolith, indicating that subduction and plate tectonics had started by ca. 4.0 Ga. An accretionary wedge at Isua (W. Greenland) demonstrates the existence of rigid lithospheric plates at 3.9–3.8 Ga; original carbon isotope ratios corrected for regional metamorphism suggest the presence of life at this time. Early life was composed of chemical bacteria that lived in hydrothermal systems.

### (3) Birth of a strong magnetosphere and initiation of photo-synthesis (2.7–2.6Ga)

A strong magnetosphere developed at ca. 2.7Ga, when stromatolites appeared along coast-lines on most continents, suggesting that photosynthesis was started by cyanobacteria. The formation of BIF was probably related to the initiation of photo-synthesis, which produced free oxygen. The formation of many Pacific-type, accretionary orogenic belts at 2.7–2.6 Ga were the result of mantle overturn. During the extensive change in surface environment, procaryotes evolved to eucaryotes.

### (4) Formation of the first supercontinent (1.9 Ga)

More than 80% of the continents were amalgamated at 1.9 Ga, since when the Wilson cycle has been the major tectonic process on the Earth.

### (5) Return of seawater into the mantle (0.75 Ga)

The snowball Earth changed to a spring Earth due to the return of seawater by renewed plate subduction into the mantle at 750 Ma during the break-up of Rodinia; accordingly the rheology and melting temperature of the mantle decreased substantially. Return flow of seawater into the mantle decreased sea-level, and emerged a large landmass like today; the accumulation of terrigenous sediment prevented oxidation of organic matter. This increased the free oxygen in the atmosphere, which facilitated the proliferation of life. Released oxygen formed an ozone layer, which cut off ultraviolet rays, enabling life to move on land by 0.45 Ga.

### (6) Largest mass extinction at the P/T Boundary (0.24–0.25 Ga)

The largest mass extinction occurred at the Permo-Triassic boundary, when Pangaea rifted with extensive explosive volcanism, which screened sunlight to decrease photo-synthesis activity on the Earth. Super-anoxic events, caused by the decreased oxygen level, took place on continental platforms, in seamount-cap reef limestones, and in the deep sea.

### (7) Birth of human-beings and the initiation of Science

At about 6 Ma, the African plume initiated rifting of the African continent and drastically changed the climate of East Africa, enabling the appearance of ancestral human-beings.

## 1. Introduction

Synthesis of the evolution of life and the history of the Earth goes back to the beginning of the 20th century when a general understanding was reached of land geology. In the second half of that century the ocean-floor was found to be younger than 200 Ma, and radiometric dating made it possible to unravel the history of Precambrian orogenic belts (which make up about 50 % of the Earth's continental crust), showing they are as old as 4000 Ma.

In the late 1960s to early 1970s, the new paradigm of plate tectonics began to explain the complexity of orogenic belts in a better way than earlier models, in particular because of the new understanding of the geology of the ocean-floor (Dewey and Bird, 1970). At the same time, new physico-chemical investigations worldwide of Precambrian geology improved understanding of plate boundary mechanisms to form oceanic and continental crust. An early synthesis of Phanerozoic and Precambrian Geology was by Windley in 1977 in "The Evolving Continents".

Since then, several books on the "Synthesis of Earth History" by Condie (1979; 1989; 1997), Windley (1984; 1995), Nisbet (1987), and Rodgers (1993) revised the earlier synthesis. All of these works, however, were deductive, in so far as they were based on compilations of world geology, including life, the surface environment, and the history of the crust, in terms of a time-sequence of geologic events. Neither the dynamics of the deep mantle nor the core was considered. Moreover, the models of Earth History were mainly based on data from well-investigated continents such as North America and Europe, in spite of the fact that general, but critical events had been documented in other continents. In those days it was difficult to differentiate global from local events.

The technical development of global, whole-mantle tomography of the deep mantle, together with new understanding of the mechanisms which release internal thermal energy discontinuously into planetary space, made it possible to understand mantle dynamics (Maruyama, 1993;1994; Fukao et al., 1994; Kumazawa and Maruyama, 1994). Since then, a new rank of thermal events has been recognized, namely, mantle overturn (Davies 1995; Breuer and Spohn 1995) which affects the whole mantle and core (Maruyama, 1997).

## 2. Earth, its internal structure and dynamics

First, we will summarize the thermo-chemical structure of the Earth, and then introduce the hierarchy of Earth's orogenesis, which is related to processes at the boundary layers within the solid Earth. Finally, we will document data that support the development of consequent events through Earth history, and in so doing we will propose a new model of Earth evolution.

### *2.1. Two thermal and material boundaries within the solid Earth*

The Earth has the shape of a weak ellipsoid: a 21 km-longer equatorial than polar radius. At 2900 km depth a boundary surface (CMB) separates an oxygen-dominant silicate mantle from a metallic oxygen-free core (Fig. 1). The core is divisible into a central solid and an outer liquid core separated by a 5100 km-deep, thermal boundary layer on which Fe crystals accumulate to form a layer enriched in light and buoyant elements which produce dynamo convection in the liquid outer core. The connection arises because the outer core contains FeNi and about 10% of light elements such as C, S, O and H as impurities, and because these light elements are preferentially partitioned into the liquid outer core; this in turn leads to oversaturation of these elements with time.

The mantle is divisible into an upper and a lower mantle separated by a thermal boundary at 660 km depth where a solid-solid endothermic reaction takes place, ringwoodite = perovskite + wüstite which has a negative Clapeyron slope.

### *2.2. Thermal structure of the Earth*

The temperatures of the above-mentioned three boundaries are estimated to be 5500K at the inner/outer core, 4000K at the CMB (Boehler, 1996), and 1900K at 660 km (Ito & Takahashi, 1989; Agee, 1998). Lateral heterogeneity, however, seems to be very high, as expected by upwelling plumes and downwellings related to subduction. For example, stagnant slabs at 660 km depth may be 600K lower than the surrounding mantle (e.g., Peacock and Wang, 1999). At the CMB beneath Asia, the coldest part of the high-V anomaly may be as much as 2000K lower than the surrounding mantle (Yuen et al., 1994).

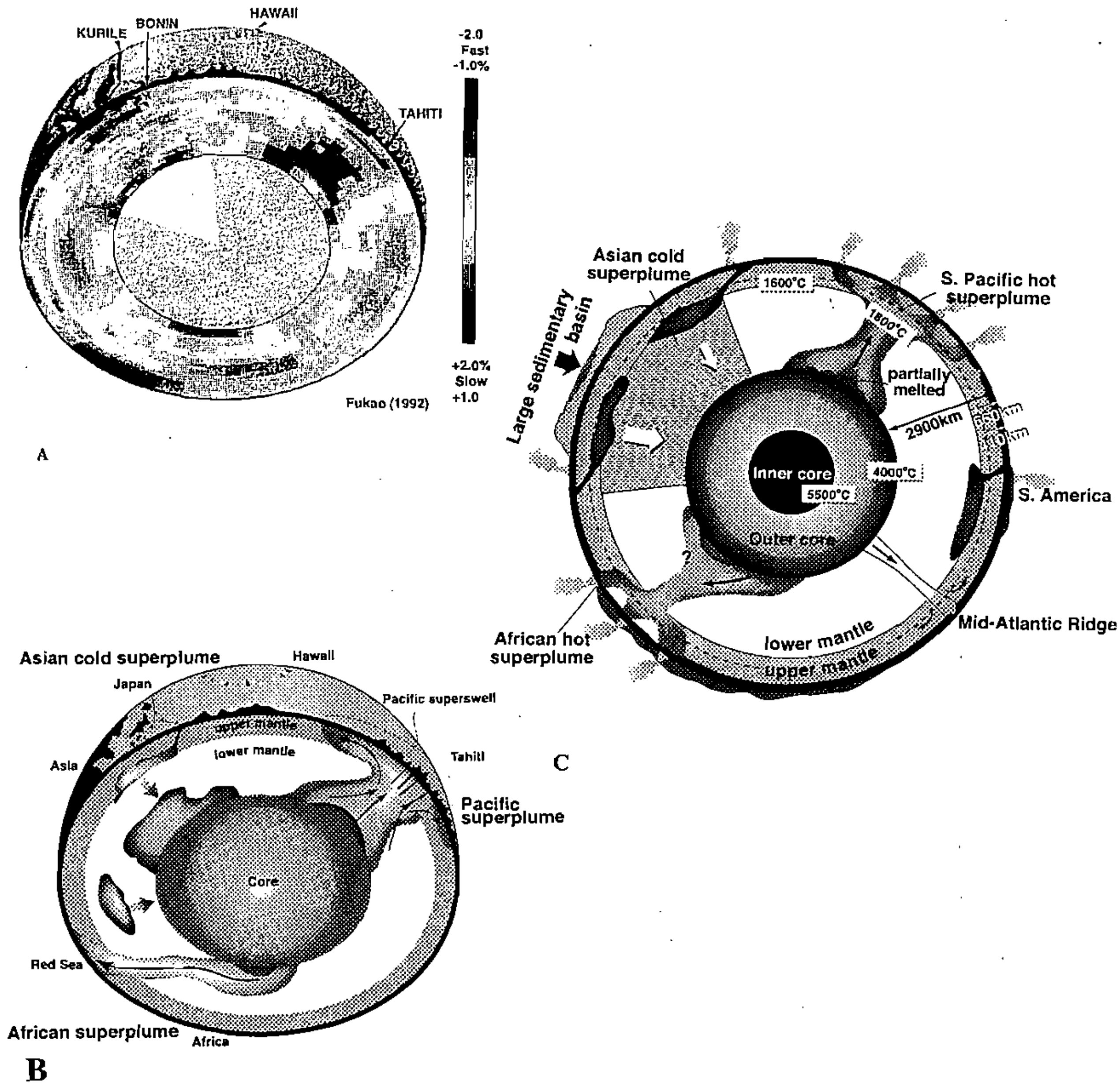


**Fig. 1.** Major structure and convection pattern of the solid Earth (modified after Maruyama, 1994). A: a snapshot of P-wave whole-mantle tomography shows the presence of huge mantle upwellings under the southern Pacific ocean and Africa. Subducted and stagnant slabs are present under the Japanese islands. B: an interpretation of the snapshot of whole-mantle tomography of A. C: a generalized model to show the major structure of the solid Earth. Two rising superplumes and one cold downwelling make-up the major convection system. The surface expression of a rising superplume is a concentration of hotspot volcanoes and of a cold superplume the presence of a huge sedimentary basin. Immediately below the hot superplumes are ultra-slow velocity zones, formed by partial melts on the CMB.

### 2.3. *Importance of boundary layers*

A boundary layer tends to develop if there are thermal and material differences within the solid Earth. The best-known example is the surface boundary layer, called a lithospheric plate. Heat moves only by conduction within the lithosphere, whereas the underlying mantle undergoes convection, hence leading to the formation of a large thermal gradient within the plate. In other words, the plate acts as a thermal blanket preventing release of internal heat from the Earth.

The mantle is about 2900 km thick, is covered by a lithospheric lid and underlain by the 300 km-thick, D" layer. This layer is up to ca. 500 km thick beneath Asia (Kendall and Shearer, 1994), but as thin as ca. 200 km under the southern Pacific, where thin, partially molten zones are present (Ishii and Tromp, 1999; Lay et al., 1998; Garnero and Helmberger, 1998; Garnero et al., 1998). There is a large thermal gradient of approximately 2000K between the top and bottom of the CMB (Boehler, 1996).

At 660 km depth, a large temperature gradient up to 700K can be expected because of refrigeration by subducting slabs (e.g., Peacock, 2001). In contrast, a rising plume, such as the Pacific superplume, may reach 1800°C, ca. 100–200K higher than the surrounding mantle. This is estimated from the topography of the 410 km and 660 km phase boundaries, both of which are the major phase boundaries characterized by olivine to wadsleyite and by ringwoodite to perovskite + wüstite, respectively, as shown in Fig. 2 (Flanagan and Shearer, 1998, Maruyama, 2002).

A thin boundary layer may be present at the inner/outer core boundary at 5100 km depth, mentioned above. The ocean/atmosphere/biosphere forms an extremely thin layer only ca. 10 km thick, connecting the density-stratified atmosphere with the lithosphere, and it acts as a material boundary layer. It is very thermally active, because it is driven by solar energy, and within it, liquid water evaporates, transporting heat from the equatorial to the polar regions by wind action.

### 2.4. *General convection pattern within the mantle*

The mantle convects at a speed of a few to ten cm/yr and with time it releases internal heat from the Earth into planetary space. There are two different modes of heat release; conduction in the surface boundary layer and convection in the mantle in general. The major convection pattern is illustrated by whole-mantle seismic tomography (Dziewonski, 1984; Su and Dziewonski, 1993; Fukao et al., 1992; 1994; Li and Romanowicz, 1996; van der Hirst et al., 1997; Grand et al., 1997; Kennet et al., 1998; Masters et al., 2000; Zhao, 2001). Two large-scale mantle upwellings under the southern Pacific and Africa, and one super-downwelling under Asia constitute the major convection system in the modern Earth. All these structures are connected from the surface to the bottom of the mantle (Maruyama, 1994, Fig. 1).

The southern Pacific superplume is characterized by a superswell ca. 2000 km across expressed by a ca. 300 m high topographic bulge, which suggests the presence of a mantle upwelling underneath (McNutt and Judge, 1990). Also, above the superswell there are 6 hotspots 500–1000 km apart (Fig. 2) which demonstrate that a superplume is a bundle of hotspots at least in the upper mantle. The details of the shape from the surface through the mantle transition zone to the bottom of mantle will be shown later.

The African superplume is visible on tomographic images, but not as clearly as the Pacific superplume (Fig. 1). Its shape is irregular, bending northward to connect with the Afar hotspot and the plumes below the African rift (Ritsema et al., 1999). The contrasting shape of the two superplumes may be related to their different tectonic settings; the Pacific-type and the Atlantic-type (Maruyama, 1994). The former is developed by downgoing cold stagnant slabs which have a ring-shaped in a three-dimensional scale. The central portion surrounded by the circum-Pacific subduction zone can be squeezed out by the cold circular downwelling. On the contrary, the Atlantic-type such as Iceland and Azores hotspots was developed by subducted slabs from the west along the North, middle and South America. The African superplume was born to break-up Pangea under Africa at 250Ma; Africa has moved northward since then. There are no subduction zones in the Atlantic and the southern Indian oceans. In Jurassic to early Cretaceous time eastward subduction from the Pacific and episodic avalanche of stagnant slabs in a linear belt may have influenced the early development of the African superplume.

The source-depth of the well-known hotspots of Hawaii and Iceland has been much debated, as to whether they continued or not to the bottom of the mantle; for Hawaii to the mid-lower mantle (Zhao, 2001), or to the CMB (Ji and Nataf, 1998), and for Iceland to the CMB (Shen et al., 1998; Bijiwaard and Spakman, 1999) or to the upper mantle (Ritsema et al., 1999). In fact, the plumes may be continuous, because a partial melt zone immediately above the CMB occurs preferentially beneath well-documented hotspots on the surface (Garnero et al., 1998).

The cold downwelling zone beneath Asia is the largest, high-V anomaly throughout the whole mantle (Fig. 1). Its presence is consistent with the subduction history of Asia, which is bounded by subduction zones on two sides. The Pacific plate from the east and the Indo-Australian plate from the south have

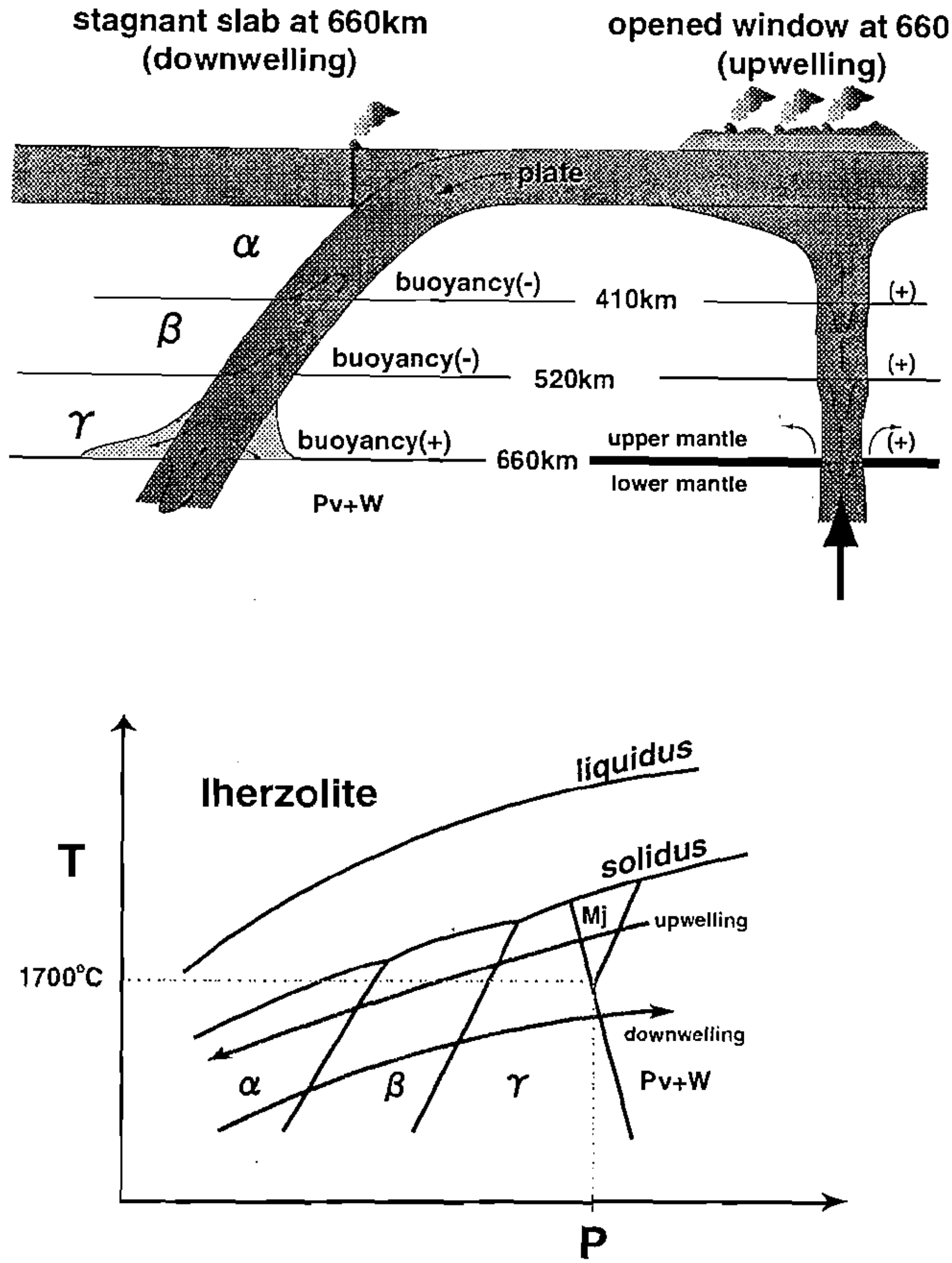


**Fig. 2.** Dynamic behavior of a stagnant slab. At 410 km and 520 km depth, the downgoing slab achieves negative buoyancy, and at 660 km positive buoyancy, because of the delay in reaction in the central, lower-T part of the slab (see the bottom diagram). Moreover, a viscosity jump (e.g., Yuen et al., 1982) from the upper to the lower mantle prevents penetration of the slab. A local degradation effect by recrystallization of the reaction from ringwoodite to perovskite + wüstite reduces the viscosity substantially to help stagnancy at 660 km depth. In contrast, in the case of a rising plume, if the T is higher than 1700°C, the 660 km depth does not act as a barrier, because the reaction has a positive slope (see the bottom diagram by Hirose, 2002). Note the presence of an opened window at 660 km depth by which allows penetration by a rising hot plume (top right). The stagnant slabs (megalith of Ringwood and Irifune, 1988) cause the discontinuous and dynamic behavior of the superplume.

been subducting beneath Asia for the last 180 Ma. The amount of subducted slabs is equal to a distance of 180,000 km (Engebretson et al., 1985). If we consider the subduction history further back to 250Ma, based on paleogeographic reconstructions (Maruyama et al., 1989), the mantle beneath Central Asia must been refrigerated by this double subduction of cold slabs. This is the reason why the strongest and largest mantle downwelling in the whole mantle has developed under Asia. Moreover, the thickest D" layer occurs at the bottom of the underlying mantle (Weber and Køring, 1992; Kendall and Shearer, 1994; Kennet et al., 1998), and a ca.5 km- thick downwarp bulge of the CMB is documented by tomography (Vasco and Johnson, 1998). Five to six planes of subhorizontal, strong, seismic reflection suggest the presence of interlayered MORB crust within the high-velocity anomaly which may have been once-stagnant slabs at the 660 km barrier. More than seven continents including Siberia, Russian platform, Kazakhstan Block, North China, South China, Tarim craton, Indochina Block and some minor blocks have collided and amalgamated since 250Ma to form Asia, suggesting that large amounts of oceanic lithosphere have subducted beneath it since then. After the completion of Paleo-Asia at 200 Ma, new subduction zones started in the east and the south framing the double-sited subduction system which has continued to the present.

Very spectacular stagnant slabs at the 660 km barrier are observed beneath the western Pacific (Fig. 1A). A ca. 300 km-thick and 1200 km-long high-V anomaly immediately above the 660 km boundary may be subducted oceanic lithosphere (Fukao et al., 1994). If the subducted Pacific lithosphere is assumed to be 50 km thick, this amounts to a 72,000 km long slab length, which equals that of all slabs subducted during the last 100 Ma (Maruyama, 1994).

The high-V anomaly near the mantle boundary layer is restricted only to subduction zones that operated during the last 180Ma, i.e., below the circum-Pacific and Tethyan orogenic belts. Huge blobs of high-V anomaly occur at 1000–1200 km depth in the lower mantle beneath Indonesia, N. America, and in the lower mantle in middle America and S. America, and in places beneath the Tethyan regions (see summaries by Fukao et al., 1994; 2001).

## 3. The dynamic controls of the Earth's orogenesis

Subducted slabs preserve their rectilinear and planar shapes in the upper mantle as documented by seismic planes and tomographic images (Zhao et al., 1994). However, at deeper levels they form blob-shapes which change discontinuously and laterally due to (1) the phase change at 660 km depth (Christensen and Yuen, 1985; Honda et al., 1993; Tackley et al., 1994), (2) a viscosity increase from $10^{19-20}$ to $10^{21-22}$ Pa.s (Yuen et al., 1982); King and masters, 1992, and (3) degradation kinetics of the reaction from ringwoodite to perovskite plus wüstite (Yamazaki et al., 1996). The best-documented example is a ca. 300 km-thick stagnant slab under the western Pacific (Fig. 1). At 660 km depth a velocity jump of the phase change reaches 6–7% in terms of the P-wave, hence every block of tomography to be averaged in velocity must not be crossed over the boundary at 660 km depth. To better constrain this, Zhao (2001) improved the P-wave whole-mantle tomographic images by giving the boundary topography at 660 km, and clearly showed that subducted slabs are always stagnant at the 660 km boundary at all subduction zones throughout the world. This suggests that the convection of the mantle is episodic. The huge 500 km thick blobs in the mid-lower mantle under Indonesia and Middle and North America were once stagnant slabs at 660 km depth, which collapsed and dropped into the lower mantle. The bimodal distribution of the high-V anomaly at 660 km and at the CMB also suggests episodic whole-mantle convection.

### *3.1. Hierarchy of the Earth's orogenesis*

Combining episodic whole-mantle convection with the avalanche model (Condie, 1998) during the geologic record, we propose that plate tectonic and plume tectonic processes throughout Earth history took place in the following four types of period.

#### *3.1.1. Normal period*

The upper mantle is mechanically separated from the lower mantle, i.e., two-layered mantle convection. Minor material passes through opened windows such as the South Pacific superplume, African superplume, and Iceland (Fig. 3). The total output of magma passing through hotpots amounts to less than 0.1 $km^3/yr$, which is less than 0.4 % of the total magma production at a mid-oceanic ridge i.e., 25 $km^3/yr$ (Table 1). Magma production at a convergent margin is 1.1 $km^3/yr$ (Reymer and Schubert, 1984). Cenozoic time after the Cretaceous pulse corresponds to this normal period. The speed of plate convergence and divergence decrease with time due to one-way passage of heat and fertile components in the upper mantle. Plate-boundary processes dominate surface tectonics.

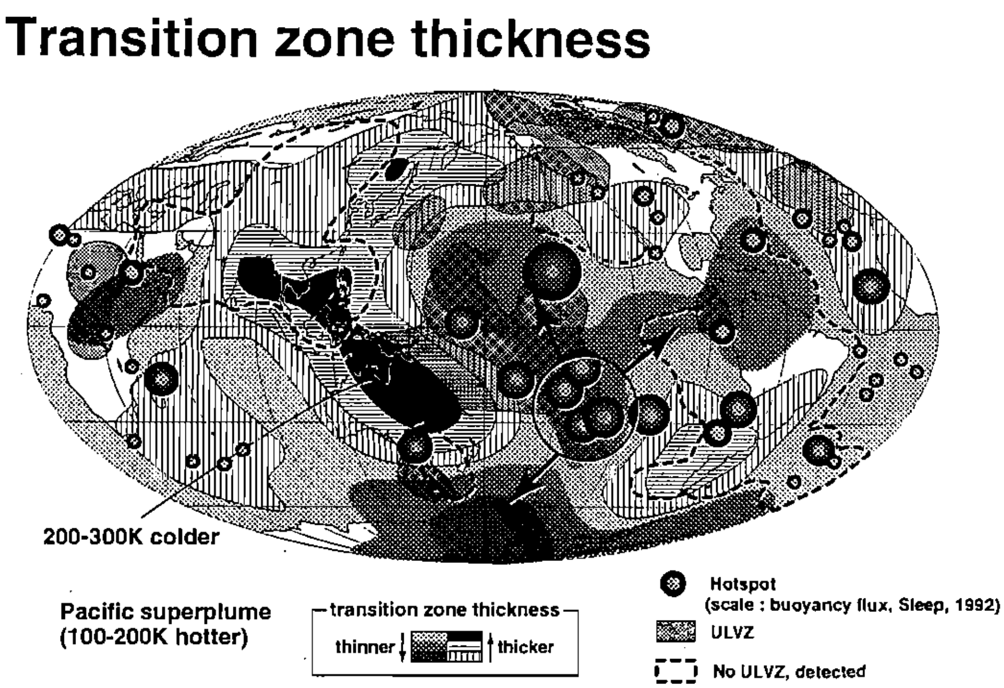


**Fig. 3.** The distribution of opened windows, which allow transportation of material from the lower to upper mantle, as deduced from the transition zone thickness of a mantle boundary layer (after Flanagan and Shearer, 1998). Note the largest window is in the southern Pacific below the Pacific Superplume. The temperature difference between upwelling and downwelling is calculated by the reaction slopes in the phase diagram of mantle boundary layers (Ito and Takahashi, 1989). Distributions of ultra-low velocity zones and hotspots are from Garnero et al. (1998) and Sleep (1992).

**Table 1.** Basic data about the Earth, after Reymer and Schubert (1984).

| Parameters | Data |
|---|---|
| Area of the Earth | $5.10 \times 10^{8}$ km$^2$ |
| Average thickness of continental crust | 38 km |
| Volume of continental crust | $7.6 \times 10^{9}$ km$^3$ |
| Total volume of continental crust | $7.76 \times 10^{9}$ km$^3$ |
| Age of the Earth | 4.56 Ga |
| Total length of destructive plate margins with active volcanism | 37000 km |
| Total length of active oceanic ridges | 56000 km |
| Thickness of oceanic crust | 6 km |
| Average rate of production of oceanic crust (Mesozoic-Cenozoic) | 25 km$^3$a$^{-1}$ |
| Present-day production rate of oceanic crust | 17 km$^3$a$^{-1}$ |
| Average velocity of subduction | 80 km Ma$^{-1}$ |
| Mean land elevation | 825 m |
| Volume of upper mantle | $3.2 \times 10^{11}$ km$^3$ |
| Volume of lower mantle | $6.0 \times 10^{11}$ km$^3$ |
| Crustal growth rate (Mesozoic-Cenozoic) | 1.06 km$^3$a$^{-1}$ |

*3.1.2. Pulse period*

This period is exemplified by the Cretaceous global events compiled by Larson (1991) and shown in Fig. 4. Global-scale superplume and plate tectonics spanned 40 m.y. from 120 Ma to 80Ma, as recorded in the magnetic record of the ocean-floor, oceanic plateaus, and sedimentary rocks (Larson, 1991). Volcanic output above the Pacific superplume reached 4000 × 2400 × 30–40 (height max.) $km^3$ which is equilvalent output of the Tharsis superplume on Mars and roughly to the total output at a mid-oceanic ridge in the normal period (Suzuki et al., 2001). Mantle volatiles such as water and $CO_2$ were brought to the surface by magmas. During the pulse period, global warming in the atmosphere and hydrosphere is well documented by deep-sea sediments probably due to increased $CO_2$. Middle to deep seawater reached 15°C, and thick forests invaded the polar regions of Antarctica and small islands in the Arctic Sea. The extensive formation of oil and black shale may reflect the global warming and resultant blooming of organisms.

It should be noted that superplume and plate tectonics took place repeatedly over 40 m.y. Consuming plate boundary processes created the 300-km wide, 3000–4000 km long TTG belt around the Pacific. An unusual observation was pointed out by Larson (1991) who emphasized that the events only took place in the Pacific domain. Increased magma production at mid-oceanic ridges did not take place in the Indian and Atlantic regions. This is the superplume pulse mechanism.

As well documented in the Cretaceous pulse period, more fertile, higher-T materials must have been transported into the upper mantle through opened windows from the lower mantle (Fig. 3). The size of the opened windows was much larger in the Pacific, and there are no windows in the Atlantic and Indian Oceans. This caused the preferential plate tectonic activity in the Pacific. Stagnant slabs in most circum-Pacific and Tethyan subduction zones finally collapsed to initiate mantle downwellings into the lower mantle in the period 120–80Ma. The transport of materials from the upper to the lower mantle promoted material transfer in the opposite direction through an opened window only in the Pacific.

Judging from the cyclic peaks of ophiolite production at 700–800Ma, 400–500Ma, 300–200Ma and 120–80Ma (Ishiwatari, 1994), and from orogenic culminations in these periods, pulsation occurred every 200–300 m.y.

*3.1.3. The time of birth of a superplume*

The African superplume was born in the latest Paleozoic during the breakup of Pangaea. The initial volcanism is characterized by extremely volatile-rich products, such as kimberlites and carbonatites, followed by flood basalts. Finally, con-

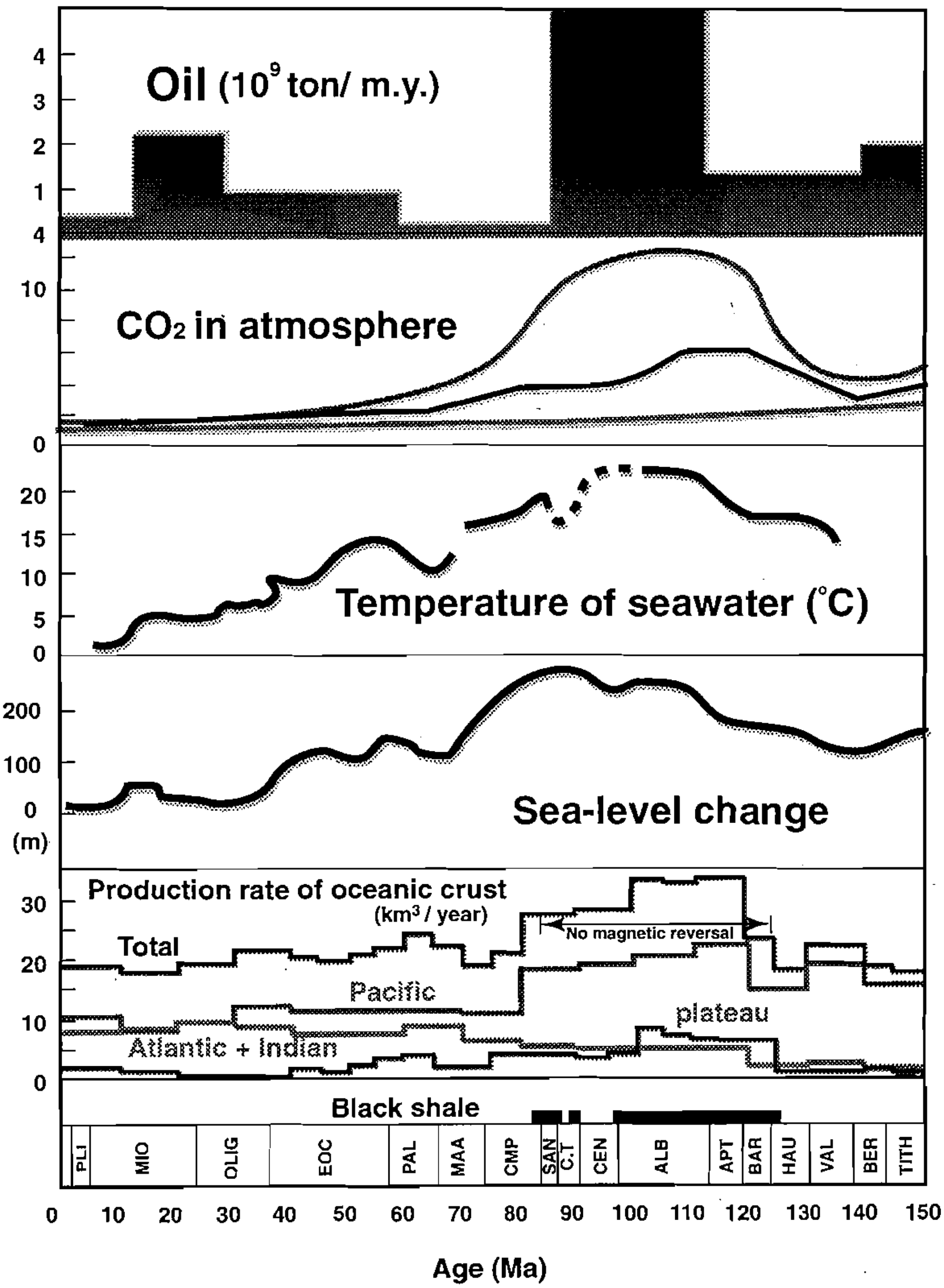


Fig. 4. Cretaceous pulse of the Pacific superplume, complied by Larson (1991). Note that both superplume tectonics and plate tectonics lasted for more than double the time of a Normal period (see Fig. 5). Also note that it happened only in the Pacific.

tinuous MORB volcanism produced a ca. 6 km- thick, new oceanic crust. It has long been known empirically that the breakup-time of Pangaea corresponds to the mass extinction at the P/T boundary (Valentine and Moores, 1970). Recent data on this mass extinction indicate the ubiquitous occurrence of super-anoxia in platform sediments, deep-sea cherts and reef limestones (Isozaki, 1997) which continued for about 15 m.y. Within these anoxic events, there was repeated development of acidic tuffs with kimberlitic affinities (Isozaki, 2000).

The origin of kimberlite and associated rocks is not yet fully understood. Yet, it is undoubtedly derived from the lower mantle, because diamonds are included in minerals from the lower mantle (Kaminsky et al., 2001). A highly speculative idea is an origin from the outer core where gravitationally unstable light elements such as C, H, O and S amount to ca. 10% in Fe-Ni metallic alloy (Stevenson et al., 1983; Stevenson, 1990). A growing solid inner core led to oversaturation of those light elements in the outer core, because of selective partitioning into a liquid phase. Those elements trapped during the early growth of the metallic core from the primordial mantle at 4.55 Ga were removed via a superplume to the surface because of gravitational instability. These components are stable in the oceans and atmosphere and have a severe influence on the survival of life, although detailed mechanisms are yet unclear.

The Pacific superplume was born at 700–800Ma during the breakup the supercontinent Rodinia (Maruyama, 1994). At this time and/or later a similar major event caused a catastrophic change of the surface environment in Vendian/Cambrian time (Tucker, 1992).

### *3.1.4. Mantle overturn*

If the upper mantle was mechanically separated for a long time from the lower mantle, particularly in an early period of Earth history when the mantle was still hot with a high Rayleigh number, the upper mantle would cooled down by plate tectonics, whereas the lower mantle would heat up by the decay of radiogenic elements. If this double-layered convection continued, the density of the upper mantle would eventually become less than that of the lower mantle, and this would give rise to mantle overturn (Breuer and Spohn, 1995, Fig. 5). This occurred on Venus at about 700–500 Ma and led to extensive basaltic volcanism on the surface as clearly shown by a low and homogeneous cratering rate on the Venusian surface (Head et al., 1992). Planet Earth probably suffered from mantle overturn, particularly in its early history, when there was more effective radiogenic heating and as a consequence of previous double-layered mantle convection.

Subducted slabs previously ponded at the 660 km boundary would have been transported into the lower mantle after the mantle overturn, whereas more

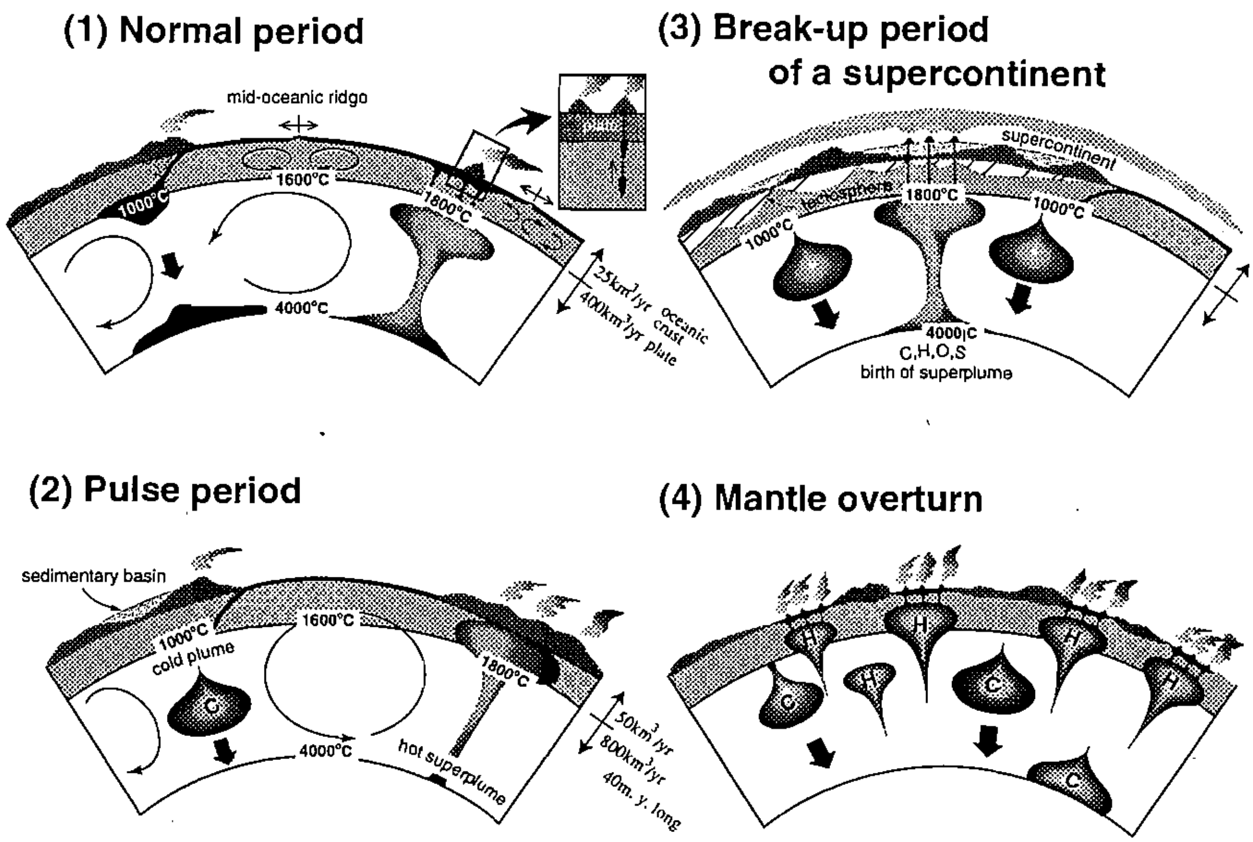


**Fig. 5.** Hierarchy of mantle dynamics, (1) Normal period, (2) Pulse period, (3) Birth period of a superplume, and (4) Mantle overturn. With increasing rank of hierarchy, materials and heat energy move more extensively from the deeper mantle to the surface.

fertile and higher-T materials from the lower mantle would have passed in plumes into the upper mantle, where they accelerated plate tectonics and hotspot activity. Extensive island arcs, oceanic islands and plateaus and Pacific-type orogens formed as a result of the mantle overturn. Some flood basalts may have come from recycled MORB from the bottom of the upper mantle .

The main periods of mantle overturn in Earth history were at 2.7–2.6 Ga and 2.1–1.9 Ga, when extensive plume-generated magmatism and subduction-generated orogenesis took place as will be discussed later.

## 4. A comprehensive synthesis of the history of life and Earth

The evolutionary history of the Earth may be simply stated as the long-term change of a highly active young planet to an inactive old one by the loss of prestigious amounts of heat from the interior to interstellar space. However, the process of heat loss was not constant through time. The multispheric structure of

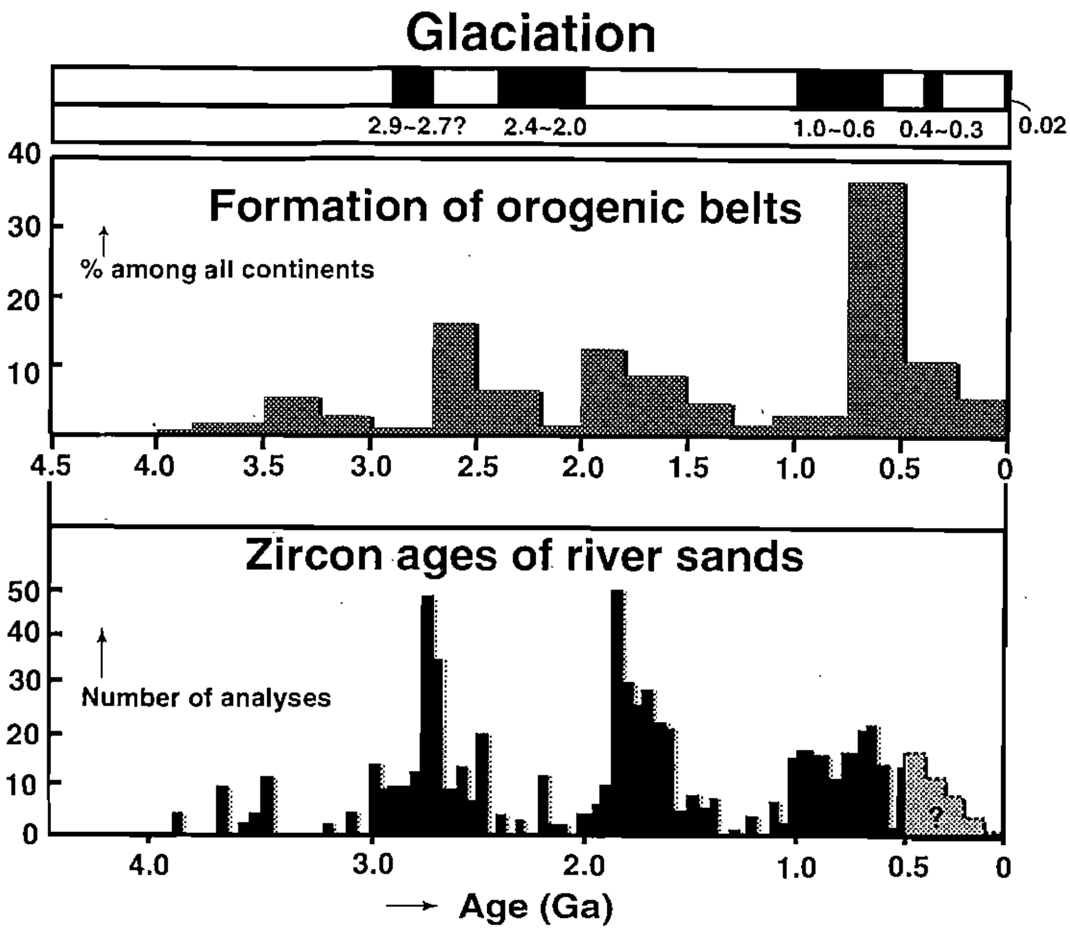


**Fig. 6.** Global-scale glaciation (top), episodic formation of orogenic belts (middle) and frequency distribution of zircon ages of river sands (after Condie, 1989; bottom). The data suggest episodic growth of continental crust. Rapid formation of orogenic belts took place after a quiescent period of volcanism and glaciation, i.e., at 3.0–2.8Ga and 2.2–2.0Ga and 1.3-1.0Ga. Global-scale mantle overturn can explain the changes at 2.8–2.6Ga and 2.0–1.9Ga (Windley and Maruyama, 2002) and the initiation of return flow of seawater into the mantle at 0.75Ga (Maruyama, 1997).

the planet and newly recognized hierarchy in geological events suggest the main processes were highly episodic. The higher level periods in the hierarchy, such as whole-mantle overturn or birth of a superplume, are expected to have far greater heat transport than the remainder. Therefore, in clarifying the history of Life and Earth, we need to focus on the major events that bound the highest level periods.

From this viewpoint, we have undertaken a thorough compilation of world geology from which come the following important conclusions (Fig. 6). 1) The chronological distribution of Pacific-type (including Cordilleran-type) orogenic peaks and of zircon-forming igneous events during the last 4.0 billion years indicates a clear episodicity through time with several distinct peaks. 2) The orogenic/igncous time-peaks concentrate at 2.7. 1.9 and 0.6 Ga., which are all preceded by a precursory period, characterized by global glaciation and lack of orogeny. 3) These three time-peaks also correspond to the activity of large-scale basic layered intrusions and continental flood basalts. 4) Orogenic belts formed prior to 1.9 Ga lack sedimentary rocks of granitic composition. 5) The lateral extent of pre-1.9 Ga orogenic belts is generally short, 700 km long on average, much shorter than the 3000 km typical of most Phanerozoic orogenic belts. These observations clearly indicate that the pattern of plate tectonics and large igneous activity changed drastically after the unique 2.7–1.9 Ga overturn period.

Considering a concept of focusing on the higher level period in the hierarchy, we propose the following the biggest seven events for the Earth history. (Fig. 7).

### *4.1. Earth Formation (4.6 Ga event; Fig. 8)*

The Earth was born at 4.56–4.55Ga by extensive collision and accretion of planetesimals with the resultant formation of a surface magma ocean (Abe, 1998). The Moon was born at the same time. Anorthosite, the oldest (4.55 Ga) rock on the Moon, presumably formed by flotation in the magma ocean. The estimated depth of the magma ocean, calculated from the thickness of the 100 km-thick anorthosite layer, is about 1500–2000 km, suggesting whole-melting of the Moon. The very small size of the metallic core of the Moon indicates that its bulk chemical composition is similar to that of the Earth's mantle. These lines of evidence suggest that the most probable origin of the Moon was a giant impact (Melosh and Kipp, 1989; Ida et al., 1997), which was an inevitable process of planetary formation through homogeneous accretion. If the giant impact occurred, the Earth must have undergone whole-scale melting.

During the early growth of the Earth, material separation of the metallic core, silicate mantle and primordial atmosphere was probably completed by 4.5 Ga.

### *4.2. Onset of Plate Tectonics (4.0 Ga event; Fig. 9)*

After the instantaneous formation, the planet experienced a long-term, continuous cooling history, in spite of minor addition of heat created by decay of radioactive elements in the mantle. As the magma ocean cooled to form the initial terrestrial crust, a huge amount of vaporized $H_2O$ in the atmosphere liquidized to form the primary ocean. As soon as the primary ocean formed, the surface of the Earth became sufficiently rigid for lithospheric plates to form above the asthenospheric mantle. Driven by heat-generated convection within the mantle,

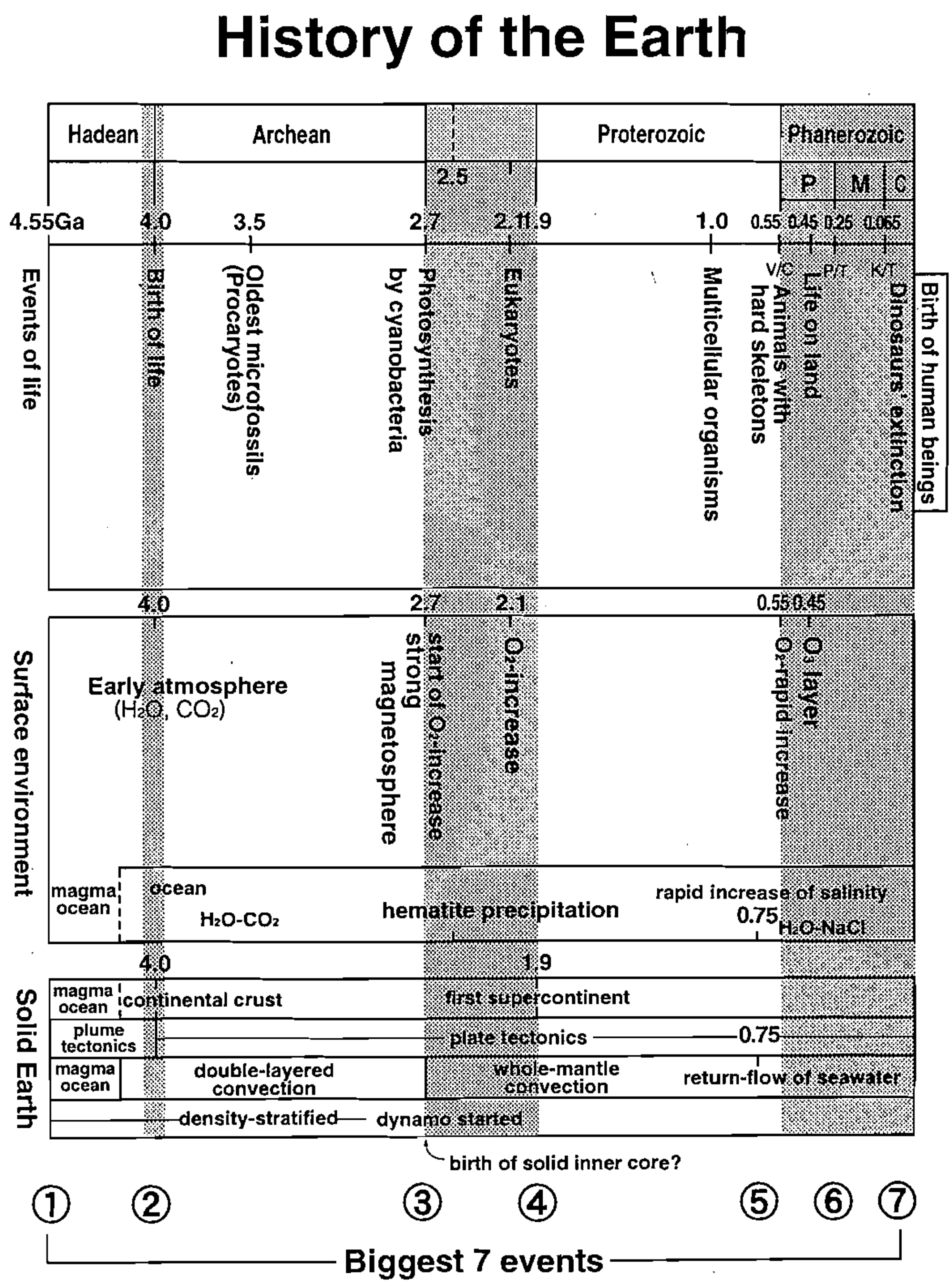


**Fig. 7.** Summary history of the Earth. The biggest seven events are shown. Note the correspondence between the events of life and those of the surface environment and solid Earth.

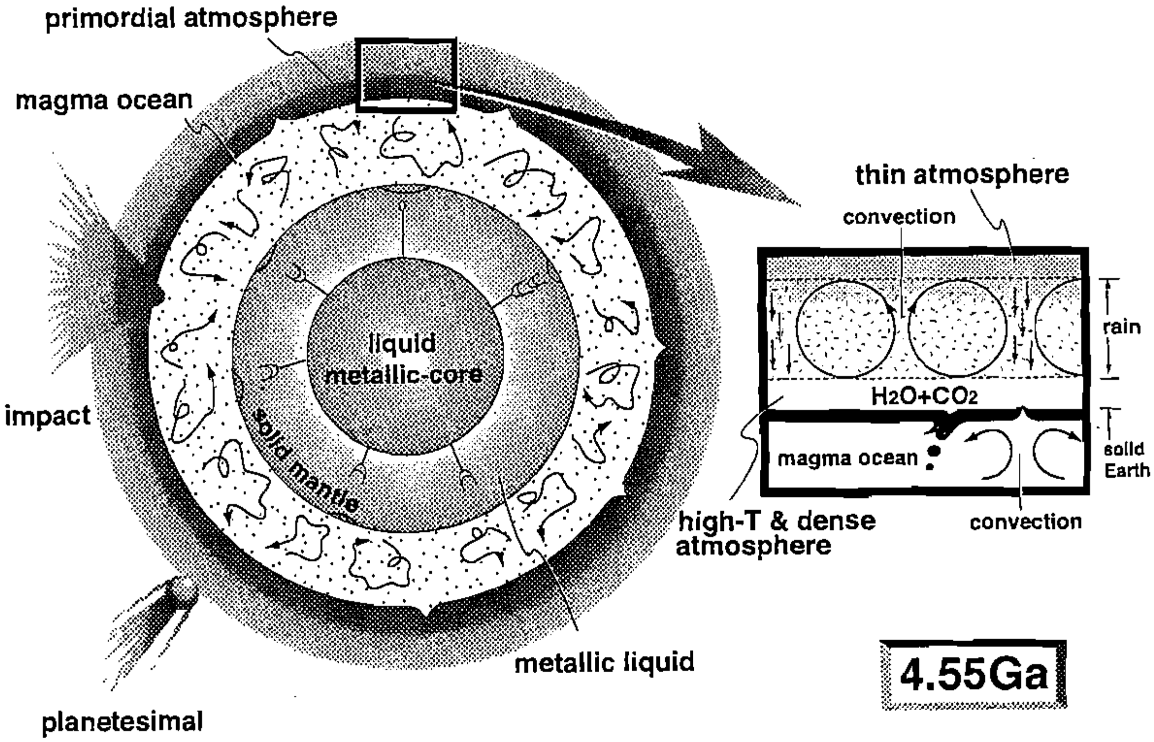


Fig. 8. Birth of the Earth and formation of a magma ocean at 4.56–4.55Ga. If a giant impact occurred to form the Moon, the whole Earth must have melted. If not, the surface 1000 km may have been covered by a magma ocean to promote separation of the core from the silicate mantle.

the initial plates started to move to create linear plate boundaries, i.e. divergent mid-oceanic ridges and convergent trenches.

The oldest zircon grain on Earth is dated at 4.4 Ga (Wilde et al., 2001), and oxygen-isotope data suggest a probable origin in granitic magma and the presence of liquid water on the Earth (Mojzsis et al., 2001). However, oxygen-isotope data alone cannot prove the existence of a primary ocean at 4.4 Ga. The oldest rock, the 4.0 Ga Acasta gneiss in northern Canada, has a TTG composition and an andesitic protolith (Bowring and Williams, 1999), which clearly indicates plate tectonic activity at 4.0 Ga, including subduction of a hydrous oceanic plate and partial melting to form the continental crust. In this paper, we tentatively assign the initial time of continent formation as 4.0 Ga. A possibility still remains for much older plate tectonic activity, because pre-4.0 Ga continental crust, if present, may have been completely eroded or destroyed by later tectonism.

As the primary ocean was able to dissolve considerable $CO_2$ from the ambient atmosphere, the ocean formation triggered a rapid draw-down of atmospheric $CO_2$, thus creating effective cooling of the planet (Kasting, 1993; Tajika, 1998).

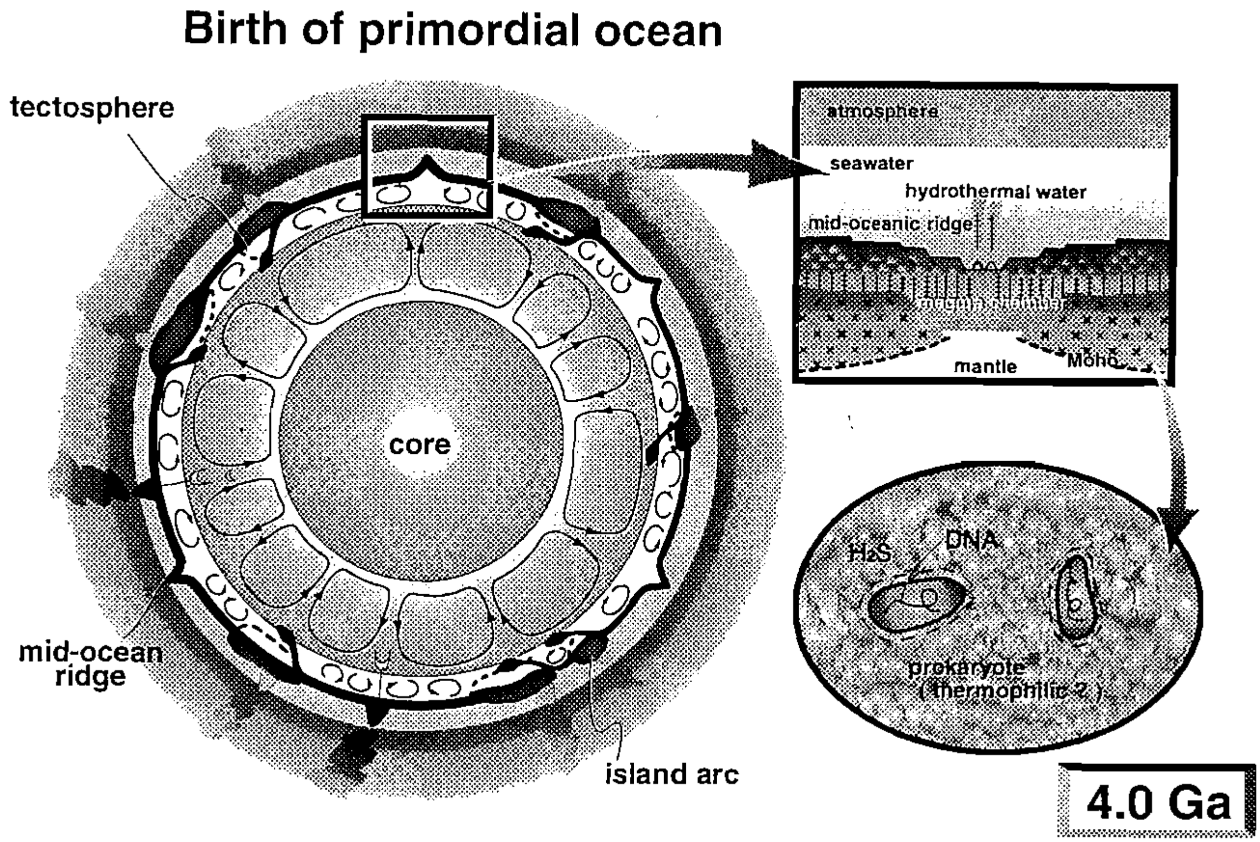


**Fig. 9.** The primordial ocean was born after convecting rain-atmosphere reached the surface (Fig. 8) to initiate plate tectonics at 4.0Ga. Early life started in hydrothermal vents at mid-oceanic ridges.

The formation of the primary ocean also facilitated the birth of life on Earth. Study of carbon isotope ratios and new microfossils have provided important information on the oldest terrestrial life at Isua in Greenland and Pilbara in Western Australia (Schidlowski, 1988; Ueno et al., 2001a,b; Awramik et al., 1983; Schopf and Packer, 1987). In particular, Ueno et al (2001a) identified very low delta C-13 org values as low as −42 per mil from 3.5 Ga filamentous bacteria, suggesting that chemo-autotrophic life already existed in the Early Archean. The occurrence in the Pilbara region of bacteria-bearing silica dykes of white smoker-type strongly suggests that the oldest life-forms were thermophile bacteria (Fig., 10; Ueno et al., 2001a), which inhabited hydrothermal vents in a mid-oceanic ridge (Kitajima et al., 2001). These new geological lines of evidence are in good accordance with the latest aspects of the earliest branching in the phylogenic tree based on the genetic linkage among modern bacteria (e.g. Stetter, 1994; Isozaki and Yamagishi, 1998).

The oldest examples of a subduction-related accretionary complex and subduction-related regional metamorphic rocks are at Isua, Greenland, (Komiya

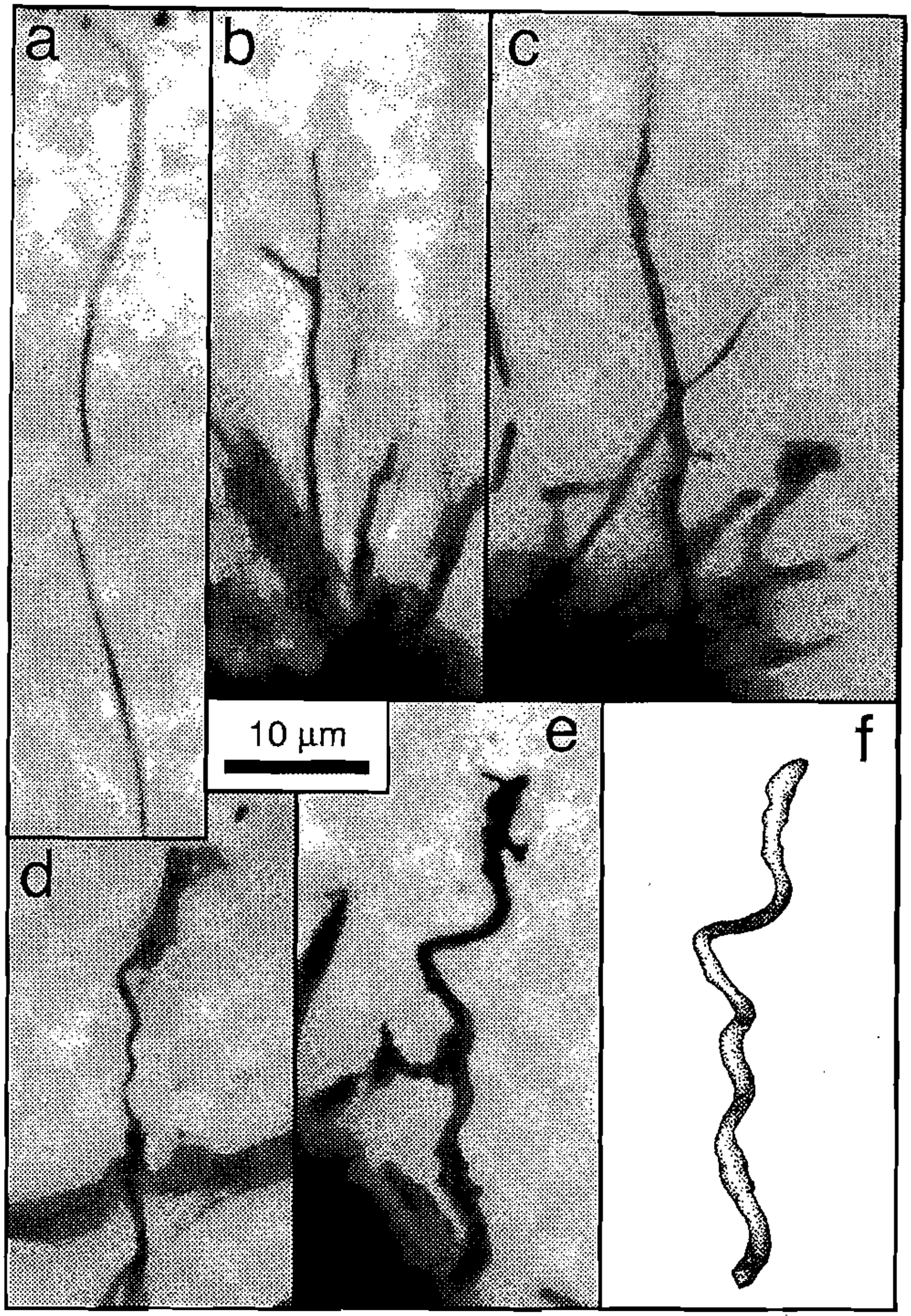


**Fig. 10.** Optical photomicrographs of carbonaceous filaments from the ca. 3.5 Ga black silica dike at Loc. 1 (b-f) and Loc. 2 (a and b) of Ueno et al. (2001): (a) thread-like filament, (b and c) aggregate of filaments radiating from the holdfast-like kerogen clots, (d and e) spiral filaments, and (f) the schematic reconstruction of spiral filament shown in Fig. e. (a), (b), (c), (d) and (e) are photomontages at eight, five, nine, twelve and twenty four different focal depths, respectively. Scale bar is 10 $\mu$m for all Figures.

et al., 1999; Hayashi et al., 2000). They demonstrate that plate tectonics was already working at 3.9 Ga. Thus, besides the first continental crust, we suggest that the first ocean and the first life also appeared at about 4.0 Ga.

The widespread occurrence of pillowed basalt at Isua indicates the existence of extensive water; i.e. an ocean, by 3.85 Ga. The structural styles and primary relationships of tholeiitic basalts with chert and other sediments reveal that they formed at an ancient mid-oceanic ridge (Komiya et al., 1999). Judging from the thickness of pillowed basalt, the mid-oceanic ridge was covered by seawater at least 1 km deep. The potential temperature of the mantle, calculated from the tholeiitic basalt, was 150°C higher than that of equivalent, present-day, plume-source mantle (Ohta et al., 1996; Komiya, 1998).

Knowing the potential mantle temperature and the surface temperature of a water-covered planet, we can calculate the average thickness of the oceanic crust and the lithosphere in the Archean. Sleep & Windley (1982), Bickle (1986), and Nisbet & Fowler (1983) calculated that Archean oceanic crust was about 20 km thick. Davies (1992) pointed out that subduction could not have occurred if the Archean oceanic crust was 17–18 km thick, because thin oceanic lithosphere with a thick crust would have been much lighter than the asthenosphere. His conclusion, however, is negated by the above-mentioned results from the Early Archean accretionary complex at Isua in Greenland. This discrepancy probably originates from an underestimate of the degree of partial melting of hydrous oceanic crust at that time. When the effect of partial melting is fully considered, the average density of subducting oceanic crust can be calculated to be about 3.55 $g/cm^3$. This provides a much larger density contrast, i.e., slab-pull force for subduction, than at present (Hayashi et al., 2000), and therefore suggests highly active plate tectonics in the Archean.

The accretionary complex in Greenland provides the following new information about the early Earth at 3.9 Ga; 1) no significant landmass with a granitic crust existed at that time. 2) Trench-fill terrigenous clastic sediments were mostly derived from a basaltic provenance. 3) The presence of water-lain sediments and pillowed basalts demonstrates the existence of water on the surface of the Earth (Nutman et al., 1997). 4) The presence of pillow basalts overlain by cherts and clastic sediments together with hydrothermal vent system confirm that modern-style ocean floor was present. 5) Plate convergence took place, not against a continental margin, but with a mid-oceanic island arc, like the modern Mariana arc in the western Pacific. 6) The zoned pattern in the orogenic belt suggests that multiple collision/amalgamation of numerous small island arcs created a large Archean continental block.

The tectonic activities of plumes and plates waned with time, and became very slow in the Late Archean, leaving no major orogenic belts of 3.0–2.8 Ga age. This was probably due to the fact that mantle convection had slowed down considerably.

### *4.3. End-Archean Mantle Overturn (2.8-2.7 Ga event; Fig. 11)*

Being quite different from the present Earth, other terrestrial planets (Mercury, Venus, and Mars) and even the Moon lack strong global geomagnetic fields (Stevenson et al., 1983). So did the Earth before 2.7 Ga. A strong geomagnetic field, like that of today, appeared suddenly at 2.8–2.7 Ga (Hale, 1987). This timing corresponds to the worldwide appearance of stromatolites (colonies of cyanobacteria) as the pioneer photosynthesizers. The development of a geomagnetic field probably stopped high-energy particles in the solar wind from penetrating through the atmosphere to the surface of the Earth, thus allowing organisms, once confined to the deep-sea, to invade shallow seas where light was available.

The oxygen hazard to the prevailing reducing environment started at this time. Consumption of photosynthesis-generated $CO_2$ and the emission of free $O_2$ on a global scale may have completely changed the background conditions of the surface environment, in particular, the biosphere. All the dissolved ferrous iron ($Fe^{2+}$) in the reduced ocean had been stabilized as ferric iron oxide under new $O_2$-enriched conditions. As a consequence, a huge amount of iron was deposited in the world's oceans to form thick and extensive banded iron formations (BIF). Extensive sweeping of all ferrous iron from seawater may have changed the color of the ocean from dark-gray/black to blue, like today (Maruyama and Isozaki, 1998).

The strong geomagnetic field of the Earth was obviously due to vigorous fluid flow of the outer core (Stevenson, 1990); however, the reason why this sudden activation occurred at 2.7 Ga still remains a mystery. According to the mantle overturn model, an irreversible change in mantle convection took place, from double layer convection (in the upper and lower mantle) to whole mantle convection. As a result stagnant slabs previously accumulated at 660 km depth formed a cold megalith and sank down to the CMB to induce localized cooling on the surface of the outer core. Local cooling of 4000°C in the outer core by the megalith at 2000°C generated a robust downflow and thus convection within the outer core. Birth of the solid inner core may have played a potentially important role to bear the compositional convection flow to keep the Earth's strong dynamo thereafter, because of large partition coefficient of light elements such as C, H, O, and S between the solid inner and liquid outer core (Stevenson, 1990; Sumita et al., 1995; Yoshida et al., 1996). This "mantle overturn" is the highest rank of

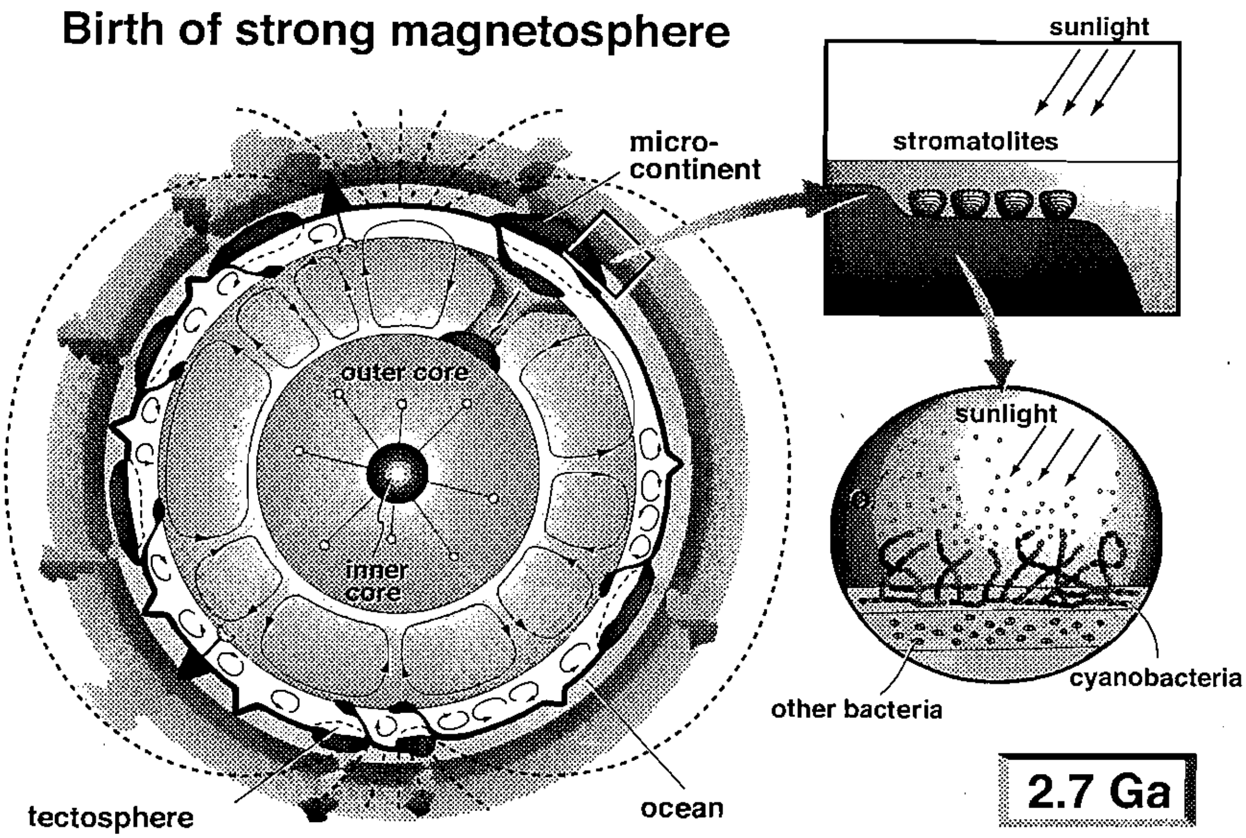


**Fig. 11.** Birth of a strong magnetosphere to protect life. The widespread appearance of stromatolites on the Earth strongly indicates the initiation of photosynthesis and increasing free oxygen in the atmosphere. The mantle overturn caused collapse of the density-stratified core structure and extensive convection, which started the dynamo. The birth of the inner solid core was also critical to keep the compositional convection system in the liquid outer core.

global tectonic processes.

The evidence for mantle overturn is widespread in late Archean orogenic belts, e.g. oceanic plateaus, oceanic arcs and subduction-accretion complexes (Polat et al., 1998; Kusky and Polat, 1999), continental flood basalts (Van der Westhuizen et al., 1991), large igneous complexes and layered intrusions (e.g. Stillwater, Usushwana, Millindinna, see Windley, 1995), abundant mantle-derived Ni, Fe, Cu-Zn and Au deposits (Barley et al., 1998), and the input of mainly mafic plateau-type volcanic detritus into clastic sediments from 2.5 Ga (Lahtinen, 2000). The igneous complexes are different from those in Phanerozoic Pacific-type orogenic belts; in general, they were derived from high-temperature magmas. The activity of the mantle, as indicated by movement of plumes and plates, was very high at 2.7–2.6 Ga, when Pacific-type orogenic belts formed extensively through-

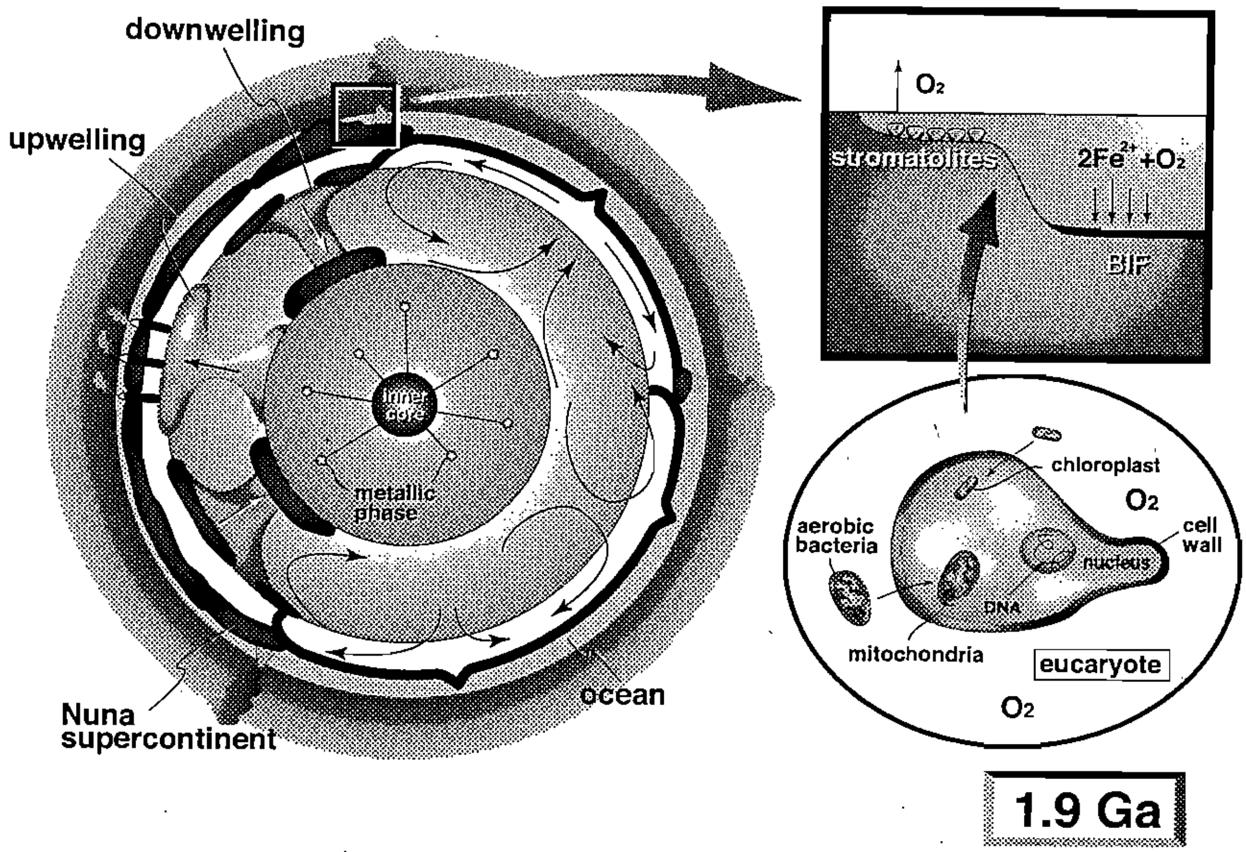


**Fig. 12.** First supercontinent Nuna was formed at 1.9Ga. Prokaryotes may have evolved to eucaryotes at this time.

out the world. However, this culmination in mantle activity waned with time, and by 2.2 Ga plate-related orogeny had almost stopped. The first global freezing with extensive glaciation occurred on the Earth at about 2.3 Ga; the "Paleoproterozoic Snowball Earth" (Kirschvink et al., 2000).

### *4.4. Supercontinent Debut (1.9 Ga event; Fig. 12)*

After the pre-2.1 Ga recess in mantle activity, the Earth became reactivated again with violent volcanism, and rifting/dispersal of continents. The average size of continents increased considerably after 2.0 Ga. By 1.9 Ga, a large continental mass equivalent in size to present-day North America appeared for the first time in Earth's history. The 1.9 Ga continent representing proto-North America formed by the collision/amalgamation of eight distinct blocks composed of multiple arc complexes centered on the Superior province (Hoffman, 1989). Paleogeographic reconstruction indicates that this continental mass named Nuna was approximately 3000 km across and was almost equivalent in size to several, current, major continents.

It is generally regarded that the average size of plates (lithosphere) corresponds to that of ambient convention cells in the mantle, because major plates are bounded by ridges and trenches where mantle upwelling and downwelling take place. A convection cell in the mantle usually has an aspect ratio between vertical and horizontal dimensions of about 1:1 that guarantees the most stable convection. Thus the horizontal extent of the Nuna convection cell was nearly 3000 km which is similar to the average length of a single Phanerozoic orogenic belt. The size of the 1.9 Ga Nuna continent suggests that modern-style mantle convection, i.e. intermittent whole-mantle convection, had started after the 2.7–2.1 Ga transition interval. Although the Nuna continental mass was much smaller than younger supercontinents such as Rodinia and Pangea, it should be called the first supercontinent because it represents the first large mass that collected most of the continental crust at that time. This event at about 1.9Ga was the onset of the modern-day alternation of continental assembly and breakup in the Wilson-cycle. The activity of a superplume from the lower mantle was most likely responsible for the continental breakup (Condie, 2000; Condie et al., 2001).

The oldest individual fossil of mesoscopic size is Grypania from a 2.1 Ga ironstone in Michigan (Han and Runnegar, 1992). Its size and morphology (over 4 cm long, coiled) suggest that Grypania is the oldest known eucaryote, probably a kind of photosynthetic algae. Recently, however, biomarker molecules suggesting a eucaryotic origin were found in much older 2.7 Ga rocks from Australia (Brocks et al., 1999; Summons et al., 1999), although the credibility of this discovery is questioned mainly because of possible later contamination. The oldest multicellularity was recognized around 1.4 Ga by finding biomarker called collagen that is essential to glue individual cells.

The Nuna supercontinent broke up into several fragments by 1.8 Ga. At 1.4–1.2 Ga, these continental fragments reunited again to form the supercontinent of Rodinia (McMenamine & McMenanine, 1992; Dalziel, 1997). Remnants of this assembly are observed in and against Grenvillian orogenic belts throughout the world. After an orogenic climax at 1.2 Ga, however, the activity of plumes and thus plates declined sharply between 1.0 and 0.75 Ga. The onset of another global freezing, the "Neoproterozoic Snowball Earth", from 750 Ma (Kirschvink, 1992; Hoffman et al., 1998) characterizes this tectonically quiet interval.

### *4.5. Water Drainage (0.8-0.7 Ga event; Fig. 13)*

The break-up of Rodinia at 0.8–0.7 Ga (or 800–700 Ma) (Hoffman, 1991) gave rise, near its center, to the Pacific Ocean (Maruyama, 1994). Smaller continental fragments began to assemble again around 540 Ma to form a semi-supercontinent Pannotia (previously referred as Gondwana) centered on present-

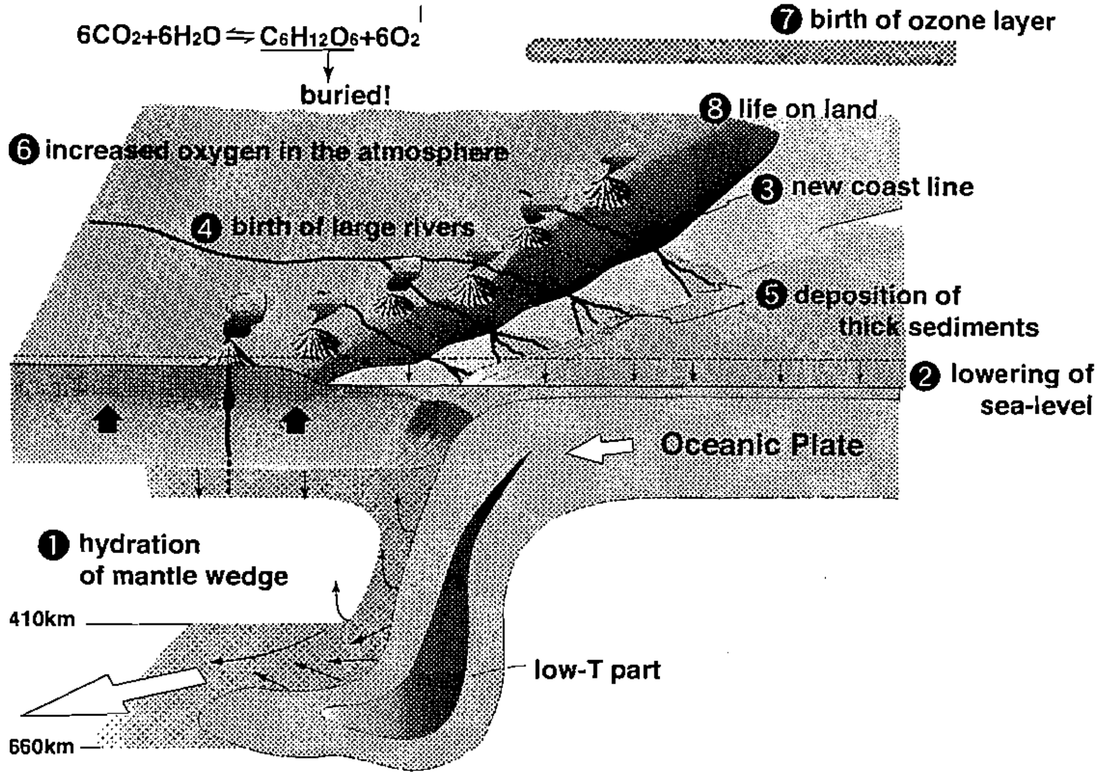


**Fig. 13.** Surface environmental change from the latest Proterozoic to the Phanerozoic. The initiation of the return flow of seawater into the mantle by hydrated slabs caused the hydration of mantle wedges and resultant storage of water in the mantle boundary layer, which in turn caused uplift of the continental margin by the expansion effect of serpentinization; this was accentuated the lowering of sea-level. Emergence of large landmasses created large rivers. Deposition of voluminous sediments buried organic matter, which increased the free oxygen in the atmosphere. Life evolved as a result of the increase in oxygen; it moved onto the land, and flourished after the formation of an ozone layer.

day Africa. The exceptionally short interval of less than 200 m.y. between two supercontinents clearly suggests that mantle activity revived very quickly at 800–700 Ma after the preceding, dormant period.

A dramatic change in the Earth's landscape led to a remarkable diversification of surface environments including the development of major continental river systems and extensive deserts. This change in global landscape led not only to a total increase in clastic sediments but also to changes in seawater chemistry (Tucker, 1992). All these geological phenomena were the consequence of an unusual sea-level drop related to water loss from the Earth's surface (Maruyama, 1997; Maruyama and Liou, 1997; Maruyama and Isozaki, 1998).

The most critical evidence for this water loss at 800–700 Ma comes from a compilation of subduction-related metamorphism in the past. Using ancient metamorphic rocks as records of paleo-temperature/pressure in subduction zones, Maruyama et al. (1996) reconstructed the evolutionary path of thermal gradients of the planet and found a clear break at 700–800 Ma that separates an older warmer Earth from a younger colder Earth. This gap is indicated by metamorphic parageneses of hydrous minerals such as lawsonite and amphibole in a high P/T grid. In the steeper thermal gradient before 700–800 Ma, hydrous minerals could not subduct into the mantle because they were decomposed at a shallow depth; net loss of seawater had started on the surface, and the mantle wedge beneath subduction zones was rapidly hydrated. Subduction at trenches of water in the form of hydrous minerals led to two significant effects which enhanced mantle convection; i.e. lowering of the melting temperature of mantle rocks and lowering of mantle viscosity to accelerate material flow (Karato, 2000).

If we assume that the water content of mantle wedge rocks was 0.5 w% before 1.0 Ga and 6.5 w% after 800–700 Ma, a huge volume of water, about to 200–300 m deep, was transported from the Earth's surface to the mantle (mantle wedge to subcontinental mantle deeper than the mantle transition zone along the Wadati-Benioff plane). The drastic landscape change on the surface was probably due to this water loss. At 600 Ma, the total area above sea level increased from 5 % of the whole Earth's surface to 30 %, as today (Maruyama, 1997). This led to the development of major river systems, increase in clastic sediments, a change in seawater composition, and increased partial pressure of atmospheric $O_2$ (Maruyama and Isozaki, 1998).

The "Neoproterozoic Snowball Earth" persisted on the surface from 750 Ma to 580 Ma. During this time interval, severe glaciation followed by warming was repeated at least three times. The estimated temperature gap between the coldest time (−50°C on average) and the warmest (+50°C on average) is up to 100 degrees Celsius, which was high enough to terminate the majority of existing biota (Hoffman and Schrag, 2000). This cyclicity was controlled by the change in atmospheric $CO_2$, owing to the balance between volcanic input and consumption by weathering/photosynthesis.

Immediately after the Snowball Earth period, explosive diversification of biota took place, comparable to the filling of the empty barrel of the biosphere after a mass extinction. Great biological achievements at that time include a remarkable increase in body size and the invention of sex. In particular, the latter opened a new window for later diversification by almost unlimited combination-patterns of genes. The Ediacaran fauna with a large body size appeared immediately after the final glaciation of the Snowball period, and it was followed by the Cambrian Chengjian-Burgess fauna that first experienced serious predation games. The Vendian-Cambrian event is a possible analogue of the Permo-Triassic boundary event described below.

Water drainage was the fate of a cooling terrestrial planet covered by water. When the temperature of the subducting slab decreased below 600°C at 100 km depth, the return flow of seawater must have started as consequence of the cooling history of the Earth (Maruyama and Okamoto, in press). Therefore, this was a one-way process, not reversible through geologic history. Before 750Ma, water in the solid Earth moved to the surface either from the mantle boundary layer or from the outer core through plumes or superplumes in a one-way direction (Fig. 14). Archean to Proterozoic magmas from the mantle contain considerable amounts of water, e.g., 1-4 wt% water in Archean komatiites (e.g., Parman et al., 1997; Carlson et al., 2000; Shimizu et al., 2001). This magmatic water would have increased the total volume of surface water on the Earth until 750Ma.

Thus, the initiation of the return flow of seawater must be one of the critical times in the evolution of the terrestrial planet. If the present leaking rate continues, the Earth will finally loose its oceans at 1.0–1.5Ga in the future, as well as its oxygen-rich atmosphere and ozone layer. As a consequence, the Earth will become like present-day Mars (Fig. 15).

### *4.6. The Greatest Mass Extinction (250 Ma event; Fig. 16)*

Within 200 million years after the onset of the breakup of Rodinia, a new semi-supercontinent Pannotia (proto-Africa) formed on the opposite side of the Earth. Pannotia is treated here as a semi-supercontinent because it excluded two major continental blocks, Laurentia (North America) and Baltica (northern Europe). hese two collided and were amalgamated at 400–300 Ma by closure of the Iapetus (paleo-Atlantic) ocean, giving rise to the Appalachian-Caledonian and Hercynian orogenic belts. The final merger of this combined block with the remaining continents formed the supercontinent of Pangea at about 300 Ma.

At 250 Ma another major global event started mainly in Africa. The impingement of the African superplume rapidly changed the surface environment and brought about the greatest mass extinction in the Earth's history. Statistical analysis of the fossil record reveals that more than 70 % of marine invertebrate taxa, such as trilobites, rugose corals, fusulinids, algae, and bryozoans, were terminated in a short period of time (Sepkoski, 1984; Erwin, 1993). In addition, biota on land including plants and insects were severely affected by this environmental perturbation.

Recent stratigraphic studies of the strata around the Permian-Triassic boundary (PTB) have identified new aspects of the environmental change at that unique time. In particular, deep-sea cherts (Isozaki, 1994) and paleoatoll limestones in a Jurassic accretionary complex in Japan provide valuable information

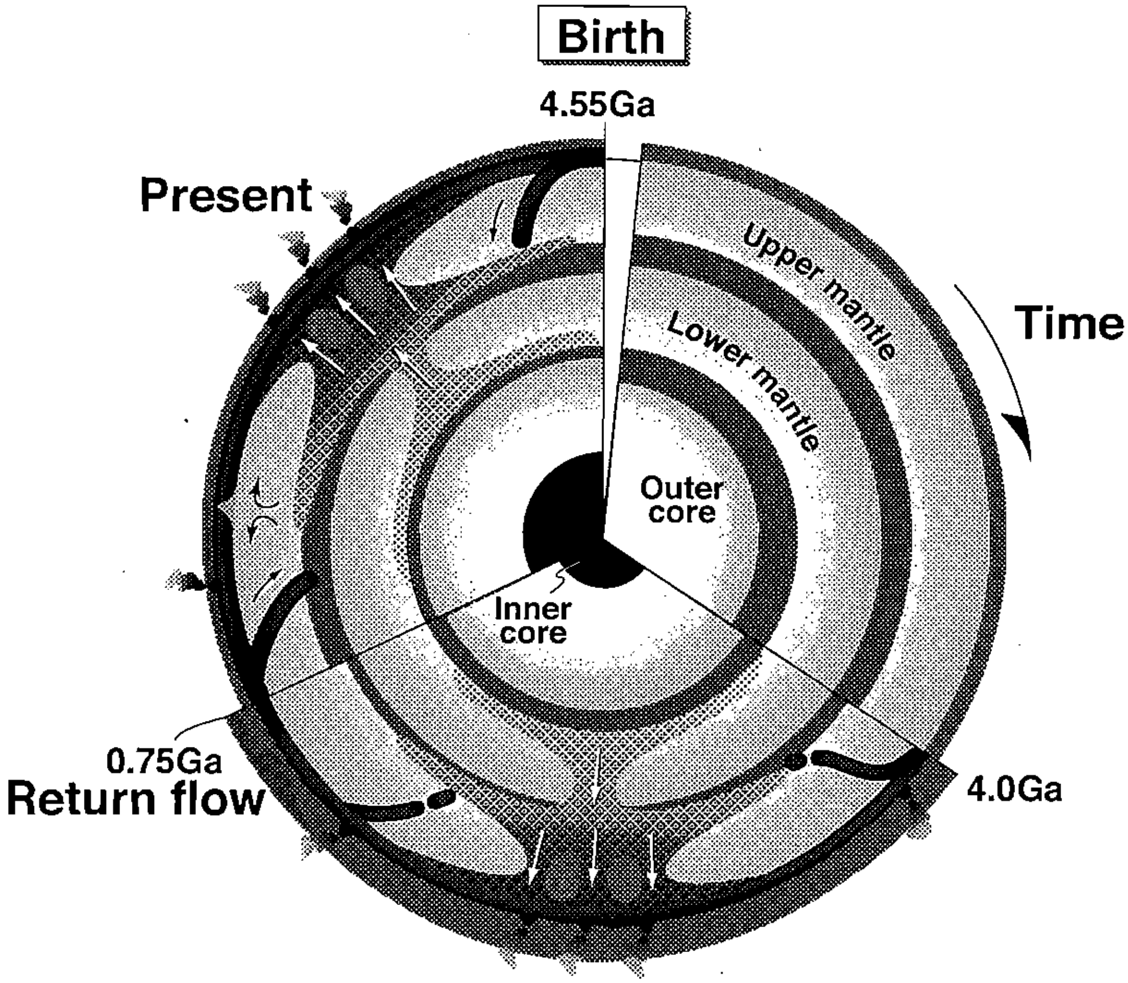


**Fig. 14.** Schematic illustration of the history of water on the Earth. Note the two large water storage rooms in the solid Earth, the outer core and the mantle boundary layer. Throughout Earth history, water moved to the surface in rising plumes to increase the surface water, but surface water has been subducted into the mantle to hydrate the lithosphere since 750Ma.

on the extremely long oxygen depletion across the PTB; a "superanoxia" event. The secular change of redox state in deep-sea chert records a nearly 20 million year-long oceanic anoxic event across the PTB in the superocean Panthalassa (Isozaki, 1997).

The development of deep-sea anoxia (i.e. stratification of the ocean) for more than 1 million years is impossible in the present-day oceanic circulation system. Across the PTB, this unusual condition was brought about when all photosynthesis stopped on the Earth (Isozaki, 2000).

The PTB (251 Ma) corresponds to the timing of initial breakup of Pangea. A rising superplume from the deep mantle reached the base of the African continent, and led to rifting and intense volcanism. Enriched in volatile components such as $CO_2$ and $H_2O$, the eruptions were violent and spread a huge quantity

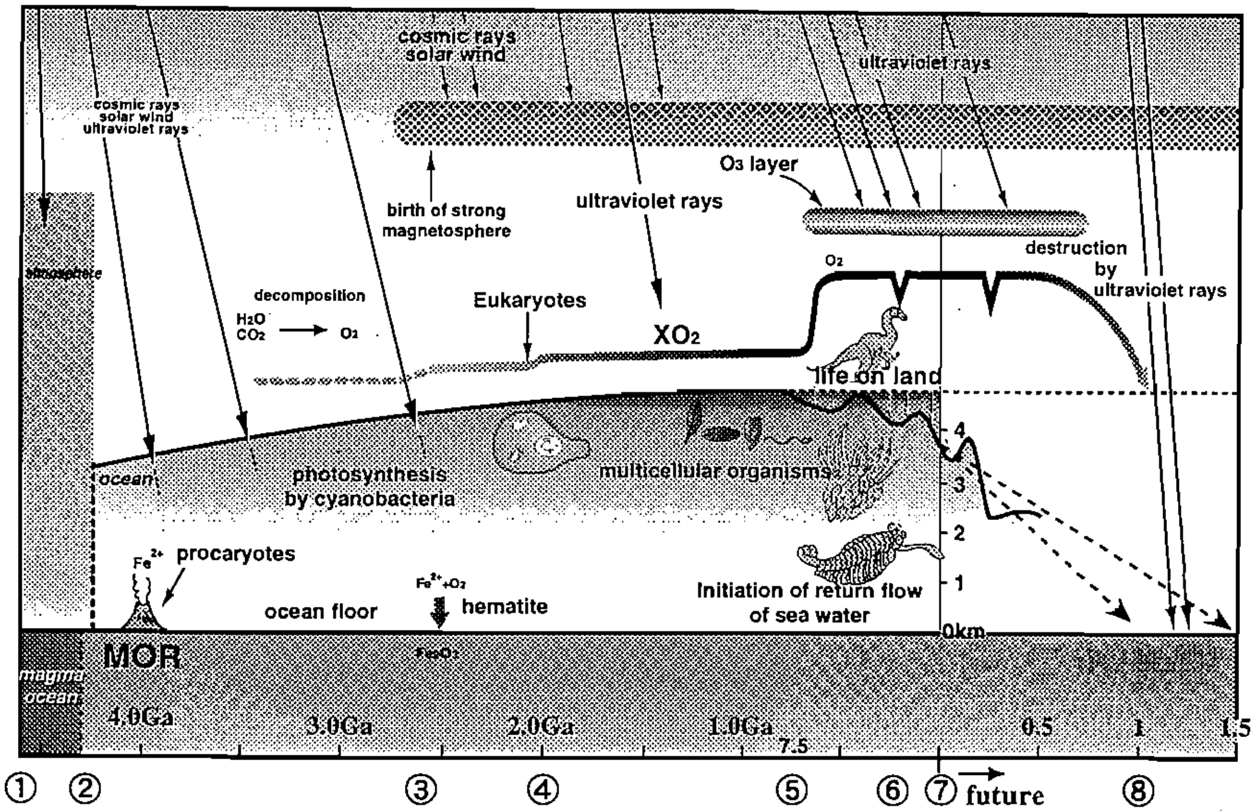


**Fig. 15.** A cartoon to show the change of surface environment and life after the birth of the Earth. Life forms enlarged their living territory and diversified with time. The Earth will loose its surface water in ca. 1.0–1.5 Ga in the future, when all life will be extinguished.

of ash over extensive regions. Heavy metal elements and poisonous gases may have destroyed respiratory, circulatory and nervous systems of various biota, in particular those dependent on $O_2$ respiration. In addition, dust and aerosols injected into the stratosphere may have remained for a long duration to initiate sunlight blocking and/or acid rain which damaged photosynthetic plants on land and marine cyanobacteria. During this long-lasting volcanism, the collapse of the base of the food web may have brought about mass extinction of herbivorous and carnivorous animals. In addition, global warming by excess greenhouse $CO_2$ from volcanoes may have accelerated the environmental deterioration (Isozaki, 2000).

## *4.7. Human origins (6 Ma event)*

At about 30 Ma, the break-up of Africa was initiated by a superplume rising under eastern Africa. This tectonic event started in the north near the present-day Red Sea and propagated southwards, splitting the eastern third of Africa from the remainder by a N-S trending fault. The impingement of a large

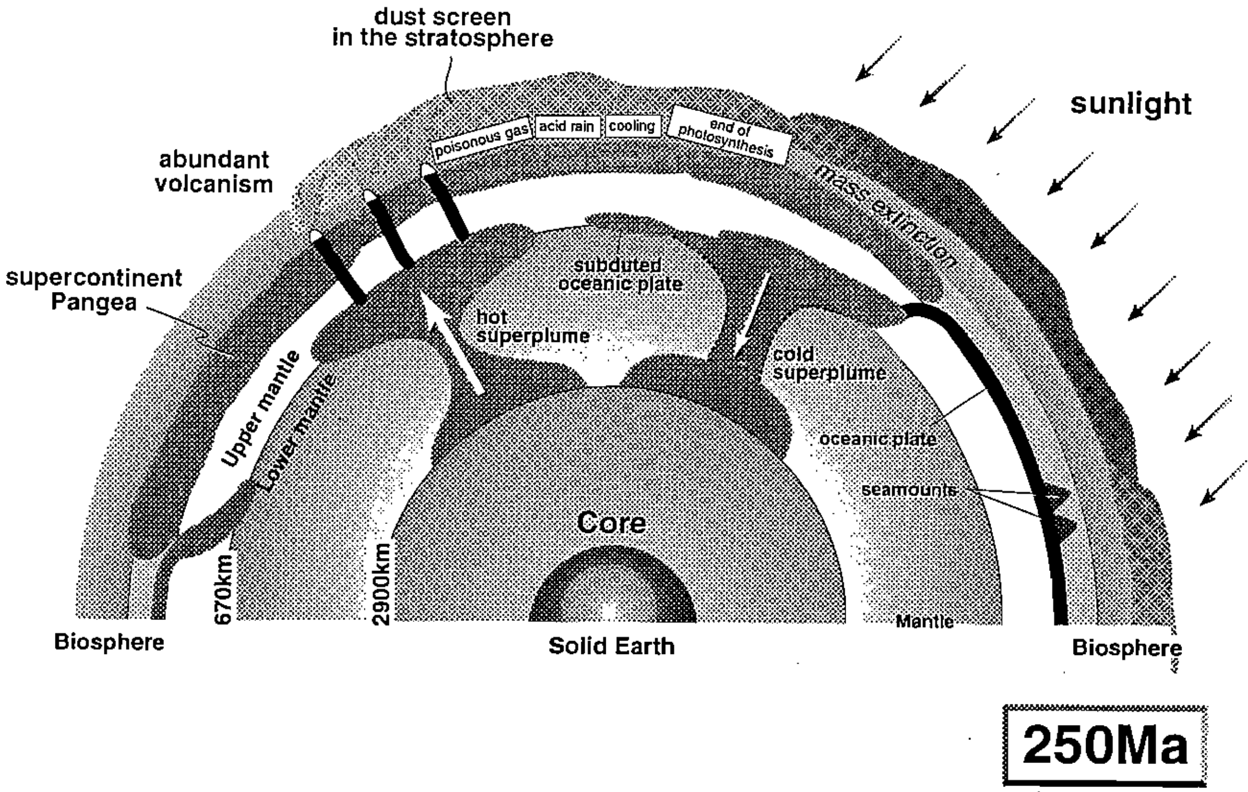


**Fig. 16.** Birth of the African superplume and mass extinction at the Permo-Triassic boundary (after Isozaki, 1999). Explosive gaseous volcanism by kimberlites and carbonatites prevented photosynthesis, and caused the great mass extinction. See details in the text.

plume head caused regional doming with surface uplift of 2–3 km over extensive areas more than 2000 km across. At the same time, many volcanoes erupted to form a new complex landscape with some elevations reaching 5000 m above sea level.

As the plume-induced surface-doming proceeded, the central elevated areas were in turn rifted apart and started to lose altitude, enabling seawater to invade the continent. The rifting of the African continent created the Red Sea and isolated Saudi Arabia from the mainland. The rifting still continues to let seawater invade the East African Rift Valley from the north, because both sides are moving apart at a rate of about 0.3 cm/year. The appearance of the Rift Valley completely changed the climate of the uplifted area and its surroundings. In particular, the formation of a 3–5 km high and 4000 km long mountain range stopped strong eastward humid winds from the Atlantic Ocean. This gave rise to a new tributary system of the Congo river in western Africa, while East Africa on the eastern side of the Rift Valley became dry. This aridity was a problem for primitive side of the Rift Valley became dry. This aridity was a problem for primitive primates that were well fed in the previous climate of a tropical rain forest. The climatic change took place at 6–5 Ma when primates acquired bipedalism, i.e. the appearance of the first hominids. The latest paleo-anthropological finding includes bones suggesting the possible oldest bipedal walker (*Orrorin* and/or *Ardipithecus*) that was unearthed from about 6 Ma beds in East Africa (e.g., Gibbons, 2002). After multiple invasions from Africa to the rest of the world, modern human beings occupied the entire land surface of the planet in a short time of period. Through periodic inventions such as tools, agriculture, and industry, we have finally developed modern culture and science.

## 5. References

Abe, Y. (1998) Formation of the Earth system. In "*Evolving Earth*", Earth and Planetary Science Series, 13, Iwanami-shoten, 1–54.

Agee, C. B. (1998) Phase transformations and seismic structure in the upper mantle and transition zone. In "*Reviews in Mineralogy*", Hemley R. J. ed., MSA, 37, 165–203.

Awramik, S. M., Schoph, J. W. and Walter, M. R. (1983) Filamentous fossil bacteria from the Archean of western Australia. Precamb. Res., 20, 357–374.

Barley, M. E., Krapez, B., Groves, D. I. and Kerrich, R. (1998) The Late Archaean bonanza: metallogenic and environmental consequences of the interaction between mantle plumes, lithospheric tectonics and global cyclicity. Precamb. Res., 91, 65–90.

Bickle, M. J. (1986) Implications for melting for stabilisation of the lithosphere and heat loss in the Archaean. Earth Planet. Sci. Lett., 80, 314–324.

Bijwaard, H. and Spakman, W. (1999) Tomographic evidence for a narrow whole mantle plume below Iceland. Earth Planet. Sci. Lett., 166, 121–126.

Boehler, R. (1996) Melting temperature of the Earth's mantle and core: Earth's thermal structure. Ann. Rev. Earth Planet. Sci., 24, 15–40.

Bowring, S.A. and Williams, I.S. (1999) Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. Contrib. Mineral. Petrol. 134, 3–16.

Breuer, D. and Spohn, T. (1995) Possible flush instability in mantle convection at the Archean-Proterozoic transition. Nature, 378, 608–610.

Brocks, J. J., Logan, G. A., Buick, R. and Summons, R. E. (1999) Archean molecular fossils and the early rise of eukaryotes. Science, 285, 1033–1036.

Carlson, R. W., Boyd, F. R., Shirely, S. B., Janney, P. E., Grove, T. L., Bowring, S. A., Schmitz, M. D., Dann, J. C., Bell, D. R., Gurney, J. J., Richardson, S. H., Tredoux, M., Menzies, A. H., Pearson, D. G., Hart, R. J., Wilson, A. H.

and Moser, D. (2000) Continental growth, preservation, and modification in southern Africa. GSA Today, 10, 1–7.

Christensen, U. and Yuen, D. A. (1985) Layered convection induced by phase transitions. J. Geophys. Res., 90, 10291–10300.

Condie, K. C. (1979, 1989, 1997) *Plate Tectonics and Crustal Evolution*, (1st, 2nd, 3rd eds.), Oxford, Pergamon Press.

Condie, K. C. (1998) Episodic continental growth and supercontinents: a mantle avalanche connection? Earth Planet. Sci. Lett., 163, 97–108.

Condie, K. C. (2000) Geologic evidence for a mantle superplume event at 1.9 Ga. G-Cubed, 1, 2000GC000095.

Condie, K. C., Des Marais, D. J. and Abbott, D. (2001) Precambrian superplumes and supercontinents: a record in black shales, carbon isotopes, and paleoclimates? Precamb. Res., 106, 239–260.

Dalziel, I. W. D. (1997) Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol. Soc. Am. Bull., 109, 16–42.

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

Davies, G. F. (1995) Punctuated tectonic evolution of the earth. Earth Planet. Sci. Lett., 136, 363–379.

Dewey, J. F. and Bird, P. (1970) Mountain belts and the new global tectonics. J. Geophys. Res., 75, 2625–2647.

Dziewonski, A. M. (1984) Mapping the lower mantle: Determination of lateral heterogeneity in P velocity up to degree and order 6. J. Geophys. Res., 89, 5929–5952.

Engebretson, D. C., Cox, A. and Gordon, R. G. (1985) Relative motions between oceanic and continental plates in the Pacific basin. Geol. Soc. Am. Spec. Pap. 206, 59 pp.

Erwin, D. H. (1993) The Great Paleozoic Crisis. Columbia Univ. Press, New York.

Flanagan, M. and Shearer, P. (1998) Global mapping of topography on transition zone velocity discontinuities by stacking SS precursors. J. Geophys. Res., 103, 2673–2692.

Fukao, Y. (1992) Seismic tomogram of the Earth's mantle: geodynamic implications. Science, 258, 625–630.

Fukao, Y., Obayashi, M., Inoue, H. and Nenbai, M. (1992) Subducting slabs stagnant in the mantle transition zone. J. Geophys. Res., 97, 4809–4822.

Fukao, Y., Maruyama, S., Obayashi, M. and Inoue, H. (1994) Geologic implication of the whole mantle P-wave tomography. J. Geol. Soc. Japan, 100, 4–23.

Fukao Y., Widiyantoro S., and Obayashi M. (2001) Stagnant slabs in the upper and lower mantle transition region, Reviews in Geophysics 39, 291–323.

Garnero, E. J. and Helmberger, D. V. (1998) Further structural constraints and uncertainties of a thin laterally varying ultralow-velocity layer at the base of the mantle. J. Geophys. Res., 103, 12495–12509.

Garnero, E. J., Revenaugh, J., Williams, Q., Lay, T. and Kellogg, L. H. (1998) Ultralow velocity zone at the core-mantle boundary. In "*The Core-mantle Boundary Region*", Geodynamics Series 28, AGU, 319–334.

Gibbons, A. (2002) In search of the first hominids. Science, 295, 1214–1219.

Grand, S. P., van der Hirst, R. D. and Widiyantoro, S. (1997) Global seismic tomography: a snapshot of convection in the Earth. GSA Today, 7, 1–7.

Hale, C. J. (1987) Paleomagnetic data suggest link between the Archean-Proterozoic boundary and inner-core nucleation. Nature, 338, 496–499.

Han, T. M. and Runnegar, B. (1992) Megascopic eucaryotic algae from the 2.1 billion-year-old Negaunee iron formation, Michigan. Science, 257, 232–235.

Hayashi, M., Komiya, T., Nakamiura, Y., and Maruyama, S. (2000) Archean regional metamorphism of the Isua supracrustal belt, southern West Greenland: Implications for a driving force for Archean plate tectonics. Int. Geol. Rev., 42, 1055–1115.

Head, J. W., Crumpler, L. S., Aubele, J. C., Guest, J. E. and Saunders, R. S. (1992) Venus volcanism: Classification of volcanic features and structures, associations, and global distribution from Magellan data. J. Geophys. Res., 97E, 13153–13197.

Hirose, K. (2002) Phase transformations in pyrolitic mantle around 670-km depth: implications for upwelling of plumes from the lower mantle. Jour. Geophys. Res., in press.

Hoffman, P. F. (1989) United plates of North America, the birth of a craton: early Proterozoic assembly and growth of Laurentia. Ann. Rev. Earth Planet. Sci., 16, 543–603.

Hoffman, P. (1991) Did the breakout of Laurentia turn Gondwanaland inside-out? Science, 252, 14109–14112.

Hoffman, P. F., Kaufman, A. J., Halverson, G. P. and Schrag, D. P. (1998) A Neoproterozoic snowball Earth. Science, 281, 1342–1346.

Hoffman, P. F. and Schrag, D. P. (2000) Snowball Earth. Sci. Am., Jan., 68–75.

Honda, S., Balachander, S., Yuen, D. A. and Reuteler, R. (1993) Three-dimensional mantle dynamics with an endothermic phase transition. Science, 259, 1308–1311.

Ida, S., R. M. Canup, and Stewart, G. R. (1997) Lunar accretion from an impact-generated disk. Nature 389, 353–357.

Ishii, M. and Tromp, J. (1999) Normal-mode and free air gravity constraints on lateral variations in velocity and density of Earth's mantle. Science, 285, 1231–1236.

Ishiwatari, A. (1994) Circum-Pacific Phanerozoic multiple ophiolite belts. *Circum-Pacific Ophiolites*, eds., Ishiwatari, A., malpas, J. and Ishizuka, H., VSP, The Netherlands, 7–28.

Isozaki, Y. (1994) Superanoxia across the Permo-Triassic boundary recorded in pelagic chert in Japan. Can. Soc. Petr. Geol. Memoir 17, 805–812.

Isozaki, Y. (1997) Permo-Triassic boundary superanoxia and stratified superocean: records from lost deep sea. Science, 276, 235–238.

Isozaki, Y. (2000) Plume winter: scenario for the greatest biosphere catastrophe, across the Permo-Triassic boundary. 31st Inter. Geol. congr. Abstr. CD-ROM.

Isozaki, Y. and Yamagishi, A. (1998) The early life; aspects deduced from field geology and molecular biology, Kagaku (Science), 68, 821–828.

Ito, E. and Takahashi, E. (1989) Post-spinel transformations in the system $Mg_2SiO_4$-$Fe_2SiO_4$ and some geophysical implications. J. Geophys. Res., 94, 10637–10646.

Ji, Y. and Nataf, H. (1998) Detection of mantle plumes in the lower mantle by diffraction tomography: Hawaii. Earth Planet. Sci. Lett., 159, 99–115.

Kaminsky, F. V., Zakharchenko, O. D., Davies, R., Griffin, W. L., Khachatryan-Blinova, G. K. and Shiryaev, A. A. (2001) Superdeep diamonds from the Juina area, Mato Grosso State, Brazil. Contrib. Mineral. Petrol., 140, 734–753.

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

Karato, S. (2000) *Rheology and Earth Science*, Univ. Tokyo Press, Tokyo, 251 pp (in Japanese).

Kendall, J. M. and Shearer, P. M. (1994) Lateral variations in D" thickness from long-period shear wave data. J. Geophys. Res., 99, 11575–11590.

Kennett B. L. N., Widiyantoro S., and Van der Hilst R. D. (1998) Joint seismic tomography for bulk sound and shear wave speed in the Earth's mantle, Jour. Geophys. Res., B: Solid Earth 103, 12469–12493

King, S. D. and masters, G. (1992) An inversion for radial viscosity structure using seismic tomography. Geophys. Res. Lett., 19, 1551–1554.

Kirschvink, J. L. (1992) Late Proterozoic low-latitude global glaciations: the Snowball Earth. In "*The Proterozoic Biosphere*", Schoph, J. W. and Klein, C. (eds.), Cambridge Univ. Press, Cambridge, UK, 51–52.

Kirschvink, J. L., Gaidos, E. J., Bertani, L. E., Beukes, N. J., Gutzmer, J., Maepa, L. N., and Steinberger, R. E. (2000) Paleoproterozoic Snowball Earth: extreme climatic and geochemical global change and its biological consequences. Proc. Nat. Acad. Sci. USA, 97, 1400–1404.

Kitajima, K., Maruyama, S., Utsunomiya, S. and Liou, J. G. (2001). Seafloor hydrothermal alteration at an Archean mid-ocean ridge. J. of metamor. Geol., 19, 581–597.

Komiya, T. (1998) Estimation of Archean mantle potential temperature from the MORB composition. Kagaku (Science), 68, Iwanami-shoten, 747–750 (in Japanese).

Komiya, K., Maruyana, S., Nohda, S., Matsuda, T., Hayashi, M. and Okamoto, K. (1999) Plate tectonics at 3.8–3.7 Ga: Field evidence from the Isua accretionary complex, southern West Greenland. J. Geol, 107, 515–554.

Kumazawa, M. and Maruyama, S. (1994) Whole earth tectonics. J. Geol. Soc. Japan, 100, 81–102.

Kusky, T. M. and Polat, A. (1999) Growth of granite-greenstone terranes at convergent margins and stabilization of Archean cratons. Tectonophysics, 305, 43–73.

Lahtinen, R. (2000) Archaean-Proterozoic transition: geochemistry, provenance and tectonic setting of metasedimentary rocks in central Fennoscandian Shield, Finland. Precamb. Res., 104, 147–174.

Larson, R,L. (1991) Latest pulse of Earth: Evidence for a mid-Cretaceous superplume. Geology, 19, 547–550.

Lay, T., Williams, Q. and Garnero, E. (1998) The core-mantle boundary layer and deep Earth dynamics. Nature, 392, 461–468.

Li, X. D. and Romanowicz, B., 1996, Global mantle shear velocity model developed using nonlinear asymptotic coupling theory. Jour. Geophys. Res., 101, 22245–22272.

Maruyama, S. (1993) The biggest six events thorough the Earth history, 1. Hadean/ Archean boundary. Ann. Meeting of Geol. Soc. Japan, 217 (in Japanese).

Maruyama, S. (1994) Plume tectonics, J. Geol. Soc. Japan, 100, 24–49.

Maruyama. S. (1997) Whole-Earth dynamics, Kagaku (Science), Iwanami-shoten, 67, 498–506 (in Japanese).

Maruyama, S. (1997) Initiation of return flow of seawater into mantle at 750Ma and the Proterozoic/Phanerozoic boundary. AGU Fall Meeting, EOS, F826.

Maruyama, S. (2002) Hierarchy of the Earth's orogenesis. Proceedings of the International Workshop, Superplume, Tokyo Institute of Technology, Tokyo, 278–279.

Maruyama, S. and Isozaki, Y. (1998) *The history of life and the Earth*, Iwanami-shoten, 275 pp (in Japanese).

Maruyama, S. and Liou, J. G. (1997) Initiation of ultrahigh-pressure metamorphism and its significance on the Proterozoic-Phanerozoic boundary. The Island Arc, 7, 6–35.

Maruyama, S. and Okamoto, K. (2002) water transportation mechanism from the subducting slab into the mantle transition zone. Tectonophysics, in press.

Maruyama, S., Liou, J. G. and Seno, T. (1989) Mesozoic and Cenozoic evolution of Asia. In "*The Evolution of the Pacific Ocean Margins*", Ben-Avraham, Z. ed., New York, Oxford Univ. Press, 75–99.

Maruyama, S., Terabayashi, M. and Liou, J. G. (1996) Blueschists and eclogites of the world. Int. Geol. Rev., 38, 485–594.

Masters, G., Laske, G., Bolton, H. and Dziewonski, A. (2000) The relative behavior of shear velocity, bulk sound speed, and compressional velocity in the mantle: Implications for chemical and thermal structure. In "*Earth's deep interior: Mineral physics and tomography from the atomic to the global scale*", Eds, Karato, S. et al., Geophys. Monograph 117, 63–87.

McMenamin, M. A. S. and McMenamin, D. L. S. (1992) *The Emergence of Animals.* Columbia Univ. Press, New York. 217pp.

McNutt, M. K. and Judge, A. V. (1990) The superswell and mantle dynamics beneath the south Pacific. Science, 248, 969–975.

Melosch, H. H. and Kipp, M. E. (1989) Giant impact theory of the Moon's origin: first 3-D hydrocode results. Lunar Planet. Sci. Conf., 20, 685–686.

Mojzsis, S. J., Harrison, T. M. and Pidgeon, R. T. (2001) Oxygen isotope evidence from ancient zircons for liquid water at the Earth's surface 4300 Myr ago. Nature, 409, 178–181.

Nisbet, E. G. (1987) *The Young Earth: an Introduction to Archaean Geology.* Allen & Unwin, Boston.

Nisbet, E. G. and Fowler, C. M. R. (1983) Model for Archean plate tectonics. Geology, 11, 376–370.

Nutman, A. P., Mojzsis, S. A. and Friend, C. R. L. (1997) Recognition of >3850 Ma water-lain sediments in West Greenland and their significance for the early Archaean Earth. Geochim. Cosmochim. Acta, 61, 2475–2484.

Ohta, H., Maruyama, S. and Takahashi, E., Watanabe, Y. and Kato, Y. (1996) Field occurrence, geochemistry, and petrogenesis of the Archean mid-oceanic ridge basalts (AMORB) of the Cleaverville area, Pilbara craton, Western Australia. Lithos, 37, 199–221.

Parman, S. W., Dann, J. C., Grove, T. L. and de Wit, M. J., 1997, Emplacement conditions of komatiite magmas from the 3.49 Ga Komati Formation, Barberton Greenstone belt, South Africa. Earth Planet. Sci. Lett, 150, 303–323.

Peacock, S. M. (2001) Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle? Geology, 29, 299–302.

Peacock, S. M. and Wang, K. (1999) Seismic consequences of warm versus cold subduction zone metamorphism: Examples from northeast and southwest Japan. Science, 286, 937–939.

Polat, A., Kerrich, R. and Wyman, D. A. (1998) The late Archean Schreiber-

Hemlo and White River-Dayohessarah greenstone belts, Superior Province: collages of oceanic plateaus, oceanic arcs and subduction-accretion complexes. Tectonophysics, 289, 295–326.

Reymer, A and Schubert, G. (1984) Phanerozoic addition rates to the continental crust and crustal growth. Tectonics, 3, 63–77.

Ringwood, A. E. and Irifune, T. (1988) Nature of the 650-km seismic discontinuity: Implications for mantle dynamics and differentiation. Nature, 331, 131–136.

Ritsema, J., van Heijst, H. J. and Wodhouse, J. H. (1999) Complex shear wave velocity structure imaged beneath Africa and Iceland. Science, 286, 1925–1928.

Rogers, J. J. W. (1993) *A History of the Earth*, Cambridge Univ. Press, Cambridge, U. K.

Schidlowski, M. (1988) A 3,800-million-year isotopic record of life from carbon in sedimentary rocks. Nature, 333, 313–318.

Schopf, J. W. and Packer, B. M. (1987) Early Archaean (3.3-billion to 3.5-billion-year-old) microfossils from Warrawoona Group, Australia. Science, 237, 70–73.

Sepkoski, J. J. (1984) A kinematic model of Phanerozoic taxonomic diversity. III. Post-Paleozoic families and mass extinctions. Paleobiology, 10, 246–267.

Shen, Y., Soloman, S., Bjarnason, I. and Wolfe, C. (1998) Seismic evidence for a lower mantle origin of the Iceland plume. Nature, 395, 62–65.

Shimizu, K., Komiya, T., Hirose, K., Shimizu, N. and Maruyama, S. (2001) Cr-spinel, an excellent micro-container for retaining the primitive melts–Implications for a hydrous plume origin for komatiites. Earth, Planet. Sci. Lett., 189, 177–188.

Sleep, N. H. (1992) Time dependence of mantle plumes: Some simple theory. Jour. Geophys. Res., 97, 20007–20019.

Sleep, N. H. and Windley, B. F. (1982) Archaean plate tectonics: constraints and inferences. J. Geol., 90, 363–379.

Stetter, K. O. (1994) The lesson of Archaobacteria. In "*Early Life on Earth*". Columbia Univ. Press, 143–160.

Stevenson, D. J. (1990) Fluid dynamics of core formation. In "*Origin of the Earth*", Newsom, H. E. and Jones, J. H. eds., Oxford Univ. Press, 231–249.

Stevenson, D. J., Spohn, T. and Schubert, G. (1983) Magnetism and thermal evolution of the terrestrial planets. Icarus, 54, 466–489.

Su, W. and Dziewonski, A. M. (1997) Simultaneous inversion for 3-D variations in shear and bulk velocity in the mantle. Physics, Earth Planet. Inter., 100, 135–156.

Sumita, I., Yoshida, S., Hamano, Y. and Kumazawa, M. (1995) A model for the structural evolution of the Earth's core and its relation to the observations. In

"*The Earth's Central Part: Its Structure and Dynamics*", Ed. Yukutake, T., Terra Sci. Pub. Co., 231–260.

Suzuki, N., Utsunomiya, A., and Maruyama, S. (2001) The history of the Pacific Superplume. EOS Trans. AGU, 82 (47), 1221.

Summons, R. E., Jahnke, L. L., Hope, J. M. and Logan, G. A. (1999) 2-Methylhopanpoids as biomarkers for cyanobacterial oxygenic photosynthesis. Nature, 400, 554–557.

Tackley, P. J., Stevenson, D. J., Glatzmaier, G. A. and Schubert, G. (1994) Effects of a multiple phase transitions in a 3D spherical model of convection in the Earth's mantle. J. Geophys. Res., 99, 15877–15901.

Tajika, E. (1998) The evolution of the Earth system, In "*Evolving Earth*", Series of Earth & Planetary Science, Iwanami-shoten, 13, 55–153 (in Japanese).

Tucker, M. E. (1992) the Precambrian-Cambrian boundary: seawater chemistry, ocean circulation and nutrient supply in metazoan evolution, extinction and biomineralization. Jour. Geol. Soc. London, 149, 655–668.

Ueno, Y., Isozaki, Y., Yurimoto, H. and Maruyama, S. (2001-a) Carbon isotopic signatures of individual Archean probable microfossils from Western Australia. Int. Geol. Rev., 43, 196–189.

Ueno, Y., Yurimoto, H., Yoshioka, H., Komiya, T. and Maruyama, S. (2001-b) Ion microprobe analysis of graphite from ca. 3.8 Ga metasediments, Isua supracrustal belt, West Greenland: Relationship between metamorphism and carbon isotopic composition. Geochim. Cosmochim. Acta. In press.

Valentine, J. W. and Moores, E. M. (1970) Plate tectonic regulation of faunal diversity and sea level; a model. Nature, 228, 657–659.

Van der Hirst, R. D., Widiyantoro, S. and Engdahl, E. R. (1997) Evidence for deep mantle circulation from global tomography. Nature, 386, 578–584.

Van der Westhuizen, W. A., Debruiyn, H. and Meintjes, P. G. (1991) The Ventersdorp supergroup — an overview. J. Afr. Earth Sci., 13, 83–105.

Vasco, D. W. and Johnson, L. R. (1998) Whole-earth structure estimated from seismic arrival times. J. Geophys. Res., 103, 2633–2671.

Weber, M. amd Køring, M. (1992) A search for anomalies in the lowermost mantle using seisimic bulletins. Phys. Earth Planet. Inter., 73, 1–28.

Wilde, S. A., Valley, J. W., Pech, W. H. and Graham, C. M. (2001) Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature, 409, 175–178.

Windley, B.F. (1977, 1984, 1995) *The Evolving Continents*, 1st, 2nd, 3rd eds. Chichester, Wiley.

Windley, B. F. and Maruyama, S. (2002) Mantle overturn at 2.8–2.7Ga. Proceedings of the International Workshop, Superplume, Tokyo Institute of Technology, Tokyo, 285–286.

Yamazaki, D., Kato, T., Ohtani, E. and Toriumi, M., 1996, grain growth rates of $MgSiO_3$ perovskite and periclase under lower mantle conditions. Science, 274, 2052–2054.

Yoshida, S., Sumita, I. and Kumazawa, M. (1996) Growth model of the inner core coupled with the outer core dynamics and the resulting elastic anisotropy. Jour. Geophys. Res., 101, 28085–28103.

Yuen, D. A., Sabadini, R. and Boschi, E. V., 1982, Viscosity of the lower mantle from rotation data. J. Geophys. Res., 87, 10745–10762.

Yuen, D. A., Cadek, Ò., Boehler, R., Moser, J. and Matyska, C., 1994, Large cold anomalies in the deep mantle and mantle instability in the Cretaceous. Terra Nova, 6, 238–245.

Zhao, D. (2001) Seismic structure and origin of hotspots and mantle plumes. Earth Planet. Sci. Lett., 192, 251–265.

Zhao , D., Hasegawa, A. and Kanamori, H. (1994) Deep structure of Japan subduction zone as derived from local, regional and teleseismic events. J. Geophys. Res., 99, 22313–22329.