Paper 13: The Geological Rock Record

"...the past history of our globe must be explained by what can be seen to be happening now." Hutton, 1788

The small Earth models presented in this series of papers extend from the early-Archaean, approximately 4,000 million years ago, through to the present-day with one model extended to 5 million years into the future. Age dating studies suggest that during early-Archaean times the ancient crusts were just starting to stabilise, implying that the first minerals were cooling and crystallising to form recognisable rocks. Similarly, age dating from Moon rocks has returned ages extending to approximately 4,540 million years old, which potentially extends knowledge about the Earth-Moon system back a further 500 million years. Because of the age constraints of rocks on Earth, prior to 4,000 million years ago there is no physical evidence in the Earth's rock-record to say what the Earth was like during these pre-Archaean times. There is enough subtle evidence preserved in the early Earth and Moon rock-record though to make some speculation.

Conventional cosmological studies consider that formation of the Earth was by accretion of interstellar debris during pre-Archaean times. Accretion was considered to have been complete by the early-Archaean and, once stabilised, the size of the ancient Earth was assumed to be the same, or very similar to the size of the present-day Earth. In order to account for the presence of continental crusts on a constant radius Earth, the ancient crusts were considered to have either fully covered the Earth by about 4,000 million years ago and have since been recycled through the mantle throughout geological time with no net change in crustal mass or, that the earliest continental crust nucleated as small localised patches and this juvenile continental crust has not been recycled back into the mantle.

Likewise, the prevailing hypothesis for formation of the Moon, although by no means definitive by empirical evidence, is that the Earth–Moon system formed as a result of a giant impact whereby a Mars-sized body hit the newly formed proto-Earth and blasted material into orbit around it. This ejected material subsequently accreted to form the Moon. Simulations of this event are said to show that most of the Moon material may have come from the impactor, not from the ancient Earth. However, more recent simulations suggest that more of the Moon may have come from the Earth rather than the impactor. Both of these conventional Earth and Moon formation considerations are, however, highly speculative and, as such, are open to further interpretation.

During 1982, Shuldiner presented evidence from ancient high-grade metamorphic rocks to suggest that Earth surface temperatures during the pre- to early-Archaean were 300 ± 100 degrees Celsius hotter than what it is now. This implies that there was no liquid water, no oceans, and no rain on the ancient Earth but probably some semblance of a primitive atmosphere. This is conceivable because the bulk of the early-Archaean rocks surviving through to the present-day are granite and volcanic rocks, along with high-grade metamorphic rocks, which all require high temperatures to form.

Also in 1982, Kröner estimated that the upper mantle temperatures on Earth during the late-Archaean to early-Proterozoic times were up to 150 degrees Celsius hotter than the present. High temperatures during early-Archaean to Proterozoic times suggested that these temperatures were attributed to a higher mantle geothermal gradient still prevailing during these ancient times.

Evidence from glacial studies suggested to Eyles and Young in 1994 that by late-Archaean to early-Proterozoic times the Earth surface temperatures had fallen significantly to maybe 30 degrees less than now. This was inferred to have enabled atmospheric gases to condense to form surface water and ice. These low Archaean temperatures were further considered to be the result of an insulating effect caused by the development and stabilisation of a primitive crust in conjunction with a declining mantle geothermal gradient.

In contrast, increasing radius small Earth modelling studies presented here have shown that the size of the early-Archaean Earth was around 27 percent of the present Earth radius—a similar size to the present Moon. At that time the entire primordial Earth crust comprised granite and volcanic rocks with very little sedimentary rocks and no large oceans. It is speculated from the crustal and mantle temperature studies of others that the pre-Archaean increasing radius Earth—times older than 4,000 million years ago—may have been incandescent, that is, hot enough to remain molten without crystallisation to form a stable crust or dateable minerals and rocks.

In order for the primordial Earth, and by inference the Moon, to be incandescent during pre-Archaean times a possible suggestion is that the Earth-Moon system was located much closer to the primitive young Sun than it is now. The very much reduced Earth-Moon size and mass existing at that time would insist that centrifugal forces and angular momentum would be vastly different to what they are now and hence this suggestion may be plausible. By Archaean to early-Proterozoic times the Earth-Moon system may have then moved sufficiently far away from the influence of the Sun's surface temperature and gravity to cool and form a stable primitive crust. Sufficiently far to also lower Earth-Moon surface temperatures enough to retain liquid water on the primitive Earth surface while still retaining a high residual geothermal gradient in the mantle.

During the distant pre-Archaean times—an indeterminate time span of maybe billions of years—it is speculated that the Earth-Moon system may have also been originally combined as a single molten planet. By combining the volume of the present Moon and the volume of the early-Archaean Earth, a pre-Archaean Earth-Moon system is readily calculated to have been approximately 2,100 kilometres radius prior to separation. At, or sometime prior to 4,540 million years ago, the Earth and Moon may have then separated. It is envisaged that this separation occurred as a result of gravitational instability of the more basaltic molten surface layer of the primitive incandescent Earth-Moon, possibly as a result of a high rotational velocity and centrifugal forces, forming a double planet. This mechanism is described in conventional literature as *fission of the Moon from the Earth's primitive basaltic crust through centrifugal forces occurring during a period of high angular momentum of the Earth–Moon system*. A high angular momentum and rotational velocity may also add further support to the suggestion that the Earth-Moon system was originally located much closer to the primitive young Sun.

It is further speculated that, once separated, this double planet scenario would have originally comprised two bodies, the Earth and the Moon, of approximately equal size—around 1,700 kilometres radius—and in close proximity co-rotating around each other as they do today. Currently, the Earth and Moon are continuing to move further apart and are now separating at a measured rate of 38 millimetres per year. It is also feasible to consider that the Earth-Moon system is also continuing to move further away from the Sun. This, more passive separation process, in contrast to a speculative impact event, may also go a long way to explain why the Moon is currently in synchronous, albeit retrograde rotation around the Earth, always showing the same face to the Earth.

This speculation is further supported by research in 2001, where a team at the Carnegie Institute of Washington reported precise measurement of isotopic signatures—variants of a particular chemical element—of lunar rocks. The team found that the lunar rocks gathered during the Apollo program carried an isotopic signature that was identical with rocks from Earth and were similarly different from almost all other bodies in the Solar System. In 2012, further analysis of titanium isotopes from surface lunar samples, and similarly in 2016 for oxygen isotopes, also indicated that the Moon has the same composition as the Earth and the two bodies are indistinguishable. This conflicts strongly with the current speculation that the precursor to the Moon originated far from Earth's orbit and was formed as a result of a giant impact between Earth and a Mars-sized body.

Not only is this isotopic signature data saying that the Moon did not originate from debris left over after, or fusion of, a giant impact between Earth and a Mars-sized body, it is also saying that the Moon and Earth may not have been involved in heavy bombardment from asteroids or comets colliding with the Earth and lunar surface. Debris from foreign asteroids or comets would have been readily detected in the research carried out by the Carnegie Institute by also showing a distinctly separate isotopic signature, which it clearly doesn't.

In contrast, it is envisaged that the original molten surface basaltic material that separated from the Earth-Moon body to form the primitive Moon was somewhat cooler than the remnant core-mantle material left over to form the Earth. The Moon is now known to have a distinct crust, mantle, and core, and Moon rock samples collected from the surface confirm the composition is iron rich, similar to the seafloor crust and ancient volcanic rocks on Earth. The inner core of the present Moon is known to be small, about 20 percent the size of the Moon, in contrast to about 50 percent estimated for most other terrestrial bodies. This small core and mantle would also offer an explanation as to why the Moon has a limited surface gravity and magnetic field and why there is no atmosphere or hydrosphere.

During the speculated Earth-Moon separation process it is envisaged that the hotter primitive core-mantle, as well as underlying remnants of the surface layer of the former Earth-Moon body, remained intact, forming the primordial Earth (Figure 1). After gradual separation of the Moon, it is further envisaged that there would have been a period of time when remnant spatter of fragments left over from this separation process would have bombarded both bodies, forming the now familiar cratering on the near side of the Moon's surface. Much cooler temperature conditions on the Moon may also explain why the primitive Moon cooled and crystallised 500 million years earlier than the primitive Earth, thus preserving this period of surface bombardment and cratering.

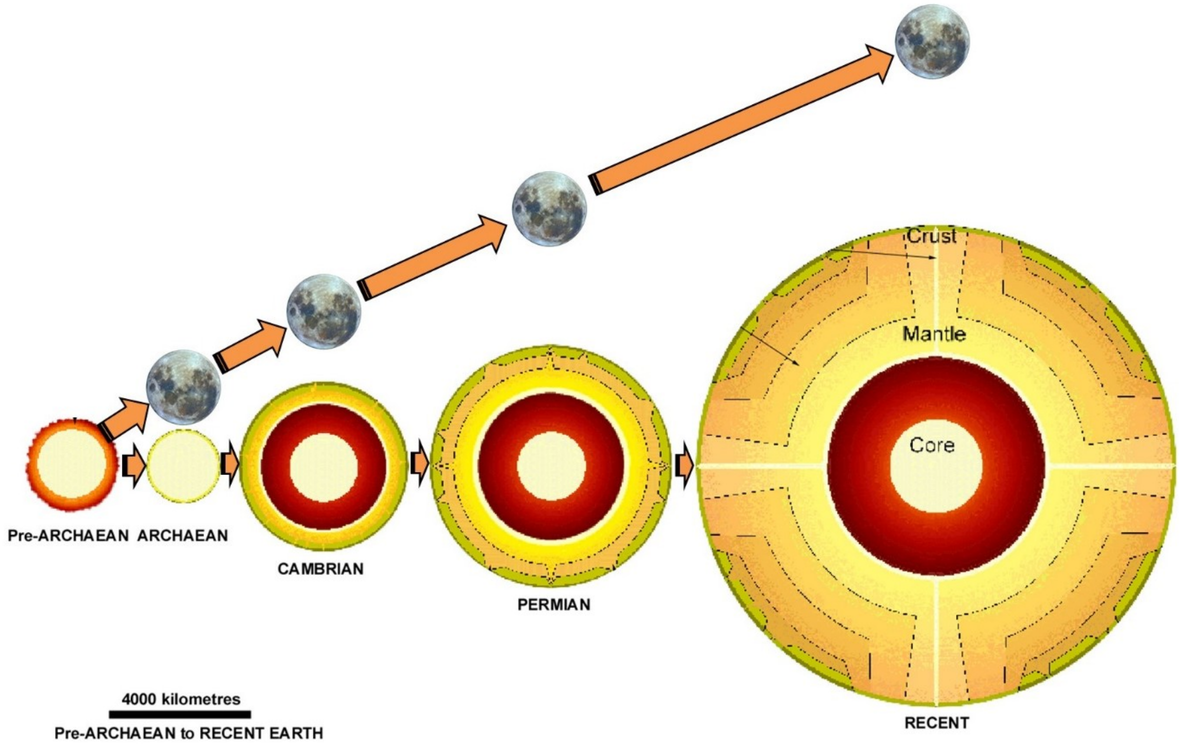

Figure 1 Speculated formation of the Earth and Moon during pre-Archaean times along with Precambrian to present-day formation of the Earth's core, mantle, and crust.

Once the Earth-Moon body separated, if that indeed occurred, it is further speculated that the remaining molten core-mantle material forming the primitive Earth began to differentiate, whereby the remaining molten elements and minerals separated into a distinct core and mantle. Over time, surface temperatures then gradually cooled sufficiently to form a new primitive silica-rich outer crust. On Earth, during this differentiation process, the expulsion of fluids and gases from the mantle similarly began to accumulate to form shallow seas and a primitive atmosphere with an accompanying further reduction in mantle temperatures over time. Since then, without a strong magnetic core, the size of the Moon has remained relatively constant while the size of the Earth has increased exponentially to the present-day.

Primitive Atmosphere and Hydrosphere

Fundamental to the concept of an increasing radius Earth is the premise that ocean waters and atmospheric gases have been accumulating throughout much of geologic time in sympathy with the formation of ancient supercontinental crusts and new seafloor volcanic crusts. It was considered by Bailey and Stewart in 1983 that *"...for an Earth undergoing expansion with time, the bulk of the oceans would have to be outgassed since the Palaeozoic, requiring fundamental changes in atmosphere, climate, biology, sedimentology and volcanology."* It was also considered by Carey in 1988 that, *"as the generation of the ocean floors depends fundamentally on the out gassing of juvenile* *water, it would therefore be expected that the volume of seawater* [and atmospheric gases] *and capacity of the ocean basins both increased, but not necessarily precisely in phase, in a related way."*

The primitive atmosphere and hydrosphere was considered by Lambert in 1982 to have been formed largely from elements and molecules degassed from the Earth's interior and subsequently modified by physical, chemical, and biological processes. Rubey proposed as early as 1975 that degassing—the removal of dissolved gases from liquids [inclusive of molten magma]—has been a continuous or recurrent process, which is still occurring today. Rubey further suggested that *"the whole of the waters of the oceans have been exhaled from the interior of the Earth, not as a primordial process, but slowly, progressively and continuously throughout geological time."*

Studies of melted igneous rocks carried out since the 1970s and 1980s have shown that the solubility of water in melted rocks increases with increasing pressure and temperature until a maximum value is reached in the mantle. Quoted examples range from 14 to 21 percent by weight of water retained in volcanic rocks at temperatures varying between 1,000 to 1,200 degrees Celsius accompanied by high pressures. For silica-rich magmas, carbon dioxide was also shown to be readily dissolved, in particular under high pressures. It was concluded from these studies that if water and carbon dioxide were available, they would both be highly soluble in magmas normally generated in the upper mantle.

Eggler in 1987 further considered that the elements carbon, oxygen, hydrogen, and sulphur would also exist in the Earth's mantle within volatile-bearing minerals—minerals capable of retaining these elements in their crystal lattices. It was also considered possible that solution of elements in crystalline minerals represents a significant repository for each of these elements within the Earth's mantle and crust. These volatile-bearing minerals occur in most volcanic and metamorphic rocks, as well as in carbonate rocks and sulphide ores. Similarly, each of the volatile minerals such as water, carbon dioxide, carbon monoxide, methane, hydrogen, sulphur dioxide, and hydrogen sulphide are soluble in silica-rich melted rocks, with water and methane being more soluble than the rest.

The main controls on the chemistry of the Archaean hydrosphere were considered by Lambert to be reactions with hot igneous rocks, seafloor weathering, and additions of new water degassed from the crust and mantle, with minor input from river systems. Oxygen isotope studies from Archaean sediments suggest that fluids in existence at that time had a similar composition to modern seawater, with prevailing seawater temperatures of up to 70 degrees Celsius.

One of the most important events occurring during the Proterozoic Era was the accumulation of oxygen in the Earth's atmosphere. Though oxygen may have been released by photosynthesis or chemical processes well back in Archaean times, it was unable to build to any significant degree until chemical sinks—the presence of unoxidized sulphur and iron—had been filled. Until about 2,300 million years ago, it has been estimated by others that oxygen was probably only 1 percent to 2 percent of its current level today. Banded iron formation rocks, which now provide most of the world's iron ore, were also a prominent chemical sink where most iron accumulation ceased after 1,900 million years ago. Red beds—sediments coloured by the iron oxide mineral hematite, indicate an increase in atmospheric oxygen after 2,000 million years ago as they are not found in older rocks. This oxygen build-up is considered in the literature to be due to two main factors: a filling of the chemical sinks, and an increase in carbon burial, which sequestered organic compounds that may have otherwise been oxidized by the atmosphere.

On an increasing radius Earth, it is suggested that degassing of the dissolved volatile elements and minerals from a primitive mantle and crust commenced during early-Archaean times. This first commenced once the primitive crust had cooled sufficiently to start crystallising and expelling excess volatile elements. It is envisaged that, once degassed, these elements would have been retained as water-rich gases in the atmosphere until such time as temperatures had cooled sufficiently to retain liquids on the surface of the Earth. Evidence suggests that a reduced atmosphere was well established during Archaean times comprising mainly water and carbon dioxide, with lesser carbon monoxide, nitrogen, sulphuric acid, sulphur dioxide, hydrochloric acid, and small amounts of nitric acid and carbonic acid. The absence of an oxygen source implied to Lambert that oxygen was not a stable component of the early atmosphere but instead was generated later by secondary processes, such as photosynthesis and microbial action.

Archaean Crust-Mantle

The Archaean extends in time from around 4,000 to 2,500 million years ago. On an increasing radius Earth this represents a period of time where surface temperatures were becoming sufficiently low to allow crystallisation and solidification of a thin crust over a mantle that still retained a relatively high temperature gradient. As cooling progressed, the early crust thickened and extended in area as primitive volcanism became widespread. Volcanic activity covered the entire primordial Earth surface and this activity was associated with a complex system of mantle plumes, where hot volcanic rock was rising through the Earth's mantle to form the Earth's crust.

During this process, hot gases were also degassed from the mantle to form a primitive atmosphere while later, once surface temperatures had cooled sufficiently, condensed fluids started to pool in low-lying depressions.

The primitive early-Archaean Earth is estimated to have had a radius of approximately 1,700 kilometres. It is suggested that by that time differentiation—a chemical processes whereby molten magmas undergo bulk chemical change—of a molten pre-Archaean Earth silica-rich magma was sufficiently advanced to form a distinct core and mantle prior to cooling and crystallisation to form a primitive surface crust. The presently known Archaean geological history commenced around 4,000 million years ago with the stabilisation and preservation of a thin outer primitive crust prior to onset of increasing Earth radius and fragmentation of the crust during mid- to late-Archaean times (Figure 2).

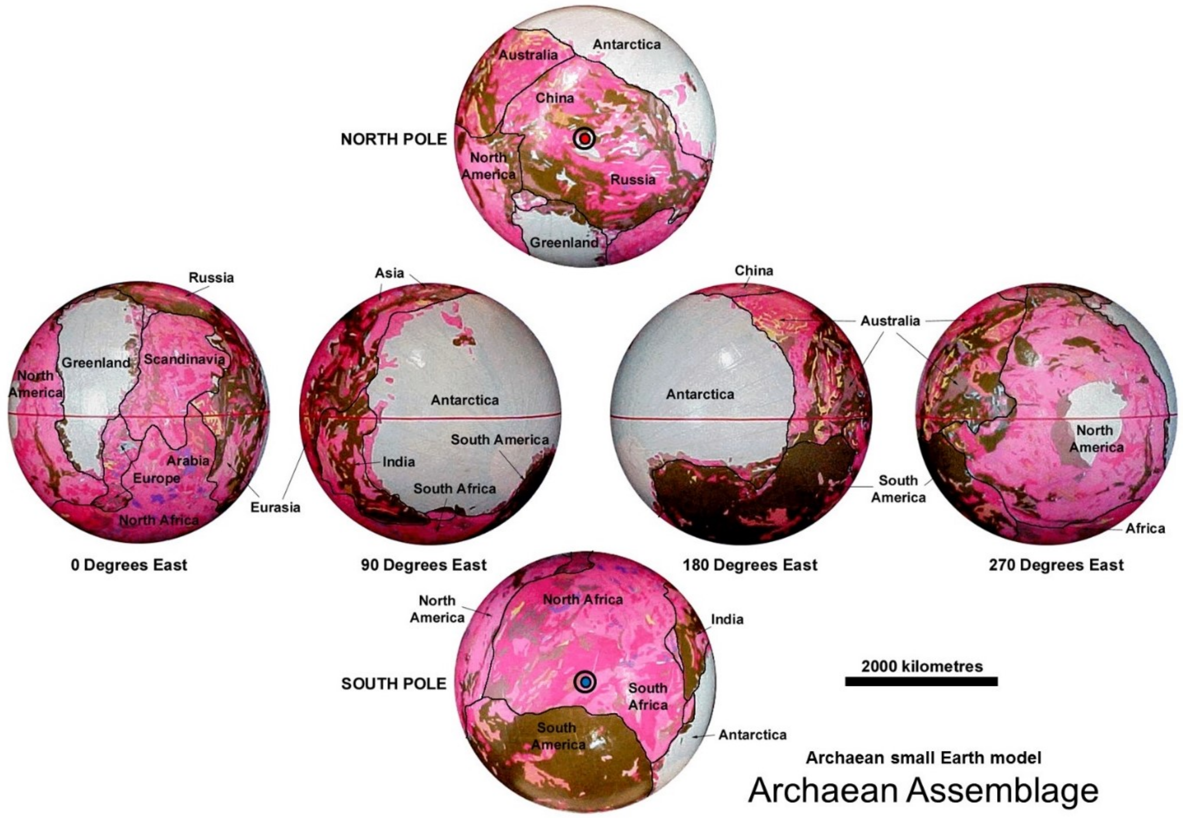

Figure 2 Primordial Archaean to Proterozoic increasing radius small Earth model. Cratons are shown as pink and red, Proterozoic basement rocks are shown as khaki. Outlines of the remnant present-day ancient crusts are shown as black lines. (Present-day Antarctic and Greenland ice-sheets are shown as pale blue areas).

The formation of localised stable patches of juvenile crusts, as suggested by Moorbath in 1982, is consistent with an early-Archaean increasing radius Earth model. During the early-Archaean, as the primitive silica-rich crust progressively cooled and crystallised, these patches of juvenile crusts eventually coalesced to enclose the entire primordial Earth with stabilised crust. Because of the small size of the primordial Earth, this event may have been globally synchronous, occurring at the same time all over the primordial Earth. The following proposal for crust-mantle evolution and development of volcanic, granite, and metamorphic crusts during the Archaean is based on a similar, albeit conventional proposal put forward by Kröner in 1982.

After the Earth-Moon system had formed and prior to the early-Archaean cooling and crystallisation phase, the pre-Archaean Earth was molten and volcanically turbulent. At that time patches of primitive juvenile crusts may not have survived the extensive volcanic plume activity and may have been, in part, re-absorbed back into the mantle, further reducing mantle temperatures in the process. By about 4,000 million years ago, mantle temperatures and heat flow had decreased sufficiently to maintain a granite and volcanic lava-dominated crust, allowing patches of juvenile volcanic rock to rapidly increase in height, area, and thickness. Growth of the crust may have also occurred through chemical change and crystallisation of the underlying upper mantle, giving rise to further cooling, thickening, and stabilisation of the overlying crusts. In contrast, regions away from the main volcanic centres may have maintained a relatively thin upper crust, which may have ultimately formed the observed loci for on-going crustal weakness, crustal extension, and basin formation during latter eras.

During early-Archaean times, the primitive crust was made of predominantly silica and alumina-rich rocks comprising a mixture of intruded granites and an assortment of iron and magnesia-rich volcanic rocks. Once cooled and stabilised, the surface of the primordial Earth was then exposed to erosion by wind and waters, in particular erosion by hot juvenile waters from volcanic eruptions. This erosion process initially deposited greywacke sediments in low lying sedimentary basins and comprised volcanic ash and rock debris and later included chemically weathered and eroded sediment derived from the action of the waters on the exposed rocks. The early sedimentary basins were initially small and isolated, becoming more extensive by about 3,800 million years ago. This early crust now forms the oldest preserved magmatic and sedimentary basin remains known on Earth today.

It is significant to again note that modern geological evidence shows that all Precambrian cratons throughout the world have been eroded by the order of 10 to 40 kilometres vertical thickness. This eroded material now forms the surrounding younger sedimentary basins and orogenic belts making up all continents on Earth today and may have been recycled many times throughout Earth history. Assuming an Earth-Moon fission process, once separated, the surface of the early-Archaean Earth may have also originally been rugged and impacted by remnant spatter of fragments left over from this separation process. The implications from this speculation is that any discourse on Archaean crusts on the present-day Earth only represents the deeper ancient crusts and not necessarily the ancient rocks or topography present on the original ancient Archaean land surface.

The formation of silica and alumina-rich granite and related volcanic rocks from a dense iron-magnesia-rich upper mantle source suggested to Lambert that the primordial molten crustal material may have initially formed as a surface layer of not more than two to three kilometres thick. Lambert considered that the high thermal gradient existing during pre- to early-Archaean times suggested that the crustal material would have continued to segregate to also form a lower region of iron-magnesia-rich rocks extending from depths of 30 to 100 kilometres thick. The present-day survival of a 30 to 40 kilometre thick Archaean crust further implied the presence of a thick stable sub-crustal zone, which may have ultimately extended still further to greater than 200 kilometres thick.

Kröner envisaged that by about 3,600 million years ago continental crust had attained sufficient thickness and rigidity to support large sedimentary basins. On an increasing radius Earth, once cooled, this continental crust was subjected to the initial phases of crustal extension and fracturing during early increase in Earth radius. The magnitude of this increase in Earth radius and crustal extension during these times was of the order of microns per year and may have initially been represented by simple cooling cracks. Over an extended period of time—hundreds of millions of years—this small crustal extension process ultimately gave rise to crustal fracture, fissuring, and rifting, generating large sedimentary basins or sharply bounded, fault controlled landscapes. These low-lying basin areas, inclusive of remaining impacted features, collected water, shallow-water sediments, and extruded volcanic lava originating from the upper mantle. A small proportion of this volcanic lava reached the surface as magnesia-rich komatiite lava, which is now known to be unique to the high mantle temperature conditions existing during Archaean times. A much larger volume of magma was also retained near the base of the crust to become the source for later volcanic eruptions and granite intrusives.

It is envisaged that on-going crustal extension of the stabilised Archaean crust during onset of an increase in Earth radius resulted in early crustal fracturing and initiation of a global network of crustal weakness. Faulting and crustal extension was focused within this network and was accompanied by deposition and accumulation of sequences of volcanic lava and eroded sedimentary rocks. The Archaean is also renowned for the presence of high-grade metamorphic terranes as preserved throughout the ancient crusts today. These terranes represent largely pre-volcanic silica and alumina-rich rocks, together with early sedimentary deposits and granites produced during early stages of crustal fissuring and basin formation. Crustal extension and sub-crustal mantle movements during on-going increases in Earth radius and surface area then provides a mechanism for stretching and extension of these rocks within the Archaean crust. Crustal extension, accompanied by high mantle temperatures also provided the necessary heat-flow for recrystallization and metamorphism of these high-grade gneissic terranes.

The Archaean Eon extended over an extremely long period of time and increase in Earth radius during this time was less than the thickness of a human hair per year. It is envisaged that over this 1,500 million year history the crustal rocks were then fractured, intruded by volcanic lava, eroded during weathering, and sediments were deposited in low-lying basins, all of which were complexly contorted and folded as a result of the steadily changing surface curvature. Because of the extremely long time involved, as well as the minute rate of increase per year, it is further envisaged that on-going erosion of the surface of the entire Earth ultimately maintained a very flat landscape throughout the latter part of this eon where erosion kept pace with changing surface curvature. This landscape may have been barren, rocky, and inhospitable by present-day standards.

The latter phase of Archaean crustal development eventually gave rise to formation of very large, stable sedimentary platform basins and shallow seas with a low elevation contrast between the continents and seas. Continental sedimentary input during that time was limited to mainly chemically precipitated sediments, such as calcium and silica-rich chert and banded iron formation rocks, with lesser fine-grained sediments. These rocks were common during mid- to late-Archaean times and formed laterally extensive deposits that are now known throughout most of the ancient crusts on the present-day Earth.

During the Archaean Eon the ancient magnetic poles were located in what are now Mongolia-China and west Central Africa, and the ancient equator passed through North America, the Baltic region, Antarctica, and Australia. There was also a well-developed climate zonation, which persisted for the entire duration of the eon. It is significant that primitive microbial life forms first evolved in the seas during this eon, possibly evolving from within carbon-rich sediments formed during the early anoxic atmosphere and seawater phase, prior to onset of an oxygen-rich atmosphere.

Proterozoic Earth

The Proterozoic Eon extended in time from around 2,500 to 541 million years ago. The eon was characterised by comparative crustal stability dominated by stable exposed continental lands, extensive sedimentary basins and shallow seas during slowly increasing changes in surface curvature. The change in Earth radius throughout the Archaean to mid-Proterozoic times amounted to approximately 60 kilometres increase in radius spread over a 3,000 million year history, and around 400 kilometres increase in Earth circumference. The increase in circumference during that time was reflected by the steadily increasing surface areas of the sedimentary basins surrounding each of the ancient cratons.

On a Proterozoic increasing radius Earth there was not a lot of difference between late-Archaean and Proterozoic times. The location of the poles and equator were essentially the same, and the distribution of exposed ancient supercontinental lands was also much the same. The distinguishing feature of the Proterozoic history was that increasing changes in surface curvature were slowly starting to take effect by increasingly elevating the exposed lands. Like the Archaean, the rate of change in surface curvature during the Proterozoic was still small enough for erosion to continually maintain a relatively flat landscape. In time, this increasing elevation contrast began to slowly increase the rate of erosion of the exposed lands, which also influenced changes to the distribution of seas and corresponding coastal outlines of the established supercontinental lands. These changes to the coastal outlines then formalised the existence and configuration of both the ancient seas and the ancient Rodinia supercontinent (Figure 3).

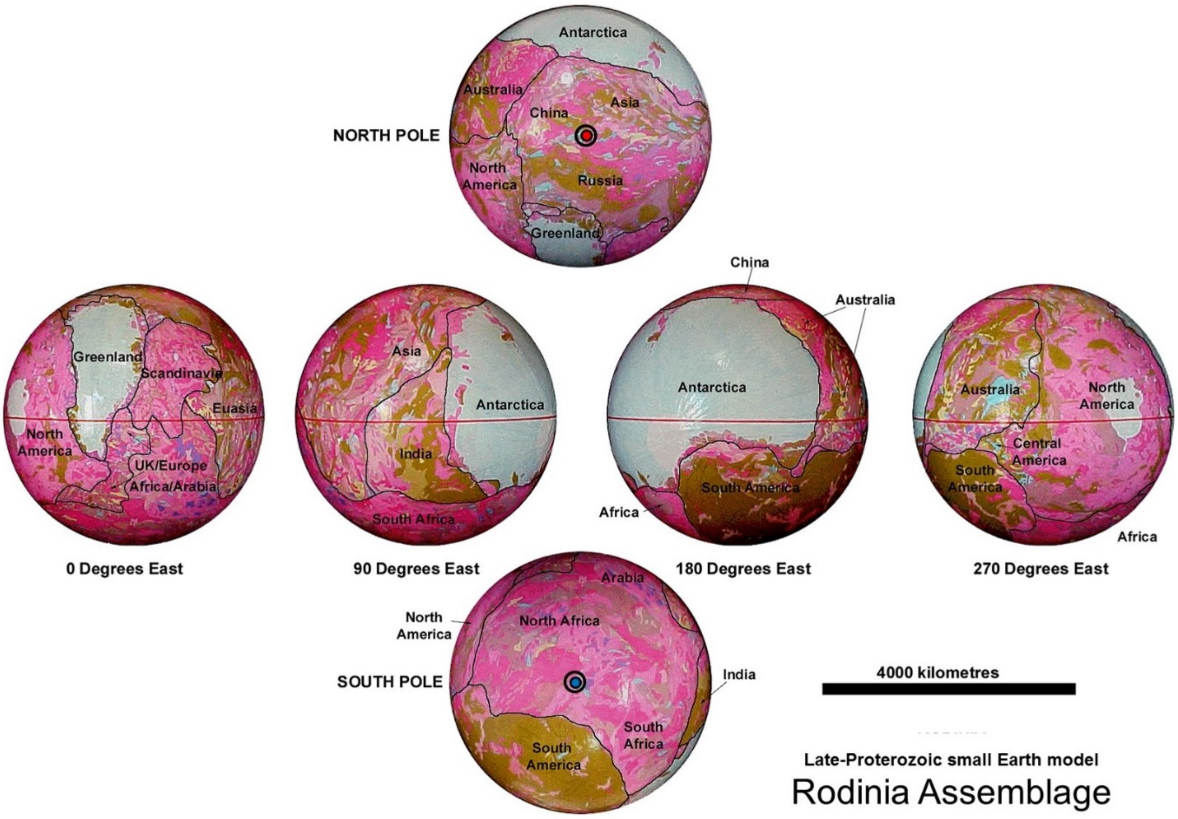

Figure 3 late-Proterozoic Rodinia small Earth supercontinent. The model shows the distribution of Precambrian cratons (pink and red) inferred to represent exposed land, and a network of basins (khaki and brown) inferred to represent continental seas. The black lines represent outlines of remnant present-day continents.

After the mid-Proterozoic—about 1,700 million years ago—the steadily increasing Earth radius and crustal conditions was reflected in the gradual onset of increasing surface curvature and increasing elevation contrast between the lands and seas. This increasing elevation contrast gave rise to changes to and distribution of sediments deposited in the established network of shallow seas during these times, changing from predominantly chemically precipitated sediments to predominantly courser grained sands and silts. The courser grain-size of these sediments, in turn, was a reflection of the increased erosional energy available to both erode and move these sediments which, in turn, is confirmation of the increased elevation contrast of the land surface during these times.

Another distinguishing feature of Proterozoic times was the changing atmospheric conditions. These conditions gradually changed from chemically reduced atmospheric conditions throughout much of the earlier Archaean, through to the accumulation of atmospheric oxygen during the Proterozoic. This transition was marked in the rock-record by the increasing accumulation of iron oxide-rich banded iron formation, calcium and magnesium carbonate rocks, and haematite-rich red beds during this time. These rock types are now found within most of the ancient terranes located on the present-day Earth and they signify globally synchronous conditions existing throughout Archaean and Proterozoic times. This transition also coincided with development and preservation of the earliest life forms, soon to explode in diversity during the following Phanerozoic Eon.

Throughout the Proterozoic Eon the ancient North and South Poles remained within what is now northern China-Mongolia and West Africa respectively. The ancient equator continued to pass through what is now North America, East Antarctica, Australia, Greenland, and Scandinavia, as well as Europe, Asia, and India; essentially the same as during Archaean times. This continuity of magnetic pole locations, as well as continuity of the equator and associated climate zonation is testament to the extremely long period of crustal stability existing during the Rodinia supercontinental configuration.

On subsequent, younger small Earth models this early Rodinia supercontinental assemblage represents a precursor to the better known Gondwana supercontinent and ultimately to the Pangaea supercontinental configuration. This transition from one supercontinent to the next was intimately related to the variation in coastal outlines during changes in sea levels and the passive nature of this transition is unique to an increasing radius Earth. On an increasing radius Earth it was only Pangaea that eventually broke up and dispersed to form the modern continents and modern oceans at around 250 million years ago.

Tectonism during the Proterozoic was essentially confined to an established global network of crustal weakness, which was coincident with the network of sedimentary basins. This tectonism was intimately related to increases in surface curvature and was marked by increased jostling of the ancient cratons. Tectonism was also accompanied by on-going crustal extension within the sedimentary basins. This tectonism generated long, narrow, elongate geosynclinal zones and may have also been accompanied by renewed volcanic activity and granite intrusion. Each of these zones coincided with the established network of sedimentary basins and in turn continued to represent a global network of crustal weakness.

Proterozoic crustal extension was confined to this network of sedimentary basins and was also accompanied by high heat flow from the mantle. Multiple phases of crustal extension-mobility-extension are a prime feature of increasing radius Earth models, continuing through to Palaeozoic times, and prior to continental crustal rupture during the early-Permian and continental breakup and dispersal during the Mesozoic and Cenozoic to the present-day.

Palaeozoic Earth

The Palaeozoic Era represents the early part of the Phanerozoic Eon and extends in time from about 541 to 252.6 million years ago. The boundary between the Proterozoic Eon and the Palaeozoic Era is located at the base of the Cambrian Period, coinciding with a time when fossils of hard body marine animal species became noticeably abundant. Compared to the preceding Precambrian times, the Palaeozoic was a time of increasingly dramatic geological, climatic, and species evolutionary change. The Cambrian Period in particular witnessed the most rapid and widespread diversification of life in Earth's history in which relatives of most modern life forms, including fish, arthropods, amphibians, and reptiles first appeared and evolved. Life during that time began in the ocean but eventually extended onto land, and, by the late-Palaeozoic, great forests of primitive plants covered the continents, many of which formed the coal beds of Europe, Russia, Australia, and North America. Towards the end of this era, large reptiles became dominant and modern plants also appeared.

On an increasing radius Earth the transition from late-Proterozoic to the Palaeozoic represents an accelerating phase of increasing Earth radius along with accelerating increases in surface area and surface curvature. During the Palaeozoic, distinct elevated ancient land surfaces were becoming prevalent, an erosional cycle was prevalent, and rivers were actively carving valleys and modifying landscapes. These land surfaces were, in turn, surrounded by a network of relatively shallow continental seas, which, in turn, defined the outline of the ancient Palaeozoic supercontinents punctuated by major extinction events during changes to both sea levels and coastal outlines.

At that time Gondwana (Figure 4) was subdivided into a North and South Gondwana, separated in part by an early Panthalassa Sea—the precursor to the modern Pacific Ocean. North Gondwana was made up of Australia, East and West Antarctica, and India, and also possibly included Tibet and Afghanistan. South Gondwana, joined at Madagascar, comprised Africa, Arabia, and South America. The ancient Laurentia and Baltica sub-continents were made up of North America, Greenland, and Scandinavia, as well as smaller islands making up England and Ireland. Similarly, the ancient Laurussia sub-continent was centred on the Precambrian regions of Mongolia and northern Russia.

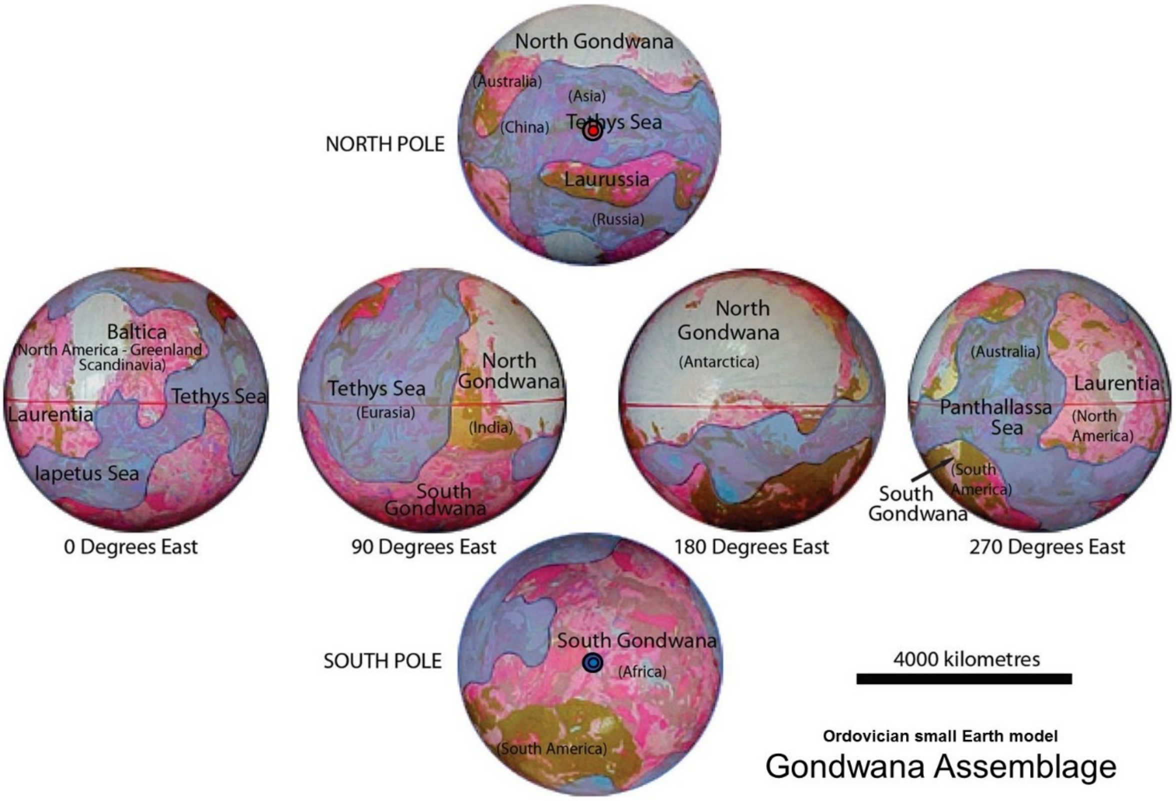

Figure 4 The Ordovician Gondwana small Earth assemblage. This model shows the ancient coastline distribution (blue lines) defining North and South Gondwana in relation to Laurentia, Baltica, and Laurussia. The ancient Tethys, Iapetus, and Panthalassa Seas form part of a global network of continental seas (shaded areas) surrounding each of the exposed supercontinents.

These exposed Gondwanan land surfaces were surrounded by the ancient continental Tethys, Iapetus, and Panthalassa Seas. Remnants of these seas are now preserved and represented by many of the ancient sedimentary basins that are located in Eastern Australia, North and South America, Europe, Asia, and Africa. These continental seas continued to maintain a global network and their outline and distribution were dictated by the changing coastal outlines and sea-levels. At that time accelerating changes to surface curvature gave rise to a marked increase in erosion of the lands and deposition of new sediments within the network of sedimentary basins. The increasing changes in surface curvature and super-elevation of the lands also initiated localised compression of the geosyncline-related sedimentary basins to form long linear fold mountain belts, further disrupting established seaways. The presence of mountain glaciers and ice sheets during a number of Palaeozoic glacial events is testament to the marked increase in land surface elevation contrast. The presence of marine glacial debris deposited within equatorial regions is also testament to the presence of continental seas extending into polar-regions.

During Palaeozoic times, the South Pole continued to be located within central West Africa in what was then South Gondwana. Similarly, the North Pole was located within Northern China-Mongolia in what was part of the northern Tethys Sea. The ancient equator passed through East Antarctica, central Australia, North America, central Eurasia, and India through what was then North Gondwana. This crustal configuration approximates conventional Plate Tectonic reconstructions in part, but differs substantially in the South Pacific region because of the need for an expanse of inferred Panthalassa and Tethys Oceans.

By late-Permian times crustal rupture of the Pangaea supercontinent (Figure 5) had commenced, which resulted in breakup of Pangaea and formation of the modern continents and modern oceans during the following Mesozoic and Cenozoic Eras.

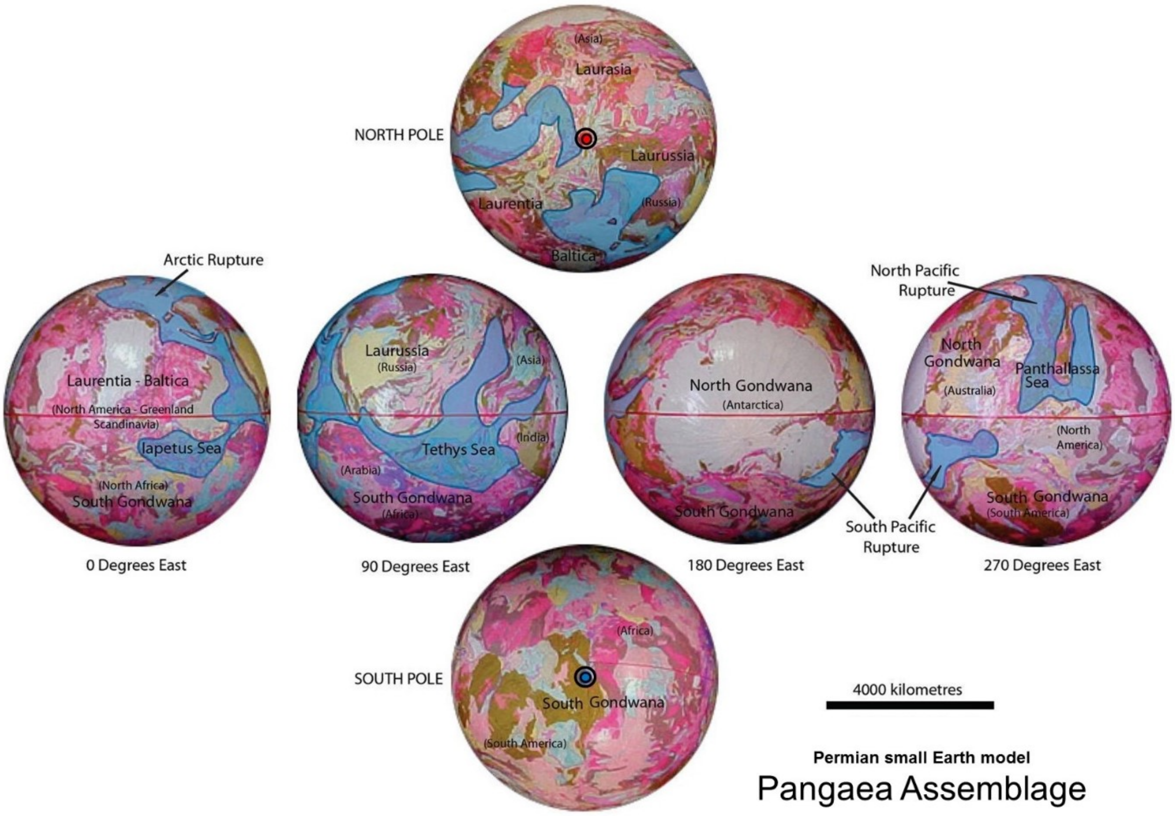

Figure 5 Permian Pangaea small Earth crustal assemblages. The model shows the ancient coastline distribution (blue lines) as well as the ancient Tethys, Iapetus, and Panthalassa Seas (blue shaded areas) forming part of a global network of continental seas. The figure also shows the locations of continental rupture commencing in the north and south Pacific and Arctic Ocean regions to form the modern oceans.

This rupturing also initiated draining of the continental seas into the newly emerging marine sedimentary basins—the forerunners of the modern oceans—and was accompanied by expulsion of new waters from the newly established mid-ocean-rift zones. Disruptions to the continental seas initiated exposure of the former sea-floors to the ravages of erosion, which resulted in an unprecedented accumulation of sediment and organic matter in the form of coal beds in newly emerging coastal environments.

These Palaeozoic times coincided with the rapid development and evolution of all modern life forms on Earth. On an increasing radius Earth this evolution of life forms was driven by the need to keep pace with the rapidly changing environmental conditions and, similarly, extinction is seen as a by-product of rapidly changing sea levels, disruptions to the continental seas, and associated environmental changes. The degree of crustal and environmental changes during this interval of time is considered to have markedly influenced evolutionary change in all life forms. The Palaeozoic Era then ended with rupture and breakup of the Pangaea supercontinental crust and draining of the continental seas into the newly opening modern oceans—the end-Permian extinction event.

Mesozoic Earth

The Mesozoic Era was an unprecedented interval of geological time extending from 252.6 million years ago to about 66 million years ago. The era began in the wake of the end-Permian extinction event, the largest mass extinction in Earth's history, and ended with the end-Cretaceous extinction event, which is best known for the demise of the dinosaurs along with many plant and animal species. The Mesozoic is also recognised as a time of significant tectonic, climate, and evolutionary change. The climate of the Mesozoic was varied, alternating between warming and cooling periods. Dinosaurs appeared in the mid-Triassic and became the dominant terrestrial vertebrates early in the

Jurassic, occupying this position for about 135 million years until their demise at the end of the Cretaceous. Birds first appeared in the Jurassic, having evolved from a branch of theropod dinosaurs. The first mammals also appeared during the Mesozoic, but would remain relatively small in size until the Cenozoic Era.

On an increasing radius Earth the Mesozoic Era commenced as a result of rupture and breakup of the Pangaean supercontinent to form the modern continents, along with draining of the continental Tethys, Panthalassa, and Iapetus Seas to initiate formation of the modern oceans (Figure 6). The subsequent migration history of the modern continents and seafloor crustal history is now preserved within the intruded volcanic seafloor lava existing throughout all of the modern oceans. This post-Pangaea interval of time also saw large apparent shifts in the location of the North and South Poles and equator, occurring as a direct result of opening of the modern oceans and an apparent shift in the location of each of the modern continents.

Draining of the continental seas during breakup was accompanied by a shift in sedimentary deposition, changing from continental to shallow marine and marginal continental basin settings. Draining of the continental seas into the newly opening marine basins also gave rise to a number of separate and discrete seas and embryo oceans, each with their own separate sea-levels, salinities, ocean currents, temperatures, and marine species. The location of the newly opening marine basins coincided with the precursors to the modern oceans and mid-ocean-rift zones. The influx of sediments within these basins, along with intruded magma and volcanism, also initiated formation of island-arcs, which were first initiated and located between the emerging modern continents.

The Mesozoic Era is also noted for its progressive breaching and merging of previously separate seas and oceans, resulting in a number of sea-level related extinction events. Breaching and merging of the North Pacific and South Pacific Oceans gave rise to the end-Triassic extinction event, and similarly breaching between Australia and Antarctica during the Paleocene Epoch initiated opening of the South Pacific Ocean and gave rise to the end-Cretaceous extinction event.

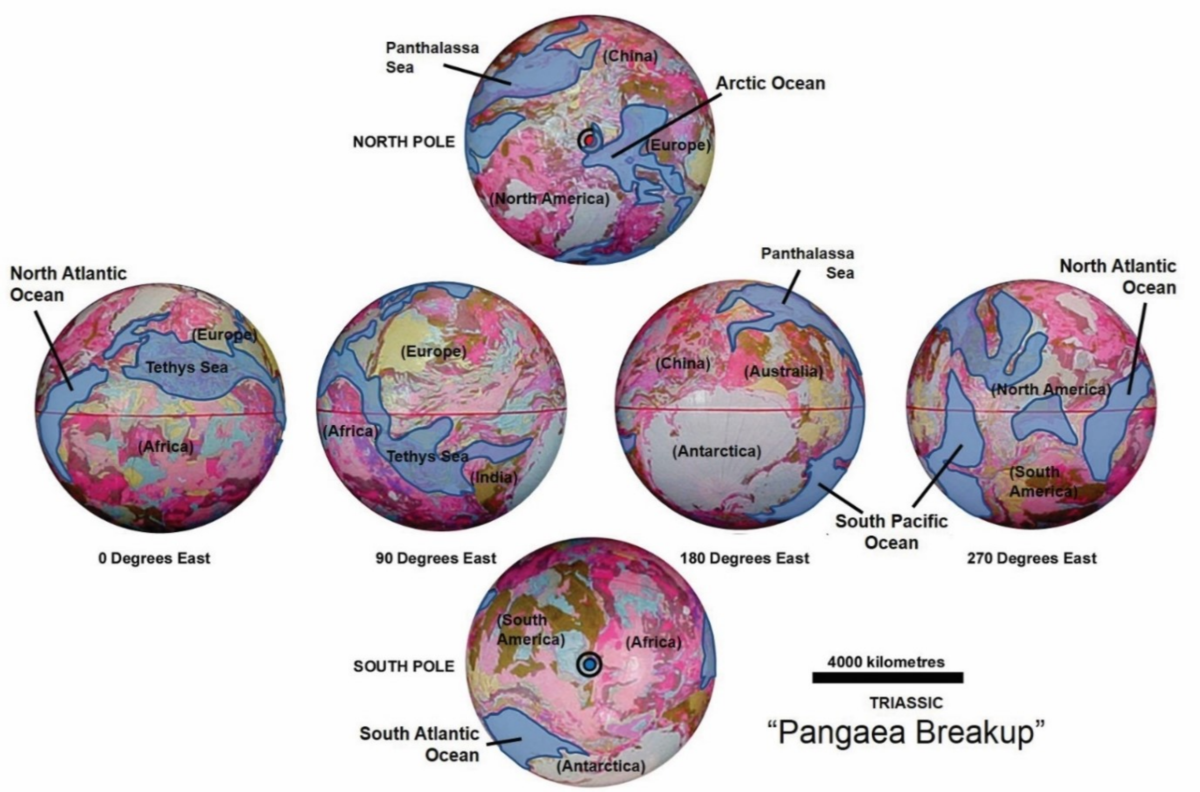

Figure 6 Triassic post-Pangaea breakup small Earth crustal assemblages. The model shows the ancient coastline distribution (blue lines) as well as remnants of the ancient Tethys, Iapetus, and Panthalassa Seas (blue shaded areas) forming part of a global network of separate continental seas. The figure also shows the locations of the modern north and south Pacific, Atlantic, and Arctic Ocean regions.

Breakup of the supercontinental crusts during the Mesozoic initiated apparent migration of the continents and opening of new oceans. Migration of the continents, in turn, affected the geographical location of the magnetic poles and severely disrupted established climate zones and influenced global climates. Breakup and disruption, in turn, affected the existing habitats and migration routes of both marine and terrestrial life forms. This disruption forced species to imperceptibly migrate over time to keep pace with the migrating continents and climate zones, to evolve or better adapt to changing climate, or simply perish if unable to keep pace with environmental change.

Continental breakup and opening of the modern oceans was accompanied by seafloor spreading along well-defined mid-ocean-rift zones, along with intrusion of basaltic seafloor lava and expulsion of new water and atmospheric gases. During this early continental breakup phase the seafloor spreading process was initially masked by input of sediments into the small marine basins as well as around the newly formed continental shelves. As opening of the modern oceans progressed further, beyond the reach of sedimentary deposition, the intruded seafloor volcanic lava was eventually exposed on the seafloor, as is now shown preserved in the Geological Map of the World.

Cenozoic Earth

The Cenozoic Era began in the wake of the end-Cretaceous extinction event some 66 million years ago and continues through to the present-day. On an increasing radius Earth the Cenozoic was marked by the establishment of symmetric seafloor spreading in all of the modern oceans. This seafloor spreading represents a preservation of the seafloor spreading and growth history of the Earth and is testament to opening and enlarging of all of the modern oceans. The Cenozoic was also a time when all of the oceans had merged into a single global ocean, thus removing the threat of further sea-level-related mass extinction events and allowing for relative stability of marine and terrestrial life forms.

Crustal extension as a result of increase in Earth radius is now predominantly confined to the mid-ocean-rift zones, with minor basin extension and rifting within the continents during adjustment for change in surface curvature. Crustal breakup of both seafloor and continental crust continues to be closely related to lengthening and propagation of the mid-ocean-ridges, and includes focused seismic activity, heat-flow, and magmatism along well-defined zones of crustal weakness.

Lengthening of the East Pacific mid-ocean-ridge spreading axis is currently occurring as a northward extension of the spreading ridge passing through the Gulf of California. In the near future this gulf will eventually rift and separate the Californian Peninsula from North America to form an island. A northward extension of the Red Sea Rift zone through the Gulf of Aqaba and Dead Sea region into Turkey will also result in rifting and separation of the Sinai Peninsula from Arabia. A northern extension of the Marianas spreading ridge will continue towards Japan and a southern extension of the Tongan spreading ridge will continue through New Zealand.

The Cenozoic Era has seen the modern continents and oceans continue to migrate and open to their current configurations. Studies here show that this will continue unabated into the near future. The era was dominated by species development being increasingly isolated within island continents, with many species now endemic to specific continents or islands. Climatic changes occurring during this time also coincided with the Antarctican continent migrating from an equatorial position into the South Polar Region. A permanent continental ice-sheet was established on Antarctica about 33 million years ago and this migration may have a direct influence on the long term effects on climate.