

**Figure 4.** Measured and simulated sound speed variances. (a) 7 May 2002 and (b) 8 May 2002.

mena such as tides, etc. which are not included in the IWAVE. Deviations, particularly between 20 and 30 m on 8 May, are due to a sudden entrainment of cold and saline waters into the experimental site. This signal disappeared within the measurement time. Deviations could be attributed to the use of initial measured profile to initialize the model, since it does not contain any information as to the current state of the IW field (direction). Hence a simulation of the measurement period has an added uncertainty due to the use of random phases for each wave component.

An ocean simulation model for IW (IWAVE) was developed and validated against the measurements. A new technique was developed for calculation of dispersion relations, which is fast and stable. The model simulates the temperature and salinity structure due to IWs in the ocean. Comparisons between the measured and modelled variances of the sound speed are in good agreement. One of the main advantages of the IWAVE model is that it requires little information on the prevailing environment, but it serves as an effective and useful tool for understating the IW dynamics as well as the impact of these waves on underwater acoustic transmission. However, parameters such as  $j_*$ ,  $P$  and number of modes are site- and season-specific. Therefore, knowledge of these parameters at the experimental site improves the reliability of the simulated field. More experiments have to be conducted to validate and also to estimate parameters like  $j_*$  and  $P$  in the model, to improve its reliability.

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## Three-phase tectonic evolution of the Andaman backarc basin

K. A. Kamesh Raju

National Institute of Oceanography, Dona Paula, Goa 403 004, India

**A three-phase evolutionary scheme since Late Oligocene for the Andaman backarc basin is proposed based on the multibeam swath bathymetry, magnetic and seismological data. A SW–NE trending spreading ridge bisects the basin. The tectonic evolution of the Andaman basin with special reference to the formation of oceanic crust within the backarc basin encompassing the backarc spreading, suggests a phase of ridge propagation. Swath bathymetry data documented topographic fabric of the ridge propagation and reveal several morphotectonic features that divide the basin into a complex western part comprising arc-parallel seamount chains, N–S trending fault systems and a relatively smooth eastern part. Spreading centre jump during Late Oligocene, rifting and extension during Middle Miocene to Early Pliocene followed by the recent true seafloor spreading since last 4 Ma define the three-phase tectonic evolution of the Andaman backarc basin. The recent phase has experienced westward propagation of**

e-mail: kamesh@darya.nio.org

**the spreading centre. It is suggested that ridge propagation modulated the crust. A schematic evolutionary sequence of the Andaman backarc basin is presented.**

**Keywords:** Andaman basin, magnetics, seafloor spreading, swath bathymetry.

THE Andaman backarc basin is a part of the major island arc–trench system in the northeast Indian Ocean. The Andaman basin is believed to have formed due to the initiation of spreading activity within the central Andaman trough. Earlier investigations in the region<sup>1–3</sup> have elucidated the general physiographic features of the Andaman Sea and delineated tectonic elements related to the subduction of the Indian plate and opening of the Andaman Sea. The complexity of this tectonic province results from various factors such as the oblique subduction, arc volcanism and ill-defined spreading centre. A brief description of the tectonic setting of the region is outlined below.

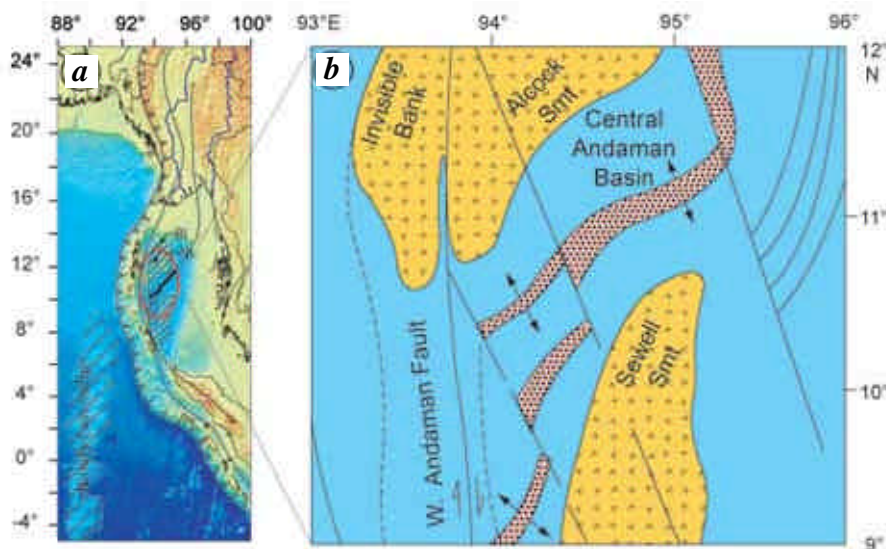
The Andaman Sea extends from Myanmar in the north to Sumatra in the south and Malay Peninsula in the east to Andaman and Nicobar islands, which form a part of the Andaman–Nicobar ridge in the west (Figure 1). The basin is marked by prominent morphological features such as Barren and Narcondam volcanic islands, Invisible bank, and Alcock and Sewell seamount complexes. Subduction of the Indian–Australian plate beneath the Southeast Asian plate occurs all along the Sunda arc, extending from the eastern Himalayan syntaxis to Banda arc, with major variations in terms of speed and direction, resulting in oblique convergence in the Andaman–Nicobar sector. The effects of oblique plate convergence include strike-slip faulting parallel to the trench axis, formation of a sliver plate, backarc extension and basin formation<sup>4</sup>. Considering the dormant Narcondam volcanic island, the active Barren Island volcano<sup>5</sup> and the Invisible bank as part of the present volcanic arc, we refer to the deep basin east of the volcanic arc as the backarc basin. Subduction of the Indian plate along the Andaman arc, formation of the Andaman–Nicobar ridge and initiation of the spreading in the Andaman Sea are some of the important tectonic events that shaped the Andaman backarc basin. Subduction is presumed to have started along the western Sunda arc following the break-up of Gondwanaland in the early Cretaceous<sup>6</sup>. The present surface trace of subduction lies at the western base of the Andaman–Nicobar ridge and the trench is filled with sediments of the Bengal Fan. The Andaman–Nicobar ridge is suggested to have formed during Oligocene or Late Eocene period and is reported to consist of seafloor ophiolites and sediments scrapped-off the underthrusting Indian plate, overlain by autochthonous sediments of shallow water fore-arc environment. A complex system of short spreading rifts and transforms in the central basin of the Andaman Sea was suggested<sup>2</sup> to be the consequence of spreading with an opening rate of 3.72 cm/yr. This spreading centre is connected to the Sagaing fault system in the eastern Burma

highlands in the north and to the Semangko fault system in the south that runs across Sumatra<sup>7</sup>.

Andaman basin remained as one of the poorly understood marginal seas due to inadequate geophysical data. Close grid marine geophysical data using the modern swath bathymetry system, magnetics and single-channel seismic data acquired by the National Institute of Oceanography, Goa as part of the investigations to explore possible hydrothermal activity in the region, provided new insights into the tectonic evolution of the backarc basin. Rao *et al.*<sup>3</sup> documented the absence of recognizable magnetic anomalies and presence of a thick pile of sediments, over the northeastern part of the spreading centre. A recent study carried out by Kamesh Raju *et al.*<sup>8</sup> based on the high-resolution swath bathymetry and other geophysical data, suggested that true seafloor spreading commenced at about 4 Ma. Schematic account of a three-phase evolutionary scheme for the backarc basin formation since Late Oligocene, is presented and the kinematics of ridge propagation was examined in the present study.

The topographic expression of the backarc spreading centre, as revealed by the 100% insonified seafloor image (Figure 2a and b) generated from multibeam bathymetry system, depicts a smooth sediment-filled 12–15 km wide rift valley in the NE to 8–9 km wide rugged and shallow rift valley toward the SW part. Based on the general topographic expression and absence of magnetic anomalies over the NE segment, an active SW and an inactive NE segment, were suggested<sup>3</sup>. However, detailed studies indicate that morphologically the spreading centre has three major segments. Integrated analysis of swath bathymetry and magnetic data and the observation of seismological data indicated that all the ridge segments are actively spreading<sup>8</sup>.

A linear trough flanked by elevated, very smooth topographic plane on either side characterizes segment C. Single-channel seismic reflection data over this segment depict a thick pile of sediments, with expressions of extensional tectonics. Seismic evidence indicates that there is more than 2 km thick sediment overburden over this spreading segment<sup>2,8</sup>. The axial trough along the entire length of segment C is well maintained in spite of high sediment influx in the region. Flanks of the spreading segment A, define a fan-shaped seafloor fabric converging towards the graben G (Figure 2b). On either side of the spreading segment A, bathymetric lineation defined by 3600 m isobaths marks the boundary of the fabric generated by the spreading centre. These lineations are termed as outer and inner pseudofaults<sup>9</sup>. The fan shaped topographic fabric documented over the spreading segment A in the western portion (Figure 2b), is a manifestation of the westward propagation of the ridge during the recent past. The propagation observed here is analogous to the active ridge propagation over Galapagos ridge, documented using high resolution Seabeam/deep-tow investigations<sup>9</sup>. Earthquake epicentre data show clusters of events located in the NE part and further north over the spreading ridge;



**Figure 1.** Geodynamic setting of northeastern Indian Ocean encompassing the Andaman Islands. *a*, Tectonic elements such as trace of subduction zone, backarc spreading centre, and fault systems compiled from the earlier studies<sup>2,8</sup> are superimposed on topographic map generated using digital data base<sup>19</sup>. *b*, Enlarged portion of study area with earlier suggested<sup>2</sup> spreading centre configuration.

CMT solutions indicate normal fault type and agree well with the dominant normal fault solutions for the events along the spreading centres<sup>8</sup>.

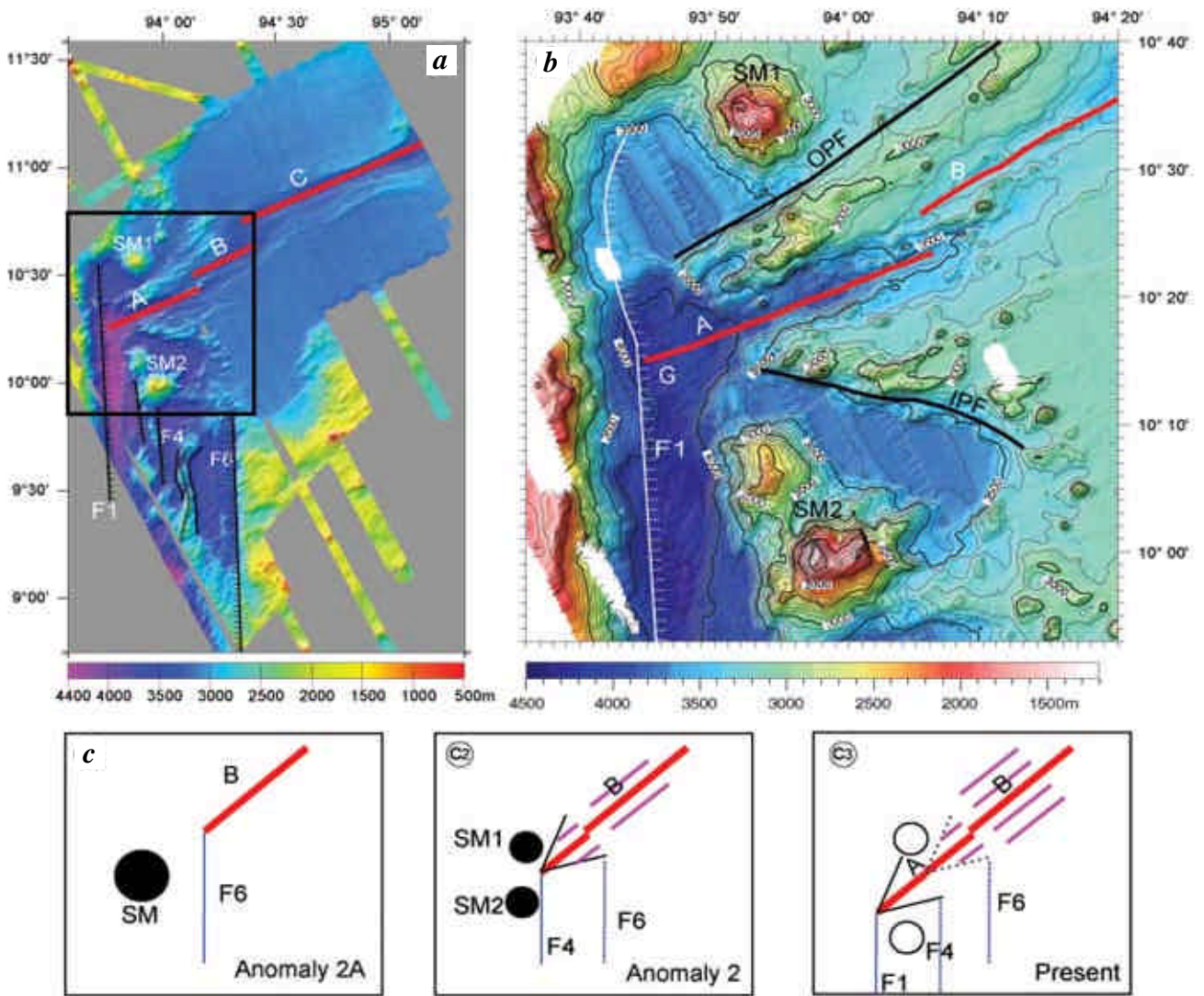
Magnetic anomalies in the region are affected by the complex bottom topography and arc volcanism in the western domain and by the effect of thick pile of sediments in the eastern part of the study area. High-amplitude anomalies are observed over the spreading segment A, arc-parallel seamounts and NS trending fault systems dominate this sector. Moderate-amplitude anomalies akin to the lineated seafloor spreading anomalies are noticed over the spreading segment and segment C is devoid of any significant anomaly signatures<sup>8</sup>. These varied signatures represent anomalies that resulted from the seafloor spreading under peculiar geodynamic conditions characteristic of marginal basins<sup>10-12</sup>. Variable half-spread rates of 1.90 cm/yr up to anomaly 2 and 0.80 cm/yr beyond anomaly 2 were assigned<sup>8</sup>.

Oblique trend of the identified magnetic lineations on either side of segment B, absence of identifiable anomalies on segment A, together with the topographic fabric (Figure 2*b*) and termination of the spreading segment at the west Andaman fault, suggest westward propagation of the spreading centre. It is probable that the near N–S trending fault systems (Figure 2) acted as migrating transforms leading to the formation of instantaneous transform zones<sup>13</sup>, at different phases of evolution of the basin in conjunction with the westward propagation of the spreading centre. In such an evolutionary scheme, the seamounts SM1 and SM2 may have been parts of a single complex, formed on the arc, and were split and moved apart by the propagating rift. A schematic representation of the sequence of propagation since anomaly 2A is depicted (Figure 2*c*). At the time of anomaly 2A, segment B may have been the western-

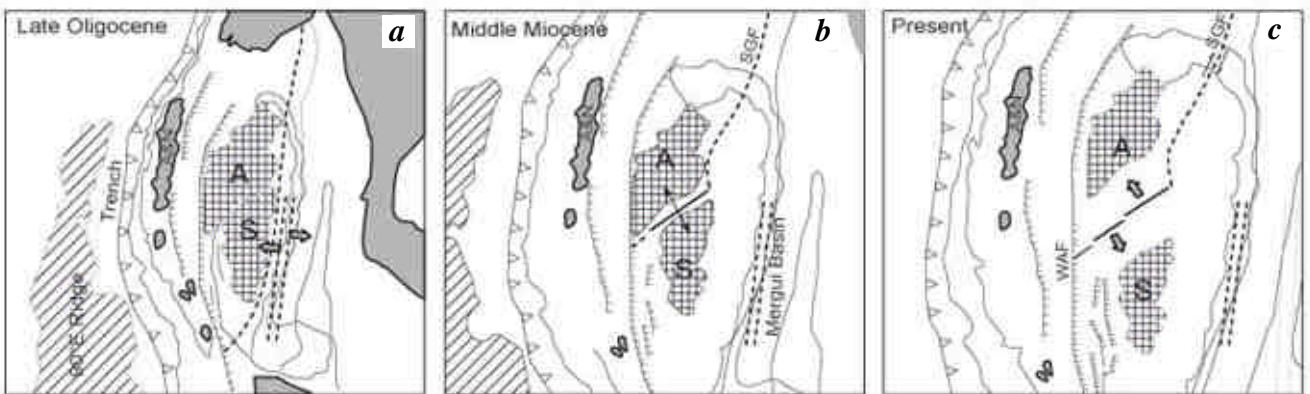
most segment of the spreading centre and was connected to the Semangko fault of Sumatra through the transform fault F6. By the time of anomaly 2, the propagator would have reached 94°E and the fault F4 represents the transform connecting to the Semangko fault. One more step of propagation to the west results in the present configuration, with the west Andaman fault, F1 as the active transform. The strike-slip solutions of the events at the southern portion of the west Andaman fault<sup>8</sup>, are the manifestation of the current motion. The propagation model suggests that the seamounts SM1 and SM2 are split by the propagator and emplaced on either side of the spreading segment A, the assumption here is that these seamounts are older than anomaly 2.

Three spreading segments characterize the backarc spreading ridge with distinct topographic and magnetic signatures in the SW and NE parts. Westward propagation of the spreading centre since anomaly 2A time (~3 m.y.) modulated the crust resulting in fan-shaped topographic fabric. The backarc spreading centre aligns along the plane joining the major regional fault system, the Sagaing fault in the north and the Semangko fault system of Sumatra in the south. The oldest identifiable magnetic anomaly (anomaly 3) in the region dates back to about 4 Ma. The revised scheme of evolution suggests the existence of thick sediments in the NE portion of the spreading axis prior to the commencement of true seafloor spreading. In the western portion, arc volcanism promoted general uplift and gave rise to several topographic highs, which prevented the deposition and in-fill of sediments.

Results from the ODP site 768 provide extensive account of the India–Asia convergence tectonic phases that followed the initial intercontinental under-thrusting<sup>14</sup>. One



**Figure 2.** *a*, Colour-coded image of seafloor generated from swath bathymetry along with major tectonic elements. A, B, C Spreading centre segments; G, Graben adjacent to the West Andaman Fault, F1, F4, F6, N-S fault systems. Box indicates the region shown in *b*. *b*, Seabed image depicting the seafloor fabric highlighting westward propagation of spreading centre. *c*, Propagation model depicting phases of westward propagation of spreading rift.



**Figure 3.** Schematic representation of three-phase tectonic evolutionary model for evolution of Andaman backarc basin. A and S, Alcock and Sewell seamount complexes, A&N, Andaman–Nicobar Islands; SGF, Sagaing Fault System; WAF, West Andaman fault.



of the fundamental tectonic phases of the India–Asia convergence is the Neogene evolution of the wider Himalayan region representing the initial uplift of the Higher Himalayas shortly after the Latest Oligocene to Early Miocene initiation of intercontinental under-thrusting<sup>15</sup>. We suggest that this extrusive tectonic phase initiated influx of enormous amount of sediments into the Martaban shelf and further south, and also altered the kinematics by prompting the initiation of extensional activity along the fault connecting the Sagaing and Semangko fault systems. This extensional activity during the Early/Middle Miocene period initiated separation of the Alcock and Sewell seamount complexes.

A proto Andaman Sea was suggested to have existed as an extensional basin in place of the present Mergui–North Sumatra basin during the Early Miocene period and the activity got abandoned during Middle Miocene and shifted westward<sup>2</sup>. We propose that the extensional regime has shifted to the west, probably as a consequence of the Early Miocene intercontinental underthrusting, to a location between the Alcock and Sewell seamount complexes. Subsequently, a phase of rifting has taken place between the Alcock and Sewell seamount complexes during the Middle Miocene up to Early Pliocene (about 4 Ma). During this phase, development/joining of several regional faults such as the West Andaman Fault and fault systems west of Sewell seamounts has taken place and resulted in the formation of a linked system. During these phases of extension and rifting, and later, the region was under the influence of rapid sediment influx from the north and arc volcanism east of the Andaman–Nicobar ridge. The arc volcanism promoted uplift of the western domain<sup>12</sup>, while the eastern part underwent subsidence. Seafloor spreading commenced at about 4 Ma, resulted in further separation of the Alcock and Sewell seamounts and formed the deep basin. The spreading centre jump, initial rifting separating the Alcock and Sewell rises, and the commencement of extension through true seafloor spreading are considered as the principal phases of evolution of the Andaman backarc basin since Late Oligocene, in the proposed scheme (Figure 3). During Late Oligocene, the Sagaing Fault System was connected to the spreading system east of the Alcock and Sewell seamount complexes and joined to the fault system NW of Sumatra. In the later phase, the spreading centre has jumped to west and north to a plane between the Alcock and Sewell seamounts and initiated separation of the seamount complexes. Phases of extension and rifting have taken place between Middle Miocene and Early Pliocene. Joining of the West Andaman fault and Sumatran Fault took place at about 4 Ma<sup>16</sup>. The third phase involved the commencement of seafloor spreading and extension by true seafloor spreading during the past 4 Ma, resulting in the present configuration of the deep Andaman backarc basin.

Active backarc spreading around 4–5 Ma<sup>8</sup> was related to subducting slab deformation derived from seismotectonic information<sup>17</sup>. A broad two phase evolution with com-

ponents of extension and rifting and extension through seafloor spreading were suggested as the two main phases of evolution of the Andaman Sea<sup>17</sup>. Recent study by Curray<sup>18</sup> provided a complete and detailed account of evolution of the Andaman Sea since Early Oligocene. Our study agrees broadly with the scheme of evolution proposed by Curray<sup>18</sup> and differs in the timing of initial separation of Alcock and Sewell seamount complexes, which remains speculative; and in the proposition of propagation of the spreading rift. Based on high-resolution studies carried out, coupled with the inferences derived from recent investigations, we suggest that the evolution of the Andaman backarc basin since Late Oligocene resulted from three principal phases; (i) spreading centre jump and initial extension; (ii) extension and rifting and (iii) extension through seafloor spreading. The third phase involved westward propagation of the spreading rift since anomaly 2A.

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## Whole-earth decompression dynamics

**J. Marvin Herndon**

Transdyne Corporation, 11044 Red Rock Drive, San Diego, CA 92131, USA

**The principles of whole-earth decompression dynamics are disclosed leading to a new way to interpret whole-earth dynamics. Whole-earth decompression dynamics incorporates elements of and unifies the two seemingly divergent dominant theories of continental displacement, plate tectonics theory and earth expansion theory. Whole-earth decompression is the consequence of earth formation from within a Jupiter-like protoplanet, with subsequent loss of gases and ices and concomitant rebounding. The initial whole-earth decompression is expected to result in a global system of major primary decompression cracks appearing in the rigid crust, which persist as the basalt feeders for the global, mid-oceanic ridge system. As the earth subsequently decompresses, the area of the earth's surface increases by the formation of secondary decompression cracks, often located near the continental margins, presently identified as oceanic trenches. These secondary decompression cracks are subsequently in-filled with basalt, extruded from the mid-oceanic ridges, which traverses the ocean floor by gravitational creep, ultimately plunging into secondary decompression cracks, emulating subduction.**

e-mail: mherndon@san.rr.com

**Much of the evidence presented in support of plate tectonics supports whole-earth decompression dynamics, but without necessitating mantle convection/circulation or basalt recycling. Moreover, unlike in earth expansion theory, the timescale for earth decompression is not constrained to the last 200 million years, the maximum age of the current ocean floor.**

**Keywords:** Decompression cracks, earth dynamics, mid-oceanic ridges, oceanic basalt, plate tectonics.

FOR more than a century, scientists have recognized that opposing margins of continents fit together in certain ways and display geological and palaeobiological evidence of having been joined in the past. In the nineteenth century, Suess<sup>1</sup> envisioned a vast palaeocontinent that had broken up and partially subsided into the ocean floor. His concept was subsequently recognized as untenable, because continental rock is less dense than ocean floor basalt. Early in the twentieth century, Wegener<sup>2</sup> also proposed that the continents at one time had been united, but subsequently had separated and drifted through the ocean floor to their present positions. Wegener's theory of continental drift, generally not accepted for half a century, was revived in the 1960s, mainly as the result of investigations of oceanic topography<sup>3–6</sup>, palaeomagnetism<sup>7–9</sup>, and seismology<sup>10</sup>, and modified to become the plate tectonics theory.

Widely accepted at present despite certain unfounded fundamental assumptions, plate tectonics theory is predicated upon the idea that the ocean floor, continuously produced at mid-oceanic ridges, moves like a conveyer belt, ultimately being subducted and recirculated by assumed convection currents in the mantle<sup>11–13</sup>. Indeed, compelling evidence (e.g. seafloor magnetic striations) exists to support the idea of the seafloor being continuously produced at mid-oceanic ridges, moving away from the ridges and being subducted, for example, by entering oceanic trenches. To date, however, there is no direct unambiguous evidence that mantle convection and/or mantle circulation actually takes place; in fact, there is some evidence to the contrary<sup>14</sup>. Moreover, there is no evidence that oceanic basalt can be repeatedly recycled through the mantle without being substantially and irreversibly changed. Yet, mantle convection/circulation and basalt recycling are fundamental necessities for the validity of plate tectonics. Furthermore, plate tectonics theory does not provide an energy source for geodynamic activity.

In 1933, Hilgenberg<sup>15,16</sup> first published his observation that on a sphere with a radius of about one half of the earth's present radius, the continents more or less fit together like pieces of a jigsaw puzzle and, notably, form a uniform, continuous shell. Ideas that at some time in the past the earth's radius was significantly less than its present value and that the separation of the continents occurs as a consequence of volume expansion of the earth have been discussed for more than half a century<sup>17–21</sup>. As an alternative to plate tectonics theory, classical earth expansion theory, as