The supercontinent medley: Recent views

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> *'Punarapi jananam,*
> *punarapi maranam,*
> *punarapi jananijatare sayanam'*
> — Bhaja Govindam
>
> (Birth again, death again, repose again in mother's womb)

The above lines by the 6th century AD saint and thinker Sankara describing the human cycle of birth, death and rebirth seems applicable to earth's continents too, which also pass through cycles of birth as new crusts, growth to become continents, breakup, subduction and rest in the depths of earth, and rebirth again as fresh crusts. It took more than 100 million years of cooling of the earth before the early formed crusts could stay stable, escape recycling back into the mantle, collide with similar crusts and finally emerge out of the primeval ocean to form a microcontinent. Our ideas about the past history of continents stem from studies on several orogenic belts around the world formed by the collision of continental blocks, as well as from data on stabilization ages of very old cratonic segments combined with palaeomagnetic results and also from the existence of common lithology and fossils in continents now far apart.

An early model on the growth of earth's crust visualizes a decreasing rate of recycling of new crusts with time, enabling earth to achieve a production rate balancing the recycling-loss and maintaining a steady state system[1]. Another model conceived a steady crustal growth through time with occasional bursts in its production, while a few others emphasized recycling of crusts, and some considered recycling unimportant[2–4]. Recent contributions on mantle chemistry, particularly on Sr, Nd, Hf, Nb and Pb isotopes, and the progressive depletion of uranium and a few incompatible trace elements, have indicated stepwise extraction of continental crust leaving an increasing volume of depleted mantle[5,6]. Since the 1970s, the application of seismic tomography to study mantle revealed the subducting crustal slabs penetrating the 660 km discontinuity (a thermal transition zone separating the upper and lower mantle), and reaching deep into the lower mantle, contrary to the belief that they stop at this discontinuity. This was taken to imply a mixing of the two mantle zones, a revelation that heralded revisions to accepted mantle structure from the two-layered convection mode to single whole mantle convection. In the wake of this new thinking, Stein and Hoffmann[4] reasoned that episodes of crust-generation arose whenever the subducted continental slabs which were piled up at the 660 km barrier sank catastrophically deep into the lower mantle and modified the prevailing layered mantle convection temporarily to whole mantle convection. Such episodes, they concluded, promoted plumeheads to rise from the core-mantle boundary (D'' layer) carrying fresh crusts with replenishments to the depleted upper mantle.

Modelled on the ideas of changing mantle convection, Condie[3] inferred major episodes or superevents of catastrophic slab sinking or 'slab avalanching' as he calls it, at 2.7, 1.9 and 1.2 Ga, and minor ones in late Palaeozoic and mid-Cretaceous, the last two less intense due to changed thermal state of the mantle (i.e. decrease in Rayleigh number) making the 660 km junction more permeable. Condie associated these events with excessive juvenile crust production, an inference supported by the abundant zircon ages clustering at these time intervals and also by the Nd isotopic data of the periods. He argued that the synchronous incidence of several geological events like rise in sea level (inferred from intracratonic, passive and platform sediments), abundance of black shales, banded iron deposits and phosphorites as well as initiation of warm climate spells during the 2.7 and 1.9 Ga due to enhanced CO_2 accumulation are additional evidences[7].

Condie[8] has modelled two modes of supercontinent formation: (1) A sequential cycle lasting for 600–800 million years commencing with (a) the breakup of an already existing supercontinent and the initiation of slab avalanching followed by (b) immense plume-delivered fresh crusts to form a new supercontinent; (c) with the arrival of slabs deep into the lower mantle (at the D'' layer), fresh crusts underplate the continent's lithosphere and thermally insulate its mantle below. This facilitates heat buildup elsewhere forcing (d) mantle upwellings to break the new supercontinent and the cycle gets repeated. (2) Secondly, Condie envisages formation of a supercontinent by the merger of another large continent without itself undergoing fragmentation, e.g. growth of Pangea (450–250 Ma) to which Gondwana joined without fragmentation. The 2.7 Ga superplume event is believed to be associated with the first supercontinent through collision of thick oceanic crusts (evident from strong oceanic geochemical affinities of the Archaean greenstones), >2.7 Ga continental crusts and oceanic arcs, aided by a relatively buoyant thick subcontinental mantle lithosphere[2,3,9].

An evaluation of crustal growth through time has indicated that periods of major crustal growth and assembly of supercontinents seem to be related and nearly a dozen small and big continents, including a few submerged microcontinents, have formed, parted and reassembled[2]. The reconstruction of continents and supercontinents prior to about 1000 Ma has involved much speculation in the past, but data from several recent studies have now narrowed down many of the ambiguities. The earliest assembly, around ~3 Ga, called Ur (Figure 1 *a*) took place by the integration of some of the oldest cratons in Africa (Kaapvaal), India (Western Dharwar, Singhbhum and probably Eastern Dharwar and Bhandara–Bastar), Australia (Pilbara) and lesser known cratons in Eastern Antarctica with subsequent accretion of Zimbabwe craton to Kaapvaal and Yilgarn craton to the Pilbara craton by ~ 2.5 Ga (ref. 10). The younger continent Arctica[11] (Figure 1 *b*), was a clump of ancient cratons of Canadian Shield (also referred as Kenorland continent), Greenland, Siberia and Wyoming craton in North America (Figure 1 *b*). The continent Nena (for northern Europe and North America) (Figure 1 *c*) was formed around ~ 1.8 Ga, by fusion of parts of ~ 2 Ga old Baltic and Ukranian cratons with equally old cratons along the east-

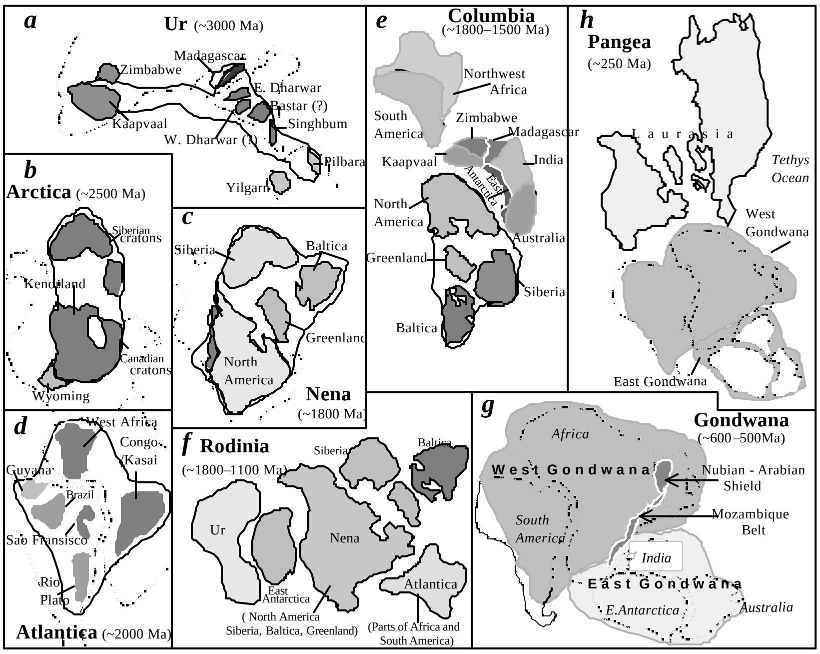

Figure 1. Supercontinents and large continental assemblies in earth's past (adapted from Rogers and Santosh[10,12]).

ern margin of Greenland and North America (Arctica). Another early continent Atlantica[11] (Figure 1*d*) (so named because it opened up to form the southern Atlantic Ocean[10]) was made out of cratons having similar geologic sequences in West Africa and N. E. South America that stabilized around ~2.1–2.0 Ga.

Recently, Rogers and Santosh[10,12] have inferred that a major supercontinent – Columbia (Figure 1*e*) that carried all of earth's continental blocks between 1.9 and 1.5 Ga existed even prior to Rodinia, the supercontinent so far considered the earliest one. They have based Columbia's existence (i) on the fit of mid-Proterozoic rift valleys in Eastern India with the rifts of Columbia region in North America (ii) from the presence of ~2.0 Ga fluvio-deltaic deposits in all cratonic blocks in South America and West Africa, and (iii) from the occurrence of petrologically and magnetically similar rocks over thousands of kilometers between Arizona and Western Russia[13]. Columbia, supposed to be a composite of Ur, Arctica, Nena, Atlantica, and created during 2100–1800 Ma global orogeny, fragmented between 1.6 and 1.4 Ga and separated Atlantica from Nena. This fragmentation is considered an outcome of relaxation of horizontal stresses, which were associated with formation of Mesoproterozoic rift valleys in India, Antarctica and North America. Such rift valleys in India are the Mahanadi, Godavari–Pranhita (now filled by younger age sediments) and the concealed rifts – Kurudvadi and Kalyana, inferred seismically to lie below the Deccan lavas. These are equated in all spatial dimensions with rifts of similar ages in Antarctica (Lambert rift) and North America (Belt, Unita rifts) which also display coeval orogenic and magmatic events besides similar gravity and magnetic structure[12,14].

The fragments of Columbia reassembled as Rodinia (Figure 1*f*) around 1100–1000 Ma. According to most favoured configurations[10,12,15–18], referred to as SWEAT (Southwest US–East Antarctica), Atlantica rotated and collided with Nena, while the expanded Ur parted from their Columbian configuration adjoining North America. However, since the reconstruction of Rodinia has been based on scant data of paleolatitudes of a few assembled members, it has given rise to some alternate models such as suturing of Eastern Australia to western North America[19], Siberia positioned adjoining western North America[20]; and of India, Madagascar, Seychelles, Siberia and South African cratons in positions differing from established Rodinia structure[21]. Based on palaeomagnetic data, a paleo-Pangean supercontinent with parts of Atlantica, Ur, and Arctica (East Gondwana-West Gondwana-Laurentia) has also been proposed[22]. In fact, recent studies have indicated that at least seven independent continents or microcontinents must have existed around 750 Ma (ref. 21). For example, the prevalence of common geological features like crustal stress patterns, rifts and magmatic events (coinciding Malani magmatism, 800–700 Ma) in NW India, Iran, Nubian-Arabian Shield, Seychelles, Madagascar, and Somalia have prompted the view that these lands must have been part of a single large landmass – the Malani supercontinent, which later accreted to Rodinia[23,24].

The northern portion of Rodinia began breaking up between 800 and 750 Ma, around which time, rifting commenced in southern Rodinia. According to Condie[18], neither the breakup of Rodinia nor its formation witnessed any unusual rates of juvenile crust production (except for a few ophiolites during Pan-African orogeny) as in the earlier superevents at 1.9 and 2.7 Ga, and hence he feels that supercontinent cycle need not always be associated with such superevents. Dalziel[25] has speculated brief existence of a supercontinent – Pannotia, during late Neoproterozoic, evolved from collision of fragmented parts of Rodinia (Baltica, Laurentia, and Siberia) with Gondwana during 580–540 Ma. Pannotia fragmented in the final phase of Gondwana formation and this phase also marked the Cambrian explosion of skeletelized metazoans (~545–500 Ma). The period was notable for global tectonic changes like the opening up of Pacific Ocean basin, erosion of orogens, oceanic spreading ridges and subduction zones[8,25]. The split of Pannotia was initiated by oceanic spreading ridge, which separated Laurentia from Gondwana, Baltica and Siberia.

The development of Gondwana, coinciding with Pan-African orogeny, took place around 600–500 Ma through fusion of East and West Gondwana[10,26] (Figure 1*g*). East Gondwana formed around the ~3000 Ma cratonic components of Ur during mid-Proterozoic and was complete with accretion of Northern India along the Central Indian tectonic zone, Australia and Eastern Antarctica with Eastern Ghats of India. The assembly of East Gondwana is, in fact, considered polyphase and at least two main periods of orogenesis between 750–620 Ma and between 570–530 Ma are discernible and also East Gondwana was never a united continent and its assembly paralleled final assembly of greater Gondwana and did not come into existence till Cambrian[27]. West Gondwana was predominantly made up of ~ 2000 Ma cratons of Atlantica, younger crusts of Kalahari–Congo cratons and Arabia (Nubian–Arabian shield) around 870–750 Ma. The East and West Gondwana collided during the Pan-African orogeny and the NW–SE trending Achchan Kovil shear zone in southern India is thought to be part of their suture which is considered to extend from Mozambique Belt to Maud Land in Antarctica. The Pan-African orogeny had also resulted in high-grade metamorphism, production of juvenile magmas, and mineralization of rare metals, humite-bearing marbles and gem stones and this orogeny is supposed to have brought about the accretion of granulite blocks in Southern India, south of Palghat–Cauvery shear zone to Archaean cratons lying to the north[10,26–29].

Pangea (Figure 1 *h*), the youngest supercontinent, began forming around ~ 450 Ma and was complete in late Palaeozoic (~ 250 Ma). It was a composite of Gondwana on its south and an already existing large continental fragment Laurasia (North America, Greenland, and Europe with accretion of some segments of Asia) on its north and it stretched N–S 15,000 km and E–W 8000 km covering all climatic zones, polar to equatorial[8,10]. According to Condie[8], Pangea was actually a continued growth of Gondwana and the latter did not fragment before merging with Pangea. In his opinion, small supercontinents, unlike the larger ones, fail to fragment completely due to insufficient thermal shielding of the mantle and consequent absence of upwelling to breakup the lithosphere of the supercontinent. But, Santosh doubts this view since the breakup of Columbia, a pre-Rodinian supercontinent, which was one of the two largest supercontinents, failed to produce plume upwellings. Even though thermal shielding beneath Pangea and associated plume activity may have initiated the breakup, there is also the view that slab pull force, combined with deep mantle convection flows, could as well be the main force behind the breakup[30].

The rifting of Pangea at ~ 170 Ma formed the northern continent Laurasia (North America, Europe and Asia) and a southern continent Gondwanaland (South America, Africa, India, Australia and parts of Antarctica and Southeast Asia), the Tethys Ocean forming between them. By ~ 100 Ma, as North America drifted away from Africa, the Central Atlantic Ocean began forming and is still growing. This drift brought about the closure of the Tethys Ocean, leaving Mediterranean, Caspian and the Baltic seas as its relics. The Indian Ocean began forming as Australia and Antarctica rotated away from Africa. At the close of Cretaceous (~ 65 Ma), Africa had rejoined Eurasia, the Indian subcontinent began heading northwards and collided with Asia and the present day pattern of continental distribution began shaping.

Several continental plate collisions, which may represent the beginnings of a new supercontinent paralleled the breakup of Pangea like the China/Mongolia–Asia (150 Ma), West Burma–South Asia (130 Ma), Lhasa–Asia (75 Ma), India–Asia (55 Ma), Australia–Indonesia (25 Ma) and several lesser scale collisions along the Pacific margins of Asia and North and South Americas between 150 and 80 Ma (refs 8, 9). In the next 50 million years, it is expected that Atlantic Ocean will stop expanding and develop subduction zone along its passive margins. Global increase in the tectonism will be active along the eastern continental margin of USA, Western Europe and West Africa and a new sea will come into existence in East Africa, and Australia is expected to cross the equator and once again continents will collide and form a single large supercontinent and resume the supercontinent cycle[31].

Considerable debate has now centered around the role of mantle plumes in triggering breakup of large continents, especially those that existed during the last one billion years, when the mantle's heat potential (Rayleigh number) was decreasing. Many doubt the ascent of plumes above the 660 km barrier where the prevailing physico-chemical conditions would tend to impede their buoyant movement further upwards. Advocates of non-plume processes have pointed out how the separation of Australia and Antarctica from Gondwana took place without any plume-related magmatism. Quite a few agencies have been identified for the continental fragmentation like plate-boundary driving forces, prevalent plate tectonic dynamics or combination of the latter and mantle upwelling from transition zone as well as from core-mantle boundary[32–34]; and their movements or migrations are not only due to plate tectonism but also induced by earth's centrifugal forces correcting the imbalanced continental mass distribution (true polar wander or TPW)[35,36]. It is obvious that there are several geological processes that could fragment and shift the continents, but their potential to do so appears to vary with time. Processes that have been very effective during early earth times seem to be less dominant in later geological periods, a feature that possibly has fuelled the current debate. Only the on-going studies on changing mantle dynamics, its thermal evolution, precise dates and possible revision of palaeolatitudes through more palaeomagnetic data could resolve some of the uncertainties and help understand the supercontinent medley.

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1. Armstrong, R. L., *Philos. Trans. R. Soc., London*, 1981, **A301**, 443–472.
2. Taylor, S. R. and McLennan, S. M., *Rev. Geophys.*, 1995, **33**, 241–265.
3. Condie, K. C., *Tectonophysics*, 2000, **322**, 153–162.
4. Stein, M. and Hoffmann, A. W., *Nature*, 1994, **372**, 63–68.
5. McCulloch, T. M. and Bennet, V. C., *Geochim. Cosmochim. Acta*, 1994, **58**, 4717–4738.
6. Sylvester, P. J., Campbell, I. H. and Bowyer, D. A., *Science*, 1997, **275**, 521–523.
7. Condie, K. C., Des Marais, D. J. and Abbot, D., *Precambrian Res.*, 2001, **106**, 239–260.
8. Condie, K. C., *J. African Earth Sci.*, 2002, **35**, 179–183.
9. Condie, K. C., *Earth Planet. Sci. Lett.*, 1998, **163**, 97–108.
10. Rogers, J. J. W. and Santosh, M., *Gondwana Res.*, 2003, **6**, 357–368.
11. Rogers, J. J. W., *J. Geol.*, 1996, **104**, 91–107.
12. Rogers, J. J. W. and Santosh, M., *Gondwana Res.*, 2002, **5**, 5–22.
13. Zhao, G., Cawood, P. A., Wilde, S. A. and Sun, M., *Earth Sci. Rev.*, 2002, **59**, 125–162; Zhao, G., Suna, M. and Wildeb, S. A., *Precambrian Res.*, 2003, **122**, 201–233; Piper, J. D. A., Mallik, S. B., Bandyopadhyay, G., Mondal, S. and Das, A. K., *Precambrian Res.*, 2003, **121**, 185–219; Rosen, O. M., *Russian J. Earth Sci.*, 2002, **4**, 1–6.
14. Mishra, D. C., Chandrasekhar, D. Ch., Venkata Raju, V. and Vijaya Kumar, V., *Earth Planet. Sci. Lett.*, 1999, **172**, 287–300.
15. Dalziel, I. W. D., *Geology*, 1991, **19**, 598–601.

16. Hoffman, P. F., *Science*, 1991, **252**, 1409–1412.
17. Moores, E. M., *Geology*, 1991, **19**, 425–428.
18. Condie, K. C., *Gondwana Res.*, 2001, **4**, 154–155.
19. Karlstrom, K. E., Harlan, S. S., Williams, M. L., McLelland, J., Geismann, J. W. and Ahall, A. I., *GSA Today*, 1999, **9**, 1–7.
20. Sears, J. W. and Price, R. A., *Gondwana Res.*, 2002, **5**, 35–39.
21. Torsvik, T. H., *Science*, 2003, **300**, 1379–1381.
22. Piper, J. D. A., *Earth Planet. Sci. Lett.*, 2000, **176**, 131–146.
23. Kochhar, N., Abstract, International Symposium on Assembly and Breakup of Rodinia and Gondwana and Growth of Asia, Osaka, October 2001.
24. Torsvik, T. H., Ashwal, L. D., Tucker, R. D. and Eide, E. A., *Precambrian Res*., 2001, **110**, 47–59.
25. Dalziel, I. W. D., *Bull Geol. Soc. Am.*, 1997, **109**, 16–42.
26. Pradeepkumar, A. P. and Krishnanath, R., *J. Geodyn*., 1999, **4**, 1–20.
27. Meert, J. G., *Tectnophysics*, 2003, **362**, 1–40.
28. Santosh, M., Yokoyama, K., Biju–Sekhar, S. and Rogers, J. J. W., *Gondwana Res*., 2003, **6**, 29–63.
29. Santosh, M., Yoshida, M. and Yoshikura, S., *Gondwana Res*., 2001, **4**, 766–768.
30. Collins, W. J., *Earth Planet. Sci. Lett*., 2003, **205**, 225–237.
31. Lunine, J., *Earth, Evolution of a Habitable World*, Cambridge University Press, Cambridge, 1999, p. 319.
32. Storey, B. C., *Nature*, 1995, **377**, 301–308.
33. Machetel, P. and Humler, E., *Earth Planet. Sci. Lett*., 2003, **208**, 125–133.
34. Storey, B. C., Alabaster, T. and Pankhurst, P. J., *Geol. Soc. London, Spl. Paper*, 1992, **68**, p. 404.
35. Evans, D. A., *Tectonophysics*, 2003, **362**, 303–320.
36. Kirschvink, J. L., Ripperdan, R. L. and Evans, D. A., *Science*, 1997, **277**, 541–545.

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SCIENTIFIC CORRESPONDENCE

Pretending to be a predator: Wasp-like mimicry by a salticid spider

Prey–predator interactions often elicit life-saving adaptations in the prey. While some predators have evolved methods for efficient prey catching, many prey species have evolved methods to protect themselves. Mimicry is one of them. Batesian mimicry is characterized by the occurrence of traits in an animal that make them appear unpalatable. Camouflages of various kinds are known. However, occurrence of traits mimicking the predator's features itself is unknown. Here we report such a case in a spider belonging to family Salticidae (jumping spiders).

Spiders do camouflage like other objects or animals, including ants, twigs, bird droppings and bark of a tree. The crab spider *Misumena vatia* (Thomisidae) can change its colour from yellow to white and vice versa[1] to hunt efficiently. Spiders (Araneae) and members of Hymenoptera do interact, and the mimicry of a major group of Hymenoptera – ants, by spiders is well documented. Some members of the family Salticidae and Clubionidae are ant mimics and 28 ant-mimicking spiders of the genus *Myrmarachne* (Salticidae) are reported from India[2]. The body segments of such mimics are structured to give an appearance of a three-segmented (head, thorax and abdomen) body pattern from a typical two-segmented (cephalothorax and abdomen) arachnid body plan. Apart from the body segments, the Chelicerae are also modified for mimicking. Some of them are known to co-exist with ants. Thus they protect themselves, as ants have very few predators. Wasps, which are another major group of Hymenoptera, are important predators of spiders. Wasps belonging to families Sphecidae and Pompilidae, provide spiders to their developing larvae as food[3]. Pompilidae lay eggs on one spider, which becomes the larval host, while Sphecidae provides 10–40 paralysed spiders, which are often immature forms, in their larval cell. Immature spiders are hunted and stored in the larval cells possibly because of the small size that allows them to be carried and due to their abundance. We have observed such larval cells of a Sphecid wasp which is yet to be identified by us, often occupying pre-existing cavities or discarded polyethylene tubing (3–4 mm diameter), to contain 10 to 22 immature salticid spiders belonging to two or three genera (*Plexippus*, *Phidippus* and *Metaphidippus*). Observations on 14 such cells have revealed immature forms of Salticidae only and no other spider family. The paralysed preys show signs of blood circulation as cardiac activity could be observed under a stereomicroscope, and sporadic leg movements could also be seen. The larva of the wasp can be seen wriggling inside these spiders. The older forms come out of the dead prey. Identification of prey species is inconclusive as they are immature specimens. The preference to Salticidae members, however, is striking. Thus, some wasp species exclusively hunt young salticids.

We have collected two male specimens of a salticid, which we identify as *Rhene danielli* (Tikader) (Figure 1*a*) based on the description of a male holotype by Tikader[4]. The specimens are 5.4 mm long with the cephalothorax measuring 2.2 mm and the abdomen measuring 3.2 mm in length. The noteworthy feature is the presence of a pattern outlined by yellow