ISSN 0869-5938, Stratigraphy and Geological Correlation, 2009, Vol. 17, No. 3, pp. 259–274. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © S.V. Bogdanova, S.A. Pisarevsky, Z.X. Li, 2009, published in Stratigrafiya. Geologicheskaya Korrelyatsiya, 2009, Vol. 17, No. 3, pp. 29–45.

# Assembly and Breakup of Rodinia (Some Results of IGCP Project 440)

**S. V. Bogdanova[a], S. A. Pisarevsky[b], and Z. X. Li[c]**

[a] *Department of Geology, Lund University, Sweden*
[b] *School of GeoSciences, University of Edinburgh, Great Britain*
[c] *Department of Applied Geology, Curtin University of Technology, West Australia*

Received October 1, 2007; in final form, July 23, 2008

**Abstract**—The principal results of project 440 "Assembly and Breakup of Rodinia" of the International Geological Correlation Programme (IGCP) are reviewed in this work. A map of that supercontinent compiled using geological and paleomagnetic data describes global paleogeography 900 Ma ago. The assembly of Rodinia, which comprised most of Precambrian continental blocks, lasted ca. 400 m.y. (from 1300 to 900 Ma). Its breakup presumably triggered by mantle superplume took place between 830 and 650 Ma. The correlation between tectonic events in different continental blocks is considered. Some problems concerning the Rodinia reconstruction and history, e.g., the slow growth of juvenile crust and effects of mantle-plume events during the amalgamation period and of glaciations at the breakup time, are discussed. The latter caused changes in the biosphere and climate, whereas postglacial periods stimulated progress in biota evolution.

**DOI:** 10.1134/S0869593809030022

*Key words*: Mesoproterozoic, Neoproterozoic, Rodinia, paleogeographic reconstruction, supercontinent, mantle plume, and glaciation.

## INTRODUCTION

The idea of a supercontinent's existence in the terminal Precambrian originated in the 1970s as a result of attempts to explain the explosion of life on the Earth and great diversity of life forms at the commencement of the Paleozoic (Valentine and Moores, 1970; Piper, 1976; McMenamin and McMenamin, 1990). In last-named work, the supercontinent was termed Rodinia for the Russian word "rodina" (giving birth), as it was parental for the subsequent Gondwana. The hydrosphere surrounding Rodinia was named the Mirovoi (worldwide) Ocean.

A keen interest to Rodinia in the 1990s was associated with the search for geological and paleomagnetic evidence of that continent's existence. In initial reconstructions suggested at that time, the disposition of building blocks in the supercontinent was interpreted controversially (Dalziel, 1991, 1997; Hoffman, 1991; Moores, 1991; Weil et al., 1998). To a considerable extent, this was a consequence of the deficiency in confident geochronological and paleomagnetic data on most continents that even put in doubt the supercontinent's existence itself (see review in Powell and Meert, 2001).

The International Geological Correlation Programme (IGCP) aimed its project 440 "Assembly and Breakup of Rodinia" at testing the hypothesis, and a great amount of new data collected since 2000 facilitated the compilation of the Geodynamic Map of the Rodinia Supercontinent (Li et al., 2008). The map summarized the available geological and paleomagnetic data on the Meso and Early Neoproterozoic evolution of each building block assembled in Rodinia whose existence time is constrained between 1600 and 700 Ma. Being a result of a collective study that involved many researchers, the map contains compromises, and there remain alternative viewpoints on some of its details.

In this work, we consider the principal results of IGCP project 440 and problems concerning the formation and breakup of the Rodinia supercontinent. We do not intend to repeat here the geological and paleomagnetic data used to compile the Rodinia map and recently presented in a special volume of the journal "Precambrian Research" (*Testing* ..., 2008). Our objective is to show that the experience of reconstructing Rodinia can be useful, when reconstruction of older Paleoproterozoic and Archean supercontinents comes into question (Rogers, 1996; Khain, 2001; Rogers and Santosh, 2002; Bleeker, 2003).

## GENERAL PRINCIPLES OF RECONSTRUCTING THE PRECAMBRIAN SUPERCONTINENTS

There are three groups of data, which gave birth to the hypothesis postulating the existence of supercontinents in the Precambrian history of the Earth.

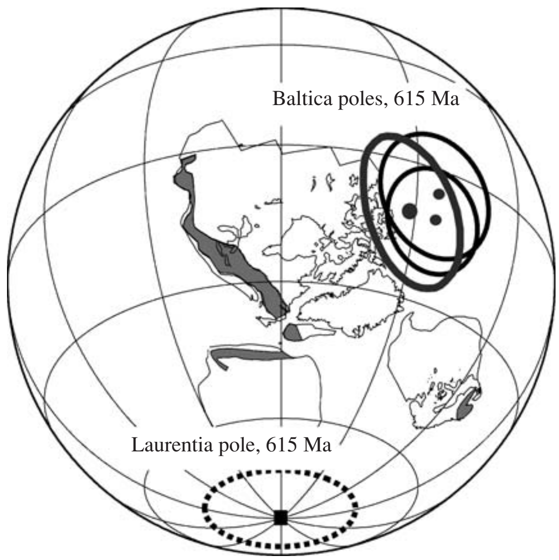


**Fig. 1.** Reconstructed paleogeographic position of Baltica and Laurentia in the Late Precambrian after Torsvik et al. (1996), Hartz and Torsvik (2002), Cawood and Pisarevsky (2006) with modifications; shadowed dark gray are collisional belts dated at 1200–900 Ma (compare with Fig. 3). Paleomagnetic poles of Baltica defined for 615 Ma plot close to the equator, which shows the incorrectness of the reconstruction. If the relative positions of Baltica and Laurentia were correct, the concurrent paleomagnetic poles of the two continents would be in proximity to each other near the Southern Pole.

Geological indications of the first group are as follows: (a) close in time collisional events manifested in most continents; (b) high peaks of juvenile crust growth in response to intense subduction; (c) lithologic and biogeochemical indicators pointing to the existence of great continental masses (high erosion rate and low sea-level, changes in the chemical and isotopic composition of seawater evidencing a considerable influx of continental material into oceans, climatic changes toward cooling, and slow evolution of life forms).

The second group includes paleomagnetic data implying the coherent drift of several continental blocks.

Data of the third group indicate breakup of giant continental masses. These are formation of large trap provinces and basic dyke swarms, sharp climatic changes, global rise of sea level because of the origin and growth of mid-ocean ridges, intense transgressions and formation of epicontinental basins, sudden increase in distribution areas of carbonate and $SiO_2$-enriched sediments, intense burial of organic matter, and abrupt diversification of biota habitats.

The reconstruction of any supercontinent should be complied with certain regulations that, taken altogether, control the correctness of its configuration, i.e., of the relative arrangement of building continental blocks. Of prime importance, therewith, are continuations of crustal structures by across boundaries of continents or their ensembles and suggesting the same geodynamic settings. Appropriate examples for the case are concurrent collisional orogens, "intercontinental" dyke swarms, epicontinental "intercratonic" sedimentary basins, and common active and passive continental margins. When neighboring continents are lacking active margins, it is possible to assume that they were parts of an earlier megacontinent. The uniformity of biologic forms on particular continents also suggests their proximity in the past, but such an approach is applicable in the Late Proterozoic reconstructions only.

Because of the similarity in the tectonic evolution of many Precambrian continents, their positioning relative to each other cannot be defined using the direct age correlation lithotectonic complexes and must be confirmed by paleomagnetic data. Despite some limitations, only the paleomagnetic method can determine at present the relative paleogeographic arrangement of two or more continents. If continents belonged to one plate, their apparent polar wander paths (APWP) should be similar. When the APWPs are comparable for all the continents, the geographic position of the latter within the supercontinent can be defined with acceptable precision (Khramov and Sholpo, 1967; McElhinny and McFadden, 2000). Unfortunately, none of the APWPs is long enough to span entirely the Precambrian because the chance that rocks retained their initial remanence during billions or hundreds million years is insignificant. The number of paleomagnetic poles established for the Precambrian is large, although not as great as for the Phanerozoic: 1111 versus 8148 (Pisarevsky, 2005). However, the available determinations do not satisfy in most cases the current criteria of their validity, as neither the initial remanence nor the dates of rocks appear to be convincingly established in most cases. The situation has considerably improved during the last few years. Although the available reliable data are still insufficient for plotting the "lengthy" APWPs, comparatively reliable segments of the paths, as long as 100–200 Ma, have been plotted nevertheless for several Precambrian continents (Laurentia, Baltica, Siberia, Kalahari, and Australia). Fortunately the Precambrian APWP plotted for Australia is consistent with the Phanerozoic APWP. In the other cases, the APWPs plotted for the Cryogenian to Cambrian period appear insufficiently reliable and controversial despite the intense work done on improving the results. On the other hand, even separate reliable paleomagnetic poles bear very important information that constrains possible reconstructions and disproves those, which are certainly incorrect. Let us consider two illustrative examples.

Torsvik et al. (1996) suggested the Late Precambrian reconstruction of Laurentia and Baltica, where the Southern Urals was connected with West Greenland (Fig. 1). Their reconstruction was based on limited, poorly dated paleomagnetic data on doleritic dykes in northern Norway and Russia (Shipunov and Chumakov, 1991; Torsvik et al., 1995). The dykes used to be regarded as the Late Proterozoic (Vendian) or Cam-

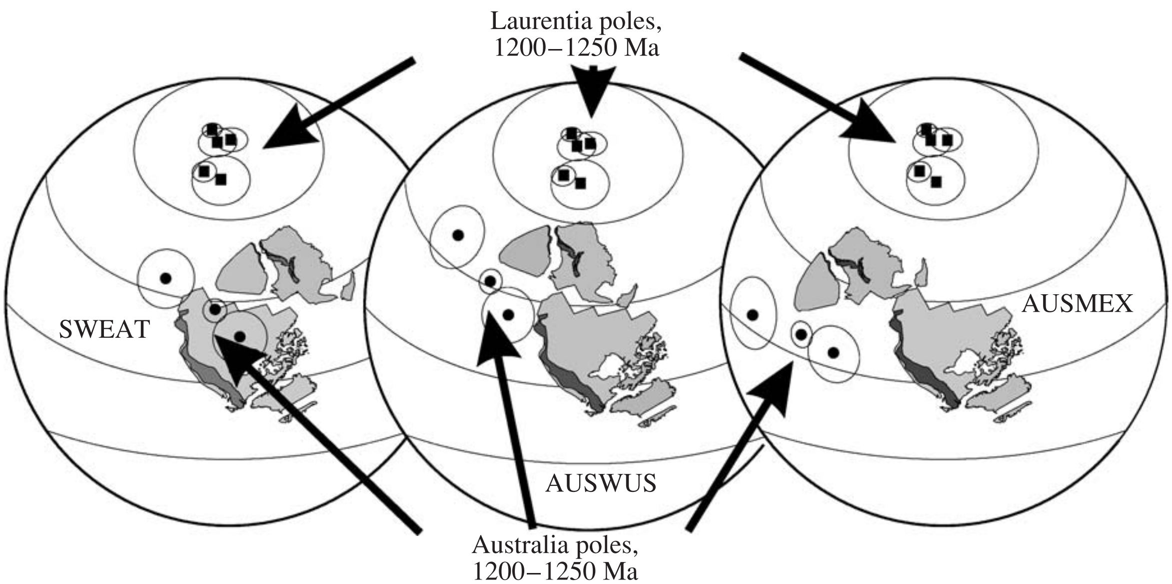


**Fig. 2.** Paleomagnetic test of Australia's and Laurentia's arrangement in different reconstructions (after Pisarevsky et al., 2003, with modifications); collisional belts dated at 1200–900 Ma are shadowed dark gray (compare with Fig. 3). As in the previous example, poles of one continent (Australia) are considerably remote from the concurrent poles of the other (Laurentia) in all the reconstructions, which are consequently incorrect for the period 1250–1200 Ma.

brian in age according to several K–Ar dates ranging from 525 ± 20 to about 580 Ma (Bekker et al., 1970; Torsvik et al., 1995; and references in these works). The subsequent Ar–Ar dating showed that at least some of the dykes correspond in age to the Devonian (Guise and Roberts, 2002). Later on, Hartz and Torsvik (2002) argued for the existence of the reconstructed configuration throughout the Meso- and Neoproterozoic. Nevertheless, their reconstruction with the curious name "Baltica upside down" contradicts meaningful geological data (see references in Cawood and Pisarevsky, 2006). In particular, researchers who compiled maps of continents for IGCP project 440 determined the Neoproterozoic passive margins on the west of Greenland and along the Uralian side of Baltica. Moreover, according to recent geological investigations in the Southern Urals (Willner et al., 2001) the passive margin was inverted into the active one at ca. 600 Ma. These results are completely inconsistent with the model by Hartz and Torsvik who postulated the intracontinental neighborhood of the Southern Urals and West Greenland until the Cambrian time of rifting and the ocean opening. New paleomagnetic and geochronological data on the Long Range dykes in Laurentia and the Egersund dykes in Baltica (Murthy et al., 1992; Kamo and Gower, 1994; Bingen et al., 1998; Hodych et al., 2004; Walderhaug et al., 2007) were used to determine the practically concurrent (615 Ma) and sufficiently reliable paleomagnetic poles. This motivated the paleomagnetic testing of different reconstructions of Laurentia and Baltica at 615 Ma. The testing showed, in particular, that the "Baltica upside down" configuration is impossible (Fig. 1).

The other example is the paleomagnetic test of Australia's and Laurentia's positioning in Rodinia. Three pertinent and the most well known models of connections between these continents were termed SWEAT (Moores, 1991), AUSWUS, (Brookfield, 1993) and AUSMEX (Wingate et al., 2002). Recent paleomagnetic data on Australian rocks dated at 1210–1230 Ma (Pisarevsky and Harris, 2001; Pisarevsky et al., 2003) and the positions of several paleomagnetic poles of the same age reliably established in Laurentia were used to test whether Australia and Laurentia were parts of one continent in pre-Rodinia time. The results showed that none of the above models is valid for the time span preceding 1200 Ma (Fig. 2).

Consequently, cross-checking geological and paleomagnetic constraints is a very effective approach for reconstructing supercontinents and has been the basic one in the case of Rodinia's reconstruction (Fig. 3). Names of continents in the schematic map of Rodinia shown in the figure correspond to those commonly used in works on paleomagnetic reconstructions and do not coincide sometimes with geological terminology. For instance, Baltica on the map means a continent or plate that existed in the terminal Proterozoic–Early Paleozoic time only and included the East European craton as its continental core (Cocks and Torsvik, 2005; Gee, 2005). In the Early Precambrian paleogeographic reconstructions, however, the terms "Baltica and the East European craton" are used identically meaning and designate a megaterrane or continent. It is naturally understandable that Baltica of the Early Paleozoic differed in dimensions and shape from the East European craton of the Paleo- to Mesoproterozoic period.

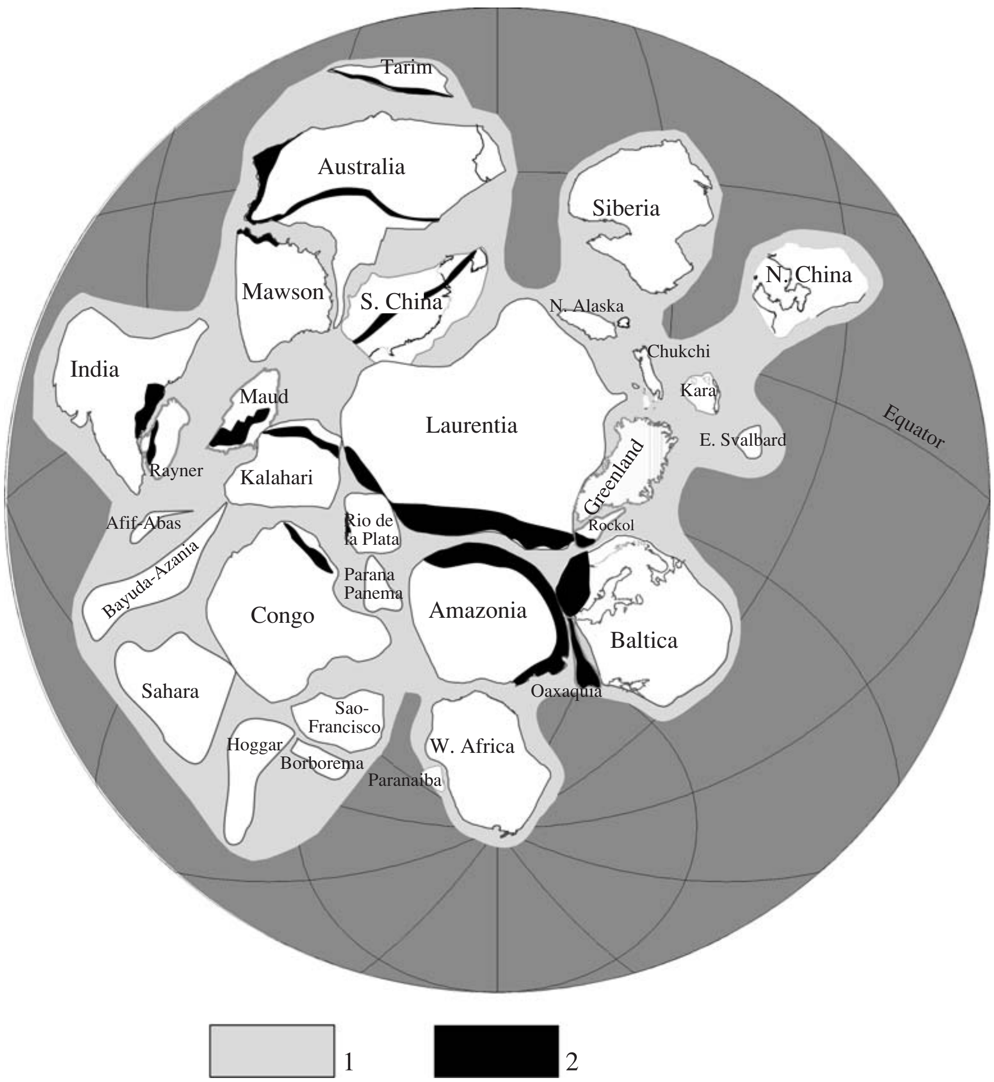


**Fig. 3.** Rodinia 900 Ma ago (after Li et al., 2008, with modifications): (1) presumable marginal shelves, (2) major collisional orogens in the period of Rodinia's assembly (compare with Fig. 5).

## PALEOGEOGRAPHY IN THE PERIOD OF RODINIA'S ASSEMBLY (1300–900 Ma)

The onset of Rodinia's formation used to be dated at 1300 Ma. As there is no possibility to date precisely the onset of any supercontinent formation (see below), we accept the mentioned traditional viewpoint. Many results of project 440 imply, however, that the main collisional events, which resulted in the appearance of a stable continental structure termed Rodinia, took place between 1050 and 900 Ma. This period postdates earlier accretionary events, which can be regarded as the first stages in the supercontinent's formation, following the understanding of some researchers who, considering the Wilson cycles, attribute the passive margin origin to the first stage in the formation of a later accretionary or collisional orogen. Being asynchronous, the events in question progressed irregularly, so that certain continents (Laurentia, Siberia, and probably Amazonia) were amalgamated earlier than the others (Baltica, India, and Australia), which joined them later. Paleogeographic reconstructions by Li et al. (2008) show something resembling a supercontinent only beginning since 1050–1000 Ma. The final stages of the collision presumably lasted until 950–900 Ma.

The Mesoproterozoic orogenic phases are indistinguishable in particular continents. Most likely, the latter were parts of larger megacontinents (e.g., of Laurentia–Siberia or Amazonia–West Africa), some of which retained their relative Paleoproterozoic or Mesoproterozoic configuration until Rodinia's breakup and probably later on.

Let us consider the correlation of tectonic events during the assembly period of Rodinia (Figs. 3 and 4).

### *Central and Southern Rodinia: Laurentia, Kalahari, East Antarctica, Amazonia, Baltica, and Congo–São-Francisco*

Laurentia coupled with West Greenland represented the largest block of Rodinia, the central one in the supercontinent according to all reconstructions. This conclusion is based on remnants of the Neoproterozoic–Paleozoic passive margins distinguishable almost everywhere along the Laurentia periphery (Dalziel, 1997). The Grenville Orogen of Laurentia is the reference structure for reconstructing paleogeodynamic settings during the formation period of Rodinia. This orogen occupying almost entirely the southeastern part of the North American Craton (Hoffman, 1989; Rivers, 1997; Davidson, 1998, 2008; Gower, Krogh, 2002) inherited to a considerable extent the Paleo- and Mesoproterozoic margin of the craton that existed already 1800 Ma ago (Karlstrom et al., 2001). The pre-Grenvillian complexes of the orogen were variably affected by the Late Mesoproterozoic orogenesis that progressed through several phases (Rivers, 1997). The Elzevirian Orogeny (1.29–1.19 Ga ago) started with the oceanic crust's subduction beneath the southern margin of the North Atlantic Craton and associated formation of island-arc and back-arc complexes. Then it resulted in the collision (particularly intense in the western part of the Grenville Belt) of Mesoproterozoic terranes ca. 1250–1190 Ma ago. The major Shawinigan (1.19–1.14 Ga), Ottawan (1.08–1.02 Ga), and Rigolet (1.0–0.98 Ga) phases of the Grenvillian Orogeny were responsible each time for crustal thickening and the high-grade and often high-P metamorphism that accompanied the collision of Laurentia with the other continents. Close in time collisional events were also characteristic of Baltica and Amazonia on the east and of Kalahari and Queen Maud Land on the west of Rodinia in terms of current coordinates (Figs. 3 and 4).

The Kalahari Craton, which includes the Archean Zimbabwe and Kaapvaal protocratons divided by the Paleoproterozoic Limpopo Belt of South Africa along with the smaller Archean Grunehogna Block of East Antarctica, was surrounded on the south and east (current coordinates) by the Namaqua–Natal–Maud Orogenic Belt (Dalziel et al., 2000; Powell et al., 2001; Pettersson et al., 2007; Jacobs et al., 2008). As in the case of the Grenvillian Orogeny, the pre-collisional formation stage of that belt (ca. 1250 Ma ago) was associated with subduction and the origin of island arcs subsequently accreted after 1135 Ma. The time span of 1090–1060 Ma presumably corresponded to the period of the Kalahari–Laurentia collision (Jacobs et al., 2008).

The correlation of the Grenvillian events in Amazonia and Baltica, as well as the positioning of these continents in East Rodinia, are considerably specified now based on recent geochronological and paleomagnetic data (Pisarevsky et al., 2003; Bingen et al., 2005; Pisarevsky and Bylund, 2006). Southeastern Laurentia, western Baltica, and southwestern Amazonia (current coordinates) had much in common until 1400–1300 Ma and belonged to the extended active continental margin of the Andean type. Paleomagnetic data suggest changes in the paleogeographic position of these continents by 1100–1050 Ma, for instance, the clockwise rotation and southward displacement of Baltica into higher latitudes away from Laurentia (Park, 1992; Pisarevsky et al., 2003; Pisarevsky and Bylund, 2006). As for the time span of 1200–1050 Ma, one of the hypotheses postulates that Amazonia, which was initially northwestward of Laurentia (current coordinates), first collided with the latter by its southwestern edge and, drifting to the northeast afterward (Tohver et al., 2002), collided with southwestern Baltica between 1050 and 960 Ma (Bogdanova et al., 2008). Conclusive collisional events of the Sveconorwegian Orogeny (980–960 Ma) involved the Oaxaquia and Chortis terranes (Murphy et al., 2004). In the history of the Grenville orogen itself, the time span of 1000–950 Ma corresponded to the period of the post-collisional extension (Gower and Krogh, 2002).

Data on the position of the Congo–São-Francisco continent (Central Africa and eastern North America) in Rodinia are controversial because of the deficiency of paleomagnetic information and features in the tectonic evolution of the craton's southern margin in the Late Mesoproterozoic–Early Neoproterozoic (De Waele et al., 2008). As is argued for in the cited work, the Congo–São-Francisco Craton originated ca. 1380 Ma ago at the time of the Kibaran Orogeny and the collision between the Archean Tanzania, Bangweulu, Angola-Kasai, Gabon, São-Francisco and other protocratonic blocks, including the Paleoproterozoic intervening belts. The Irumide Belt on the craton's southern margin provides evidence for an active continental margin during the time span of 1055–1020 Ma, and consequently that margin faced an ocean at that time. This contradicts the craton's involvement in the major period of collisional tectonics during the Rodinia's formation. Available paleomagnetic data do not exclude, however, that the Congo–São-Francisco Craton could have been near Amazonia before 900–880 Ma and was separated again afterwards (De Waele et al., 2008).

Some researchers also consider remnants of oceanic island arcs dated at 930 Ma in the Borborema Province of northeastern South America as evidence in favor of the "independence" of certain South American and African blocks and their position outside Rodinia (Cordani et al., 2003; Kröner and Cordani, 2003).

The same problems concern a group of continents of northwestern Rodinia, in particular of India that should be remote from the other continents assembled in Rodinia according to paleomagnetic data (Pisarevsky et al., 2003).

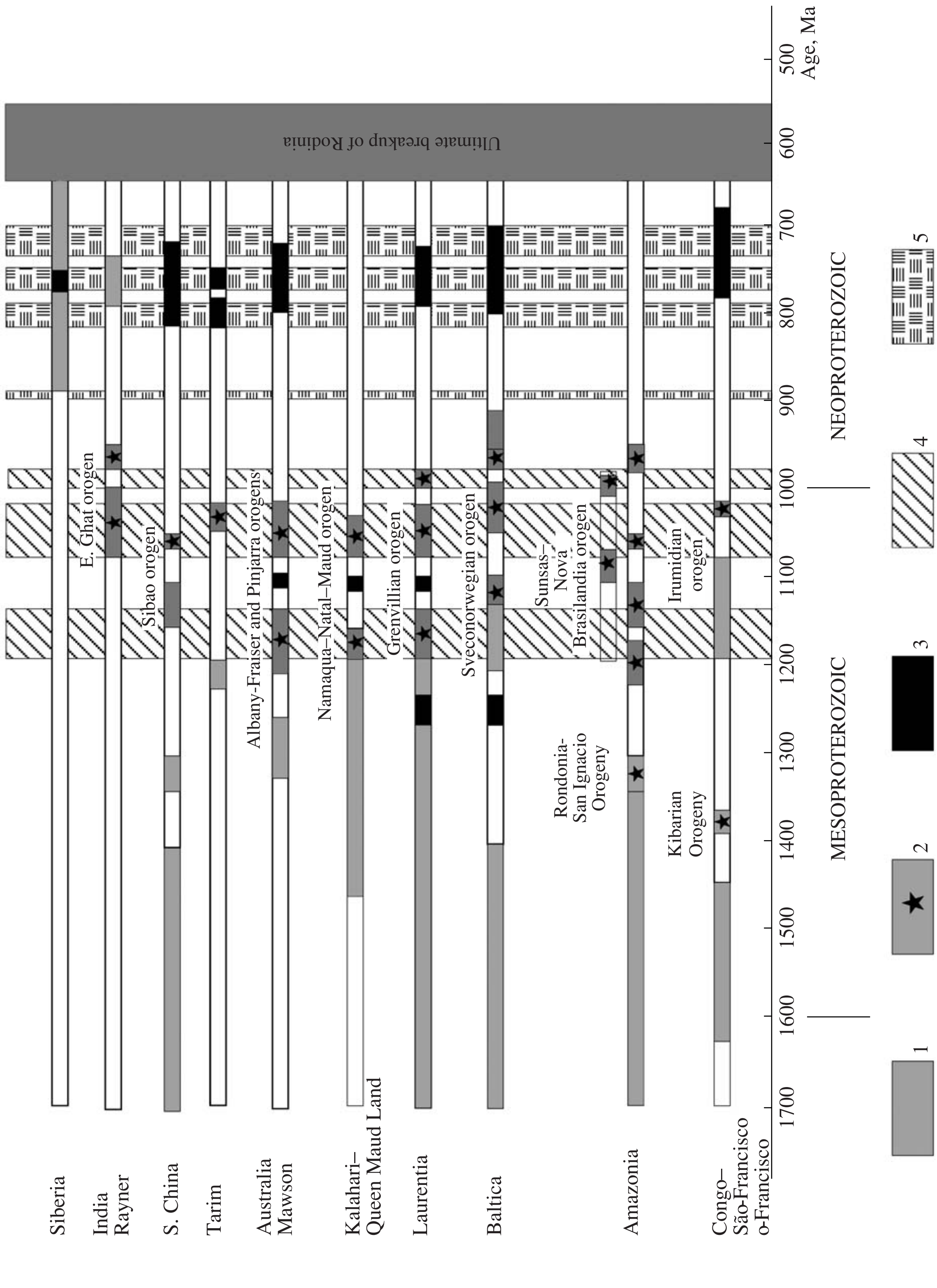


**Fig. 4.** Correlation of continental blocks based on major geodynamic regimes of 1600 to 700 Ma (see references to dates in the text) and periods of (1) accretion, (2) collision, (3) rifting, (4) Grenvillian Orogeny, and (5) mantle-plume tectonics during Rodinia's breakup.

*Northwestern Rodinia: Australia, South China, Mawson, Tarim, India, and Rayner*

The Rodinia configuration that is accepted in this work (Fig. 3) includes the Australian and Mawson cratons separated from Laurentia by the South China Craton in contrast to other reconstructions (e.g., Dalziel, 1997; Karlstrom et al., 2001; Pisarevsky et al., 2003). Li et al. (1995, 2002, 2003) suggested this position of the South China based on the correlation of tectonomagmatic events in the Cathaysia and Yangtze blocks separated by the Sibao orogen that points to a collision of the blocks 1100–1000 Ma ago (Fig. 4). The Cathaysia block is somewhat similar to the southwestern part of Laurentia, whereas the Yangtze block represents another craton. Moores (1991), Brookfield (1993), and Wingate et al. (2002) suggested alternative positions of Australia and East Antarctica relative to Laurentia. Any of the reconstructions mentioned above (Figs. 2 and 3) is acceptable only for the period post 1200 Ma (see higher).

Proterozoic evolution of the Tarim Craton and, in particular, its Neoproterozoic mafic dykes, suggest a resemblance to the Yangtze Craton. In the opinion of Lu et al. (2008a), the Tarim Craton could be near the eastern margin of Australia. Such a situation differs from that shown in Fig. 3 and must be verified in the course of additional paleomagnetic research.

In Southwest Australia, the Albany–Fraser orogen bounds the Archean Yilgarn protocraton in the southeast along the boundary with the Mawson–Gawler protocraton. Condie and Myers (1999) argued for the obduction of oceanic crust fragments onto the Yilgarn protocraton margin in the course of a collision 1330–1300 Ma ago. Two subsequent phases of collisional orogenesis (1190–1140 and ~1100–1000 Ma ago) resulted in the ultimate formation of the Albany–Fraser orogen (Clark et al., 2000; Fitzsimons, 2003). The last phase coincides in time with the Pinjarra Orogeny along the Australia western margin (Myers, 1993). In the terminal Neoproterozoic–Early Paleozoic, that margin was drawn into the Pan-African Orogeny (Collins, 2003). The continuation of those orogenic belts into the Mawson Craton (Wilkes Province) is proved by comprehensive research in Northeast Antarctica (Fitzsimons, 2000, 2003; Mikhal'skii, 2007; and references therein).

High-grade metamorphic rocks of the Rayner Province in East Antarctica, including the Enderby Land, and similar complexes of the Eastern Gats in India belong to the other collisional belt 990–900 Ma old (Fitzsimons, 2000; Dobmeier and Raith, 2003; Bhui et al., 2007). In Sri Lanka there are known island-arc complexes dated at 1100–880 Ma (Kröner et al., 2003). Nevertheless, isotopic dates obtained for granulites in South India (650–550 Ma) exclude this continent from Rodinia and suggest only its participation in the Pan-African collision along the Mozambique Belt of Gondwana (Kröner and Cordani, 2003; and references therein).

*Northeastern Rodinia: Siberia and North China*

The position of the Siberian Craton within Rodinia is debatable. As there are no manifestations of the Meso- and Neoproterozoic collisional orogenesis, researchers (Condie and Rosen, 1994; Pisarevsky and Natapov, 2003; Rosen et al., 2006; Gladkochub et al., 2007b) pointed towards the similarity in the Paleoproterozoic structure and the evolution between the Siberian Craton and Laurentia, considering this as evidence in favor of the two continents' proximity until 760–780 Ma; i.e., until the formation of a passive margin in the southern Siberian Craton and the coeval emplacement of the Franklin mafic dykes in the northern part of the latter (Ernst and Buchan, 2001; Ernst et al., 2008). On the other hand, there are geological data suggesting that the Siberian Craton was surrounded prior to 1000 Ma by passive margins almost everywhere, except its southern side probably (Pisarevsky and Natapov, 2003). The APWPs of Laurentia and Siberia for the period between 1040 and 980 Ma are similar, meaning their position was within one plate. The paleomagnetic reconstruction predicts, however, a wide spacing between southern Siberia and northern Laurentia (current coordinates). Several microcontinents (Precambrian blocks of North Alaska and the Chukchi Peninsula) could represent blocks of Rodinia filling in that space (Fig. 3). The predicted remoteness of Laurentia from Siberia (if both continents were parts of Rodinia) explains why the intense mafic magmatism 1267 Ma ago, which was responsible for the origin of the McKenzie dyke swarm, the largest one in the world, had no manifestations in Southern Siberia (Pisarevsky et al., 2008, Ernst et al., 2008; and references therein).

In the North China Craton there are also unknown geological data evidencing collisional or accretionary events of the terminal Mesoproterozoic–initial Neoproterozoic (Lu et al., 2008b). On the other hand, recent paleomagnetic data admit the possibility that this craton and Laurentia were parts of one plate until 615 Ma (Zhang et al., 2006). Similar biomarkers from rocks dated at 900–800 Ma have also been discovered in both continents (references in the above work). According to these data, the North China Craton could be part of the Neoproterozoic Rodinia. Trends of the Paleoproterozoic evolution of this craton and Laurentia are also similar to some extent (Zhao et al., 2004).

Summing up the available information about the assembly of Rodinia, we note once more that this was a succession of asynchronous events (Fig. 4). Approximately 900 Ma ago, Rodinia included most of the Precambrian continental blocks, some of which were fragments of the Paleoproterozoic megacontinents. The main collisional suture of Rodinia extended from the northwest to the southeast for a distance over 10000 km: from India and the Queen Maud Land in Antarctica via

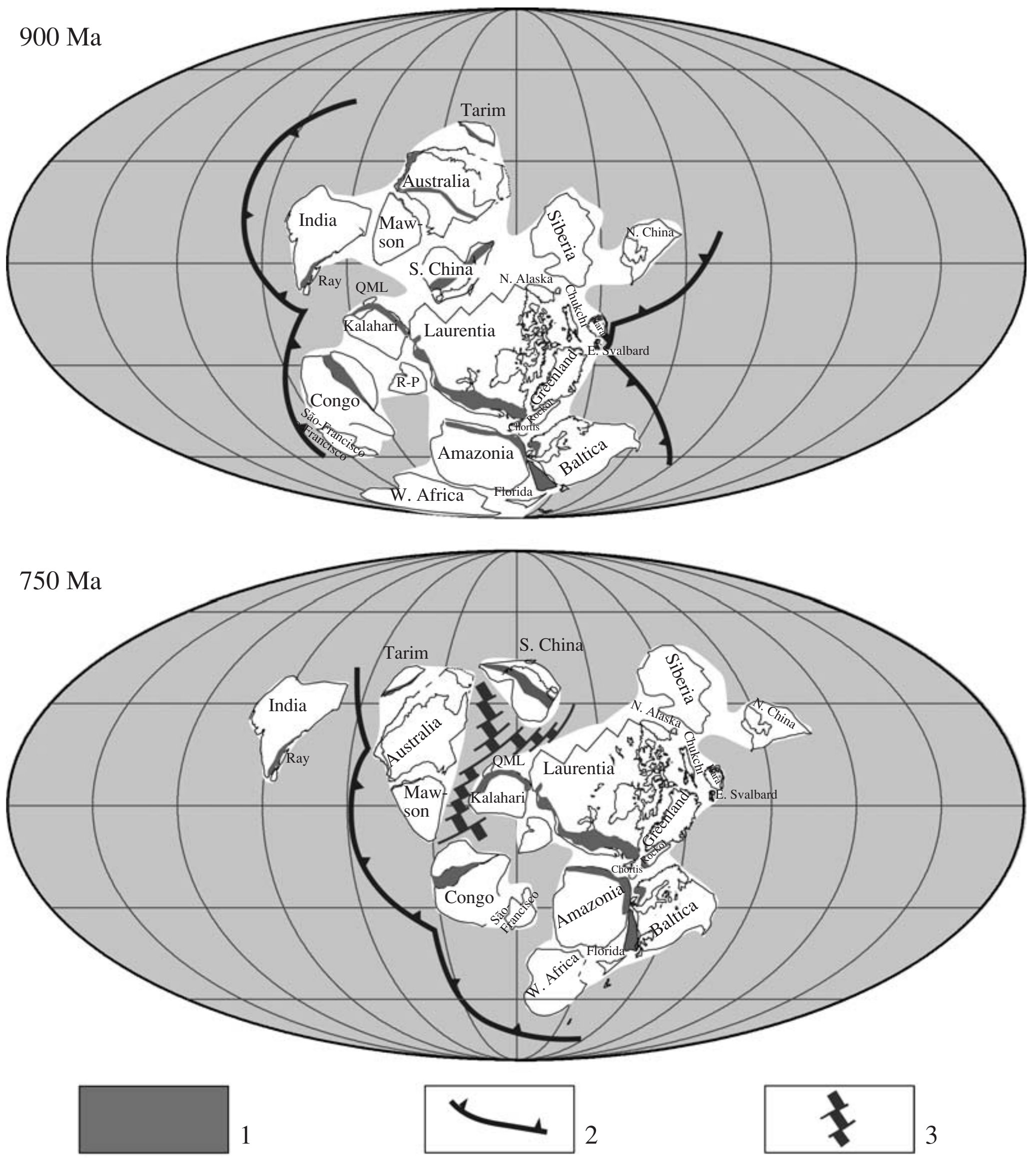


**Fig. 5.** Reconstructed configurations of Rodinia at the assembly (900 Ma) and breakup (750 Ma) time (after Li et al., 2008): (1) major collisional orogens, (2) presumable subduction zones, and (3) mid-ocean ridges.

the Namaqua–Natal Belt on the Kalahari Craton margin and the Grenville Belt of Laurentia toward the Sunsas orogen and Sveconorwegian Belt of Baltica (Figs. 3 and 5). The other shorter collisional belts were in the Australian, Mawson, and North China cratons of Northwest Rodinia.

The coastlines of the supercontinent were apparently indented, and the Mirovoi Ocean ran deep inland that is evident from the existence of passive margins around Siberia already about 1000 Ma ago. Evidence that there were active margins ~ 900 Ma ago has been found in the western periphery of Siberia (Vernikovsky and Vernikovskaya, 2006).

## BREAKUP OF RODINIA (825–700 Ma)

According to results of IGCP project 440, the history of Rodinia's breakup is consistent with models presented earlier (e.g., Dalziel, 1991, 1997; Hoffman, 1991, 1997; Powell and Meert, 2001). Paired rift belts along continental margins, swarms of radial mafic dykes, which intruded neighboring continents, and Large Igneous Provinces (LIPs), i.e., all the results of mantle-plume tectonics characterize the period of Rodinia's breakup that commenced about 830 Ma ago after a short stabilization of the supercontinent (Figs. 4 and 5).

The four major stages of the breakup, which affected to a varying extent separate blocks of Rodinia, occurred 825–800, 780–755, 740–720, and 650–

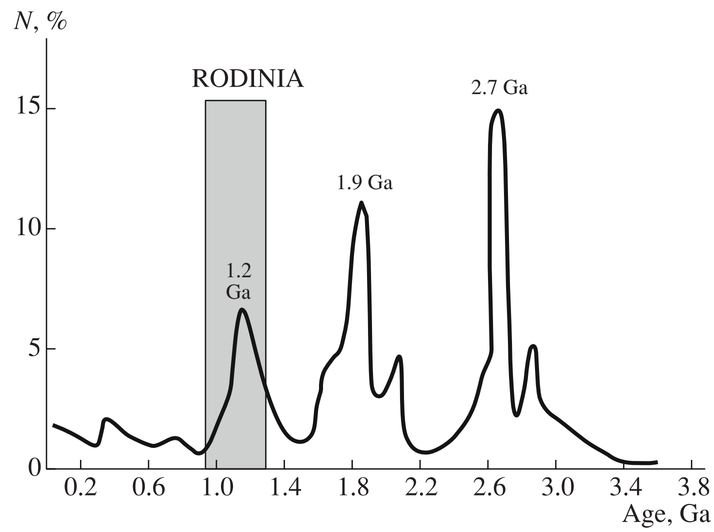


**Fig. 6.** Global peaks of juvenile crust growth (after Condie, 1998); gray vertical bar corresponds to the formation period of collisional orogens 1300 to 900 Ma ago.

550 Ma ago (Li, 1997; Ernst et al., 2008; Li et al., 2008). During Rodinia's breakup, there was an almost concurrent growth of continental crust along the boundaries of some continents, for instance along the western margin of Siberia (Vernikovsky et al., 2003; Vernikovsky and Vernikovskaya, 2006).

The breakup of Rodinia was initiated most likely by a mantle superplume whose influence is recorded in South Australia (Wingate et al., 1998), South China (Li et al., 1999), Tarim (Lu et al., 2008a), Kalahari (Frimmel et al., 2001), India (Radhakrishna and Mathew, 1996), and the Arabian–Nubian Craton (Stein and Goldstein, 1996). In the opinion of Li et al. (1999), the superplume's head was about 825–800 Ma ago under the South China Craton (Fig. 5) and caused crustal arching, intense bimodal magmatism, and accumulation of thick rift-type sedimentary successions on all the adjacent cratons. Continental rifting in the same cratons progressed in the period 800–750 Ma and advanced deep into Laurentia (Harlan et al., 2003) and presumably into Siberia (Sklyarov et al., 2003; Gladkochub et al., 2007a). India along with adjacent Madagascar and the Congo–São-Francisco Craton either were detached in that period from Rodinia, or never participated in the structure of that supercontinent (Torsvik et al., 2001; Pisarevsky et al., 2003; De Waele et al., 2008).

In the period 750–700 Ma, when the central part of Rodinia was close to the equator (Fig. 5), one more pulse of magmatism and rifting influenced many continents of the disintegrating Rodinia: West Kalahari, West Australian, South China's and Tarim's cratons, the current northern, western and southeastern margins of Laurentia, and Northwest Greenland (Ernst et al., 2008).

The last stage of Rodinia's breakup that resulted in the opening of the Iapetus Ocean took place between 650 and 550 Ma (Cawood et al., 2001; Pisarevsky et al., 2008). Another important event of approximately the same time span was the formation of a new supercontinent Gondwana. The closure of the Braziliano, Adamastor, and Mozambique oceans along with the intense development of the Panafrican Orogeny represented the main associated events (Meert, Van der Voo, 1997; Collins, Pisarevsky, 2005; Pisarevsky et al., 2008).

## SOME DEBATABLE ASPECTS OF RODINIA'S HISTORY

### *Slow Growth of the Juvenile Crust in the Mesoproterozoic and Subduction along the Perimeter of Rodinia?*

Considering the general trends of the juvenile crust's growth, Condie (1998, 2001a) drew attention to its low peak relatively to the continental crust growth ~1.3–1.1 Ga ago as compared to the peaks at ca. 2.7 and 1.9 Ga ago (Fig. 6). Indirect evidence of a lower contribution of juvenile crust has been related to the absence of large mineral deposits associated with the convergent boundaries of Rodinia (Barley and Groves, 1992). The mentioned facts seem to contradict the amalgamation of continental blocks into such a large supercontinent like Rodinia, as the subduction's role should be very significant in this case. Analyzing the problem, Condie (2001a, 2002) concluded that supercontinental cycles could be different. The assembling of a new supercontinent did not always follow the complete disintegration of the previous one, and large, partially fragmented megacontinents could be constituents of a new continental aggregate. The formation history of

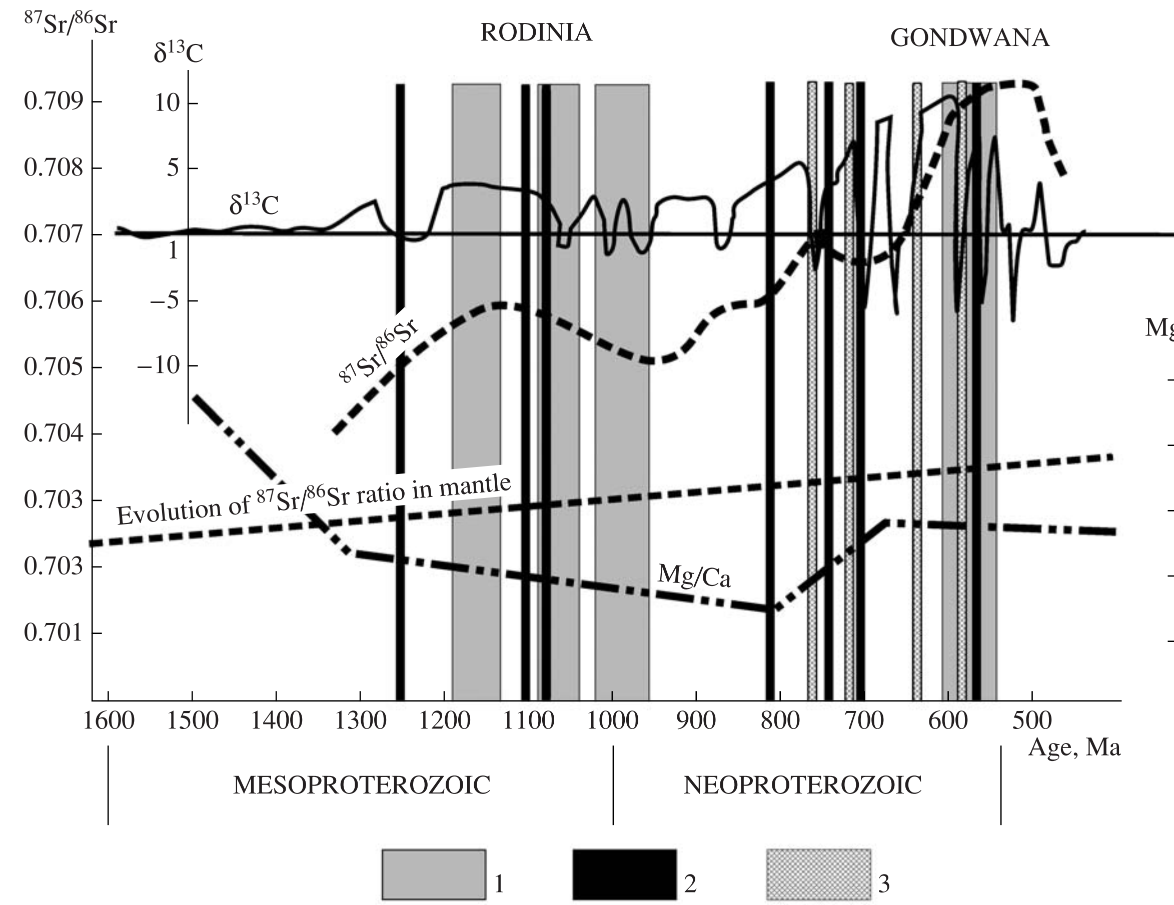


**Fig. 7.** Global biogeochemical changes during the Mesoproterozoic and Neoproterozoic: (1) principal periods of collision; (2) peaks of mantle-plume activity; (3) Sturtian (760–700 Ma), Marinoan (635–630 Ma), and Gaskiers (ca. 580 Ma) glacial epochs.
Secular variation curves of isotopic characteristics and the Mg/Ca ratio in marine carbonates show that at the time of major collisional events during Rodinia's and Gondwana's formation, seawater composition in the Mirovoi Ocean greatly depended on the continental material influx and accelerated burial of organic matter because of the high erosion rate on the high-standing supercontinents (Semikhatov et al., 2002; Sochava and Podkovyrov, 1995; Kah et al., 2001; Frank et al., 2003). The latter situation was especially characteristic of Rodinia's breakup period. Line of the Sr isotopic composition in the upper mantle is after Veizer (1989). Between 1600 and 500 Ma, the $^{87}Sr/^{86}Sr$ ratio in the continental crust increased from 0.711 to 0.715.

Rodinia suggests the possible aggregation of large fragments of the Paleoproterozoic supercontinent Columbia (Rogers and Santosh, 2002; Zhao et al., 2004). This means that the summary length of active margins and the corresponding contribution of the juvenile crust to Rodinia were not so great. In addition, the secular decline in the juvenile crust's production could reflect the general evolutionary trend of the Earth's thermal regime.

We have to state also that there are few data convincingly evidencing the subduction settings along Rodinia's perimeter (Cordani et al., 2003; Vernikovsky et al., 2003; Vernikovsky and Vernikovskaya, 2006). The subduction zones shown in Fig. 5 are presumed, and mostly logical considerations defined their position.

*Accretionary-Collisional Orogens and Mantle Plumes*

It is remarkable that periods of accretion and collision during Rodinia's formation coincided sometimes with the occurrence of mantle plumes. The two most effective mantle-plume events occurred ca. 1270–1250 and 1100 Ma ago (Figs. 4 and 7). The former, known as the Mackenzie event, resulted in the origin of the largest swarms of radial mafic dykes and sills in Northern Canada (Gibson et al., 1987; Ernst and Buchan, 2001) and Fennoscandia (Gorbatschev et al., 1987; Söderlund et al., 2006).

As is assumed in addition, the intense mafic magmatism and rifting (Keweenawan and Umkondo events, respectively), which affected ~1100 Ma ago the gigantic territory of Central Laurentia and Kalahari, lasted only 3 to 6 Ma (Hanson et al., 2004)). These and the somewhat younger (1070–1080 Ma) large igneous province Warakurna in Australia (Wingate et al., 2004) could have been formed under the influence of mantle plumes.

The Mackenzie event did not split the lithosphere ca. 1250 Ma ago (Söderlund et al., 2006), as Baltica separated from Laurentia later on, approximately 1100 Ma ago, according to the discrepancy between the APWPs of these continents (Pisarevsky et al., 2003). This puts forward the problem of the interaction between the mantle-plume and plate-tectonic events during the formation of supercontinents and, in particular, of Rodinia. Variants of possible interactions, considered in recent publications, show that they could be controlled by many factors, e.g., by the lithosphere's thickness, the size and position of continents relative to convection cells in the mantle and deep subduction zones, or by temperature in the lower mantle, etc. (Condie, 2001b; Nikishin et al., 2002; Ernst, Buchan, 2003; Lobkovsky et al., 2004). There are certain data suggesting that mantle plumes could accelerate or slow down continental growth and accretionary-collisional processes during the formation of supercontinents.

### *Supercontinental Cycles*

Supercontinental cycles were approximately as long as 600–650 Ma regardless of whether we define them beginning since the rifting stage and the disintegration of an older supercontinent or the commenced aggregation of particular continents (Khain, 2000; Lobkovsky et al., 2004). The period of Rodinia's assembly could be as long, depending on determination, as ~400 Ma, being followed by its disintegration during ~150–200 Ma. In principle, it is impossible to define the precise time constraints for the existence period of any supercontinent, because tectonic processes are perpetual: some blocks, even if they are small, become attached, while others are detached at the same time. The existence period of a supercontinent is a kind of dynamic equilibrium between these processes. If we take, for instance, the later cycles, one can see that periods of the Gondwana formation and the Iapetus opening are overlapping, or that collision of Mongolian and North China terranes with Siberia took place at the time of Pangea's breakup. Accordingly, there is nothing surprising in the fact that the first indication of Rodinia's breakup appeared in South China already 40–60 Ma after the "ultimate" formation of this supercontinent.

In our opinion, thermal convection in the lower mantle could be the principal mechanism responsible for Rodinia's assembly and breakup. The counter subduction of a cold lithosphere under Rodinia from the side of the Mirovoi Ocean, the detachment of lithospheric slabs, and the thermal effect of screening a supercontinental "blanket"—all these factors could have activated a superplume. Its daughter plumes penetrating into the lithosphere of Rodinia were capable of triggering the breakup of supercontinents. Substantiation of this scenario needs additional evidence regarding the subduction settings confined to the perimeter of Rodinia. Lobkovsky et al. (2004) presented arguments in favor of a similar evolution model in their book. On the other hand, the suggested succession of events is inconsistent with the viewpoint of Condie (1998, 2000) who postulated an approximate synchronism of superplume activity and supercontinent formation, considering the former as responsible for the contribution of the juvenile crust.

### *Neoproterozoic Glacial Periods: Effect of "Snowball Earth?"*

Neoproterozoic successions of Rodinia's breakup period include sediments deposited during the Sturtian (740–720 Ma), Marinoan (630 Ma ago), and Gaskiers (585 Ma ago) glaciations. In addition to astronomic factors (Williams, 1975; Crowley and Baum, 1993; Pavlov et al., 2005), the other possible reasons of glaciations could be a high albedo of a giant summary area of continents clustered near the equator, intense weathering, quick burial of organic matter, and $CO_2$ deficiency in the atmosphere because of reduced mantle-plume activity (Condie et al., 2001). Shown in Fig. 7 are variation curves illustrating changes in certain biogeochemical parameters during the formation of Rodinia and Gondwana. To a first approximation, postglacial periods and sharp biotic changes are correlative with Rodinia's breakup and periods of intensified mantle-plume magmatism (Chumakov, 2001; *Climate*…, 2004).

Readers can find a good deal of news concerning the "Snowball Earth" hypothesis (Kirschvink, 1992; Hoffman et al., 1998) by visiting the web site http://www.snowballearth.org. The hypothesis postulates catastrophic global glaciations in the Neoproterozoic and a series of interrelated global biogeochemical changes in seawater and atmosphere composition along with postglacial explosions in biota evolution. It is based on the widespread occurrence of glacial deposits in near-equatorial latitudes and associated specific "cap carbonates" and rocks of iron formation, which are indirectly connected with manifestations of mafic and bimodal magmatism; in other words, with rifting and mantle-plume geodynamics characteristic of supercontinental cycles (Khain, 2000; Condie et al., 2001).

Critics of the hypothesis doubted the identification of rocks selected to prove the global rank of glaciations, their synchronism, and the correctness of criteria used to determine tectonic environments of sedimentation (Eyles and Januszczak, 2004). In the opinion of these researchers, many of the Late Proterozoic reference successions, which enclose glacial sediments, and their biogeochemical features can be interpreted in terms of tectonic conditions and events characterizing Rodinia's breakup instead of reference to the eustatic sea-level fluctuations in the global ocean. Of prime importance, as they believe, were the intense rifting and associated rising of rift "shoulders," i.e., the emergence of tectonic topography ("zipper-rift" hypothesis by Eyles and Januszczak, 2004). This idea seems attractive in view of the immense thickness (up to several kilometers) and rifting-related lithology of Neoproterozoic successions.

The synchronism of glacial events in different continents has not always been proved. In many cases, glacial deposits are dated a priori, e.g., with reference to excursions of composite trends characterizing secular $\Delta^{13}C$ variations (Halvorsen et al., 2005) without being checked by other radiometric methods (Meert, 2007).

One more scenario of the Neoproterozoic glaciation was suggested based on paleomagnetic and geochronological data obtained for rocks of the South China block and characterizing the period from 820 to 720 Ma (Li et al., 2004). Interpreting their results, the authors postulated that the mantle superplume beneath northwestern Rodinia, which was in high latitudes at that time, as they assumed, caused the redistribution of the mantle's masses and quick rotation of the mantle relative the Earth's core. As a result, Rodinia arrived in the equatorial zone approximately 750 Ma ago. The activity of the mantle was concurrently declining against a background of high albedo of a still existing Rodinia that caused a sharp decrease in the concentration of the atmospheric $CO_2$ and global cooling. The possibility of the postulated events in the mantle and associated global biogeochemical changes remains debatable (Meert, 1999; Tarduno and Smirnov, 2001; Evans, 2003; Lobkovsky et al., 2004).

## CONCLUSIONS

The reconstructed paleogeography of supercontinent Rodinia in the periods of its assembly and breakup is an important result of IGCP project 440 helping us to solve the problems of the Precambrian and Phanerozoic supercontinents.

The geodynamic map of Rodinia visualizing the paleogeography of this supercontinent, which was enigmatic for a long time, assimilated the available geological, geochronological, and paleomagnetic data characterizing practically all the amalgamated continental blocks. In addition, tectonic maps of the largest assembled continents are compiled using the same legend.

The experience of reconstructing Rodinia shows that the paleogeographic arrangement of separate continental blocks substantiated by the direct correlation of tectonic events can be misleading without consideration of reliable paleomagnetic data.

According to established age constraints, Rodinia as a whole was formed ~900 Ma ago, and its ultimate breakup took place in the terminal Neoproterozoic–initial Cambrian. In compliance with conventional assessment, the complete supercontinental cycle in question was as long as 600–650 Ma (1300 to 700–650 Ma), although in a narrow sense (supercontinent of stable configuration), Rodinia existed during a much shorter time span between ~1000 and ~850 Ma.

Rodinia's breakup was associated with the activity of mantle plumes.

Glaciations of Rodinia's breakup period in the equatorial zone could be either occasional, or genetically linked with the influence of certain factors. Reasons of global glaciations and important changes in the biosphere during the Late Neoproterozoic should be the focus of subsequent research.

## ACKNOWLEDGMENTS

We are grateful to all our colleagues who participated in IGCP project 440 "Assembly and Breakup of Rodinia" and organized scientific conferences on the problem, for their co-authorship in publications, fruitful discussions, and friendly atmosphere of collaboration. The Tectonics Special Research Center at the University of Western Australia in Perth was the base of the project from 1999 to 2005.

We deeply mourn the untimely passing away of the initiators of the project Rafael Unrug (United States) and Chris M.A. Powell (Australia), and co-leader of the project Henry Kampunzu (Botswana), who did not live to see the project's success.

Reviewers E.V. Sklyarov and M.A. Semikhatov

## REFERENCES

1. Yu. R. Bekker, V. Z. Negrutsa, and N. I. Poleva, "Age of Glauconite Horizons and the Hyperborean Upper Boundary in Eastern Part of the Baltic Shield," Dokl. Akad. Nauk SSSR **193**, 1123–1126 (1970).
2. U. K. Bhui, P. Sengupta, and P. Sengupta, "Phase Relations in Mafic Dykes and Their Host Rocks from Kondapalle, Andhra Pradesh, India: Implications for the Time–Depth Trajectory of the Palaeoproterozoic (Late Archaean?) Granulites from Southern Eastern Ghats Belt," Precambrian Res. **156**, 153–174 (2007).
3. B. Bingen, D. Demaiffe, and O. van Breemen, "The 616 Ma Old Egersund Basaltic Dike Swarm, SW Norway, and Late Neoproterozoic Opening of the Iapetus Ocean," J. Geol. **106**, 565–574 (1998).
4. B. Bingen, O. Skar, M. Marker, et al., "Timing of Continental Building in the Sveconorwegian Orogen, SW Scandinavia," Norwegian J. Geol. **85**, 87–116 (2005).
5. W. Bleeker, "The late Archean Record: A Puzzle in ca. 35 Pieces," Lithos **71** (2–4), 99–134 (2003).
6. S. V. Bogdanova, B. Bingen, R. Gorbatschev, et al., "The East European Craton (Baltica) before and during the Assembly of Rodinia," Precambrian Res. **160** (1–2), 23–45 (2008).
7. M. E. Brookfield, "Neoproterozoic Laurentia–Australia Fit," J. Geol. **21**, 683–686 (1993).
8. P. A. Cawood, P. G. A. McCausland, and G. R. Dunning, "Opening Iapetus: constraints from the Laurentian margin in Newfoundland," Bull. Geol. Soc. Am. **113**, 443–453 (2001).

9. P. A. Cawood and S. A. Pisarevsky, “Was Baltica Right-Way-Up or Upside-Down in the Neoproterozoic?” J. Geol. Soc. London **163**, 1–7 (2006).

10. N. M. Chumakov, “Periodicity of Periodicity of Major Glaciations Events and Their Correlation with Endogenic Activity of the Earth,” Dokl. Akad. Nauk **367** (5), 656–659 (2001) [Dokl. **379** (5), 507–510 (2001)].

11. D. J. Clark, B. J. Hensen, and P. D. Kinny, “Geochronological Constraints for a Two-Stage History of the Albany–Fraser Orogen, Western Australia,” Precambrian Res. **102** (3–4), 155–183 (2000).

12. L. R. Cocks and T. H. Torsvik, “Baltica from the Late Precambrian to Mid-Palaeozoic Times: the Gain and Loss of a Terrane’s Identity,” Earth Sci. Rev. London **72** (1–2), 39–66 (2005).

13. A. S. Collins, “Structure and Age of the Northern Leeuwin Complex, Western Australia: Constraints from Field Mapping and U–Pb Isotopic Analysis,” Australian J. Earth Sci. **50**, 585–599 (2003).

14. K. C. Condie, “Episodic Continental Growth Models: Afterthoughts and Extensions,” Tectonophysics **322** (1–2), 153–162 (2000).

15. K. C. Condie, “Continental Growth during Formation of Rodinia at 1.35–0.9 Ga,” Gondwana Res. **4**, 5–16 (2001a).

16. K. C. Condie, *Mantle Plumes and Their Record in Earth History* (University Press, Cambridge, 2001b).

17. K. C. Condie, “The Supercontinent Cycle: Are Two Patterns of Cyclicity?” J. African Earth Sci. **15**, 179–183 (2002).

18. K. Condie and J. S. Myers, “Mesoproterozoic Fraser Complex: Geochemical Evidence for Multiple Subduction–Related Sources of Lower Crustal Rocks in the Albany–Fraser Orogen, Western Australia,” Australian J. Earth Sci. **46**, 875–882 (1999).

19. A. S. Collins and S. A. Pisarevsky, “Amalgamating Eastern Gondwana: the Evolution of the Circum–Indian Orogens,” Earth Sci. Rev. **71**, 229–270 (2005).

20. K. Condie and O. M. Rosen, “Laurentia–Siberia Connection Revisited,” J. Geol. **22**, 168–170 (1994).

21. K. C. Condie, D. J. Des Marais, and D. Abbot, “Precambrian Superplumes and Supercontinents: A Record in Black Shales, Carbon Isotopes, and Paleoclimates?” Precambrian Res. **106**, 239–260 (2001).

22. U. G. Cordani, M. S. D. Agrella-Filho, B. B. Brito-Neves, and R. I. F. Trindade, “Tearing up Rodinia: the Neoproterozoic Palaeogeography of South American Cratonic Fragments,” Terra Nova **15** (5), 350–359 (2003).

23. T. J. Crowley and S. K. Baum, “Effect of Decreased Solar Luminosity on Late Precambrian Ice Extent,” J. Geophys. Res. **98**, 16723–16732 (1993).

24. I. W. D. Dalziel, “Pacific Margins of Laurentia and East Antarctica–Australia as a Conjugate Rift Pair: Evidence and Implications for an Eocambrian Supercontinent,” J. Geol. **19** (6), 598–601 (1991).

25. I. W. D. Dalziel, “Neoproterozoic–Paleozoic Geography and Tectonics: Review, Hypothesis, Environmental Speculation,” Bull. Geol. Soc. Am. **109**, 16–42 (1997).

26. I. W. D. Dalziel, S. Mosher, and L. M. Gahagan, “Laurentia–Kalahari Collision and the Assembly of Rodinia,” J. Geol. **108**, 499–513 (2000).

27. A. Davidson, “An overview of Grenville Province Geology. Geology of the Precambrian Superior and Grenville Provinces and Precambrian Fossils in North America,” in *The Geology of North America* (Geol. Soc. Am., 1998), C–1, pp. 205–270.

28. A. Davidson, “Late Paleoproterozoic to mid–Neoproterozoic History of Northern Laurentia: An Overview of Central Rodinia,” Precambrian Res. **160**, 5–22 (2008).

29. B. De Waele, S. P. Johnson, and S. A. Pisarevsky, “Palaeoproterozoic to Neoproterozoic Growth and Evolution of the Eastern Congo Craton: Its Role in the Rodinia Puzzle,” Precambrian Res. **160**, 127–142 (2008).

30. C.J. Dobmeier and M.M. Raith, “Crustal Architecture And Evolution of the Eastern Ghats Belt and Adjacent Regions of India,” in *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*, Ed. by M. Yoshida, B. F. Windley, and S. Dasgupta, Spec. Publ. Geol. Soc. London **206**, 145–168 (2003).

31. R. E. Ernst and K. L. Buchan, “Large Mafic Magmatic Events through Time and Links to Mantle Plume Heads,” in *Mantle Plumes: Their Identification Through Time*, Ed. by R. E. Ernst and K. L. Buchan, Spec. Pap. Geol. Soc. Am. **352**, 483–575 (2001).

32. R. E. Ernst and K. L. Buchan, “Recognizing Mantle Plumes in the Geological Record,” Ann. Rev. Earth Planet. Sci. **31**, 469–523 (2003).

33. R. E. Ernst, M. T. D. Wingate, K. L. Buchan, and Z. X. Li, “Global Record of 1600–700 Ma Large Igneous Provinces (LIPs): Implications for the Reconstruction of the Proposed Nuna (Columbia) and Rodinia Supercontinents,” Precambrian Res. **160**, 159–178 (2008).

34. D. A. D. Evans, “True Polar Wander and Supercontinents,” Tectonophysics. **362** (1–4), 303–320 (2003).

35. N. Eyles and N. Januszczak, “'Zipper–rift': A Tectonic Model for Neoproterozoic Glaciations during the Breakup of Rodinia after 750 Ma,” Earth Sci. Rev. **65**, 1–73 (2004).

36. I. C. W. Fitzsimons, “Grenville-Age Basement Provinces in East Antarctica: Evidence for Three Separate Collisional Orogens,” J. Geol. **28**, 879–882 (2000).

37. I. C. W. Fitzsimons, “Proterozoic Basement Provinces of Southern and South-Western Australia, and Their Correlation with Antarctica,” in *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*, Ed. by M. Yoshida, B. F. Windley, and S. Dasgupta, Spec. Publ. Geol. Soc. London **206**, 93–130 (2003).

38. T. D. Frank, L. C. Kah, and T.W. Lyons, “Changes in Organic Matter Production and Accumulation as a Mechanism for Isotopic Evolution in the Mesoproterozoic Ocean,” Geol. Mag. **140**, 397–420 (2003).

39. H. E. Frimmel, R.E. Zartman, and A. Spath, “The Richtersveld Igneous Complex, South Africa: U–Pb Zircon and Geochemical Evidence for the Beginning of Neoproterozoic Continental Breakup,” J. Geol. **109**, 493–508 (2001).

40. D. G. Gee, “Timanides of Northern Russia,” in *Encyclopedia of Geology,* Ed. by R. C. Selley, L. R. Cocks, and

I. R. Plimer (Elsevier, New York, 2005), Vol. 2, pp. 49–56.

41. I. L. Gibson, M. N. Sinha, and W. F. Fahrig, "The Geochemistry of the Mackenzie Dyke Swarm, Canada," Mafic Dyke Swarms. Eds. Halls, H.C. and Fahrig, W.F. Geol. Assoc. Canada Spec. Pap. **34**, 109–121 (1987).
42. D. P. Gladkochub, M. T. D. Wingate, S. A. Pisarevsky, et al., "Mafic Intrusions in Southwestern Siberia and Implications for a Neoproterozoic Connection with Laurentia," Precambrian Res. **147**, 260–278 (2006).
43. D. P. Gladkochub, T. V. Donskaya, A. M. Mazukabzov, et al., "Rock Complexes Indicative of Extension in the South Siberian Craton during the Precambrian," Geol. Geofiz. **48** (1), 22–41 (2007a).
44. D. P. Gladkochub, T. V. Donskaya, A. M. Mazukabzov, et al., "Siberian Craton as a Polygon for Solving Problems of Formation and Breakup of Precambrian Supercontinents," in *Basic Problems of Tectonics*, Ed. by Yu. V. Karyakin (GEOS, Moscow, 2007b), pp. 182–185 [in Russian].
45. R. Gorbatschev, A. Lindh, Z. Solym, et al., "Mafic Dyke Swarms of the Baltic Shield," in *Mafic Dyke Swarms*, Ed. by H. C. Halls and W. F. Fahrig, Spec. Pap. Geol. Assoc. Canada **34**, 361–372 (1987).
46. C. F. Gower and T. Krogh, "A U–Pb Geochronological Review of the Proterozoic History of the Eastern Grenville Province," Can. J. Earth Sci. **39**, 795–829 (2002).
47. P. G. Guese and D. Roberts, "Devonian Ages from $^{40}$Ar–$^{39}$Ar Dating of Plagioclase in Dolerite Dykes, Eastern Varanger Peninsula, North Norway," NGU Bull. **440**, 27–36 (2002).
48. G. P. Halvorsen, P. F. Hoffman, D. P. Schrag et al., "Towards a Neoproterozoic Composite Carbon Isotope Record," Bull. Geol. Soc. Am. **117**, 1181–1207 (2005).
49. R. E. Hanson, J. L. Crowley, S. A. Bowring, et al., "Coeval Large–Scale Magmatism in the Kalahari and Laurentian Cratons during Rodinia Assembly," Science **304**, 1126–1129 (2004).
50. S. S. Harlan, J. W. Geissman, and W. R. Premo, "Paleomagnetism and Geochronology of an Early Proterozoic Quartz Diorite in the Southern Rind River Range, Wyoming, USA," Tectonophysics **362**, 105–122 (2003).
51. E. H. Hartz and T. H. Torsvik, "Baltica Upside Down: a New Plate Tectonic Model for Rodinia and the Iapetus Ocean," J. Geol. **30**, 255–258 (2002).
52. J. P. Hodych, R. A. Cox, and J. Koshler, "An Equatorial Laurentia at 550 Ma Confirmed by Grenvillian Inherited Zircons Dates by LAM ICP–MS in the Skinner Cove Volcanics of Western Newfoundland: Implications for Inertial Interchange True Polar Wander," Precambrian Res. **129**, 93–113 (2004).
53. P. F. Hoffman, "Did the Breakout of Laurentia Turn Gondwanaland Inside–Out?" Science **252**, 1409–1412 (1991).
54. P. F. Hoffman, "Precambrian Geology and Tectonic History of North America," in *The Geology of North America – An overview,* Ed. by A. W. Bally and A. R. Palmer (Boulder, Colorado: Geol. Soc. Am., 1989), pp. 447–512.
55. P. F. Hoffman, "Tectonic Genealogy of North America," in *Earth Structure: An Introduction to Structural Geology and Tectonics*, Ed. by B. A. van der Pluijm and S. Marshak (New York,1997), pp. 459–464.
56. P. F. Hoffman, A. J. Kaufman, G. P. Halverson, and D. P. A. Schrag, "Neoproterozoic Snowball Earth," Science **281**, 1342–1346 (1998).
57. J. Jacobs, S. Pisarevsky, R. J. Thomas, and T. Becker, "The Kalahari Craton during the Assembly and Dispersal of Rodinia," Precambrian Res. **160**, 142–159 (2008).
58. L. C. Kah, T. W. Lyons, and J. T. Chesley, "Geochemistry of a 1.2 Ga Carbonate-Evaporate Succession, Northwestern Baffin and Bylot Islands: Implication for Mesoproterozoic Marine Evolution," Precambrian Res. **111** (1–4), 203–234 (2001).
59. S. L. Kamo and C. F. Gower, "Note: U–Pb Baddeleyite Dating Clarifies Age of Characteristic Paleomagnetic Remanence of Long Range Dykes, Southeastern," Atlantic Geol. **30**, 259–262 (1994).
60. K. E. Karlstrom, K.–I. Ahall, S. S. Harlan, et al., "Long Lived (1.8–1.0 Ga) Convergent Orogen in Southern Laurentia, Its Extensions to Australia and Baltica, and Implications for Refining Rodinia," Precambrian Res. **111**, 5–30 (2001).
61. V. E. Khain, "Large-Scale Cyclicity in the Earth's Tectonic History and Its Possible Origin," Geotektonika **6**, 3–14 (2000) [Geotectonics **34** (6), 431–441 (2000)].
62. V. E. Khain, *Tectonics of Continents and Oceans* (Nauchnyi Mir, Moscow, 2001) [in Russian].
63. A. N. Khramov and L. E. Sholpo, *Paleomagnetism: Principles, Methods and Geological Implications of Paleomagnetology* (Nedra, Leningrad, 1967) [in Russian].
64. J. L. Kirschvink, "Late Proterozoic Low-Latitude Global Glaciations: The Snowball Earth," in *The Proterozoic Biosphere*, Ed. by J. W. Schopf and C. Klein (Cambridge University Press, Cambridge,1992), pp. 51–52.
65. *Climate in Epochs of Great Biospheric Reorganizations*, Ed. by M. A. Semikhatov and N. M. Chumakov (Nauka, Moscow, 2004) [in Russian].
66. A. Kröner and U. Cordani, "African, Southern Indian and South American Cratons were not Part of the Rodinia Supercontinent: Evidence from Field Relationships and Geochronology," Tectonophysics **375**, 325–352 (2003).
67. A. Kröner, K. V. W. Kehelpannala, and E. Hegner, "Ca. 750–1100 Ma Magmatic Events and Grenville-Age Deformation in Sri Lanka: Relevance for Rodinia Supercontinent Formation and Dispersal, and Gondwana Amalgamation," J. Asian Earth Sci. **22**, 279–300 (2003).
68. Z. X. Li, M. Cho, and X. H. Li, "Precambrian Tectonics of East Asia and Relevance to Supercontinent Evolution," Precambrian Res. **122** (1–4), 1–6 (2003).
69. Z. X. Li, D. A. D. Evans, and S. Zhang, "A 90° Spin on Rodinia: Possible Causal Links between the Neoproterozoic Supercontinent, Superplume, True Polar Wander and Low-Latitude Glaciation," Earth Planet. Sci Lett. **220** (3–4), 409–421 (2004).
70. Z. X. Li, X.H. Li, P.D. Kinny, and J. Wang, "The Breakup of Rodinia: Did it Start with a Mantle Plume Beneath South China?" Earth Planet. Sci Lett. **173** (3), 171–181 (1999).

71. Z. X. Li, X.H. Li, H.Zhou, and P. D. Kinny, "Grenvillian Continental Collision in South China: New SHRIMP U–Pb Zircon Results and Implications for the Configuration of Rodinia," J. Geol. **30** (2), 163–166 (2002).

72. Z. X. Li, L. Zhang, and C. M. Powell, "South China in Rodinia: Part of the Missing Link between Australia–East Antarctica and Laurentia ?" J. Geol. **23**, 407–410 (1995).

73. Z. X. Li, S. V. Bogdanova, A. S. Collins, et al., "Assembly, Configuration, and Break-up History of Rodinia: A Synthesis," Precambrian Res. **160**, 179–210 (2008).

74. L. I. Lobkovsky, A. M. Nikishin, and V. E. Khain, *Current Problems of Geotectonics and Geodynamics* (Nauchnyi Mir, Moscow, 2004) [in Russian].

75. S. Lu, H. Li, and C. Zhang, "Geological and Geochronological Evidence for the Precambrian Evolution of the Tarim Craton and Surrounding Continental Fragments," Precambrian Res. **160**, 94–108 (2008a).

76. Lu S., G. Zhao, and H. Wang, "Precambrian Metamorphic Basement and Sedimentary Cover of the North China Craton: A Review," Precambrian Res. **160**, 77–94 (2008b).

77. M. W. McElhinny and P. L. McFadden, *Paleomagnetism. Continents and Oceans* (San-Diego Academic Press, London, 2000).

78. M. A. S. McMenamin and D. L. S. McMenamin, *The Emergence of Animals: the Cambrian Breakthrough* (Columbia University Press, New York,1990).

79. J. Meert, "A Paleomagnetic Analysis of Cambrian True Polar Wander," Earth Planet. Sci. Lett. **168**, 131–144 (1999).

80. J. G. Meert, "Testing the Neoproterozoic Glacial Models," Gondwana Res. **11** (4), 573–574 (2007).

81. J. G. Meert and R. Van der Voo, "The Assembly of Gondwana 800–550 Ma," J. Geodynamics **23**, 223–236 (1997).

82. E. V. Mikhal'skii, "Tectonic Provinces of the Antarctic Shield in Terms of Formation of Precambrian Supercontinents," in *Basic Problems of Geotectonics*, Ed. by Yu. V. Karyakin (GEOS, Moscow, 2007), Vol. I, pp. 29–32 [in Russian].

83. E. M. Moores, "Southwest U.S.–East Antarctic (SWEAT) Connection: A Hypothesis," J. Geol. **19**, 425–428 (1991).

84. J. B. Murphy, S. A. Pisarevsky, R. D. Nance, and J. D. Keppie, "Neoproterozoic–Early Paleozoic Evolution of Peri-Gondwanan Terranes: Implications for Laurentia–Gondwana Connections," Int. J. Earth Sci. (Geol. Rundschau) **93**, 659 (2004).

85. G. Murthy, C. Gower, M. Tubrett, and R. Patzold, "Paleomagnetism of Eocambrian Long Range dykes and Double Mer Formation from Labrador, Canada," Can. J. Earth Sci. **29**, 1224–1234 (1992).

86. J. S. Myers, "Precambrian History of the West Australian Craton and Adjacent Orogens," Ann. Rev. Earth Planet. Sci. **21**, 453–485 (1993).

87. A. M. Nikishin, P. A. Ziegler, D. Abbott, et al., "Permo-Triassic intraplate Magmatism and Rifting in Eurasia: Implications for Mantle Plumes and Mantle Dynamics," Tectonophysics **351**, 3–39 (2002).

88. J. K. R. G. Park, "Plate Kinematic History of Baltica during the Middle to Late Proterozoic: A Model," J. Geol. **20**, 725–728 (1992).

89. A. A. Pavlov, O. B. Toon, A. K. Pavlov, et al., "Passing through a Giant Molecular Cloud: 'Snowball' Glaciations Produced by Interstellar Dust," Geophys. Res. Lett. **32**, L03705, 10.1029/2004GL021890 (2005).

90. A. Pettersson, D.Cornell, H. F. G. Moen, et al., "Ion-Probe Dating of 1.2 Ga Collision and Crustal Architecture in the Namaqua–Natal Province of Southern Africa," Precambrian Res. **207**, 79–92 (2007).

91. J. D. A. Piper, "Paleomagnetic Evidence for a Proterozoic Supercontinent," Phil. Trans. R. Soc. London **A280**, 469–490 (1976).

92. S. A. Pisarevsky, "New Edition of the Global Paleomagnetic Database," EOS Trans. Am. Geophys. Union. **86** (17), 170 (2005).

93. S. A. Pisarevsky and G. Bylund, "Palaeomagnetism of 935 Ma Mafic Dykes in Southern Sweden and Implications for the Sveconorwegian Loop," Geophys. J. Int. **166**, 1095–1104 (2006).

94. S. A. Pisarevsky and L. B. Harris, "Determination of Magnetic Anisotropy and a ca. 1.2 Ga Palaeomagnetic Pole from the Bremer Bay Area, Albany Mobile Belt, Western Australia," Aust. J. Earth Sci. **48**, 101–112 (2001).

95. S. A. Pisarevsky and L. M. Natapov, "Siberia and Rodinia," Tectonophysics **375**, 221–245 (2003).

96. S. Pisarevsky, B. J. Murphy, P. A. Cawood, and A. S. Collins, "Late Neoproterozoic and Early Cambrian Palaeogeography: Models And Problems," in *West Gondwana: Pre–Cenozoic Correlations Across the South Atlantic Region,* Ed. by R. J. Pankhurst, R. A. Trouw, B. B. Brito Neves, and M. J. De Wit, Spec. Publ. Geol. Soc. London **294**, 9–31 (2008).

97. S. Pisarevsky, M. T. D. Wingate, C. M. Powell, et al., "Models of Rodinia Assembly and Fragmentation," in *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*, Ed. by M. Yoshida, B. F. Windley, and S. Dasgupta, Spec. Publ. Geol. Soc. London **206**, 35–55 (2003).

98. C. M. Powell and J. G. Meert, "Assembly and Break–up of Rodinia: Introduction to the Special Volume," Precambrian Res. **110**, 1–8 (2001).

99. C. M. Powell, D. L. Jones, S. Pisarevsky, and M. T. D. Wingate, "Palaeomagnetic Constraints on the Position of the Kalahari Craton in Rodinia," Precambrian Res. **110**, 33–46 (2001).

100. T. Radhakrishna and J. Mathew, "Late Precambrian (850–800 Ma) Palaeomagnetic Pole for the South Indian Shield from the Harohalli Alkaline Dykes: Geotectonic Implications for Gondwana Reconstructions," Precambrian Res. **80**, 77–87 (1996).

101. T. Rivers, "Lithotectonic Elements of the Grenville Province: Review and Tectonic Implications," Precambrian Res. **86**, 117–154 (1997).

102. J. J. W. Rogers and M. Santosh, "Configuration of Columbia, a Mesoproterozoic Supercontinent," Gondwana Res. **5**, 5–22 (2002).

103. J. J. W. Rogers, "A History of Continents in the Past Three Billion Years," J. Geol. **104**, 91–107 (1996).

104. O. M. Rozen, A. V. Manakov, and N. N. Zinchuk, *Siberian Craton: Formation, Diamond Mineralization* (Nauchnyi Mir, Moscow, 2006) [in Russian].

105. M. A. Semikhatov, A. B. Kuznetsov, I. M. Gorokhov, et al., "Low $^{87}Sr/^{86}Sr$ Ratio in Seawater of the Grenville and Post-Grenville Time: Determining Factors," Stratigr. Geol. Korrelyatsiya **10** (1), 1–41 (2002) [Stratigr. Geol. Correlation **10** (1), 1–41 (2002)].

106. S. V. Shipunov and N. M. Chumakov, "Paleomagnetism of Upper Proterozoic Deposits in the Kola Peninsula," Geotektonika **25**, 404–410 (1991).

107. E. V. Sklyarov, D. P. Gladkochub, A. M. Mazukabzov, et al., "Neoproterozoic Mafic Dike Swarms of the Sharyzhalgai Metamorphic Massif (Southern Siberian Craton)," Precambrian Res. **122**, 359–376 (2003).

108. A. V. Sochava and V. N. Podkovyrov, "The Compositional Evolution of Meso- and Neoproterozoic Carbonate Rocks," Precambrian Res. **73**, 283–289 (1995).

109. U. Soderlund, S. A. Elming, R. E. Ernst, D. Schissel, "The Central Scandinavian Dolerite Group–Protracted Hotspot Activity or Back-Arc Magmatism? Constraints from U–Pb Baddeleyite Geochronology and Hf Isotopic Data," Precambrian Res. **150**, 136–152 (2006).

110. M. Stein and S. L. Goldstein, "From Plume Head to Continental Lithosphere in the Arabian–Nubian Shield," Nature **382**, 773–778 (1996).

111. J. A. Tarduno and A. V. Smirnov, "Stability of the Earth with Respect to the Spin Axis for the Last 130 Million Years," Earth Planet. Sci. Lett. **184**, 549–553 (2001).

112. *Testing Rodinia Hypothesis from Its Building Blocks*, Ed. by S.V. Bogdanova, Z. X. Li, E. M. Moores, and S. A. Pisarevsky, Precambrian Res. **160**, 1–210 (2008).

113. E. Tohver, B. A. van der Pluijm, R. van der Voo, et al., "Paleogeography of the Amazon Craton at 1.2 Ga: Early Grenvillian Collision with the Llano Segment of Laurentia," Earth Planet. Sci. Lett. **199**, 185–200 (2002).

114. T. H. Torsvik, L. M. Carter, L. D. Ashwal, et al., "Rodinia Refined or Obscured: Palaeomagnetism of the Malani Igneous Suite (NW India)," Precambrian Res. **108**, 319–333 (2001).

115. T. H. Torsvik, D. Roberts, and A. Siedlecka, "Palaeomagnetic Data from Sedimentary Rocks and Dolerite Dykes, Kildin Island, Rybachi, Sredni and Varanger Peninsulas, NW Russia and NE Norway: A Review," Spec. Publ. Nor. Geol. Unders. **7**, 315–326 (1995).

116. T. H. Torsvik, M. A. Smethurst, J. G. Meert, et al., "Continental Break–up and Collision in the Neoproterozoic and Palaeozoic – A tale of Baltica and Laurentia," Earth Sci. Rev. **40** (3–4), 229–258 (1996).

117. J. W. Valentine and E. M. Moores, "Plate-Tectonic Regulation of Animal Diversity and Sea Level: A Model," Nature **228**, 657–659 (1970).

118. J. Veizer, "Strontium Isotopes in Seawater through Time," Ann. Rev. Earth Planet. Sci. **17**, 141–167 (1989).

119. V. A. Vernikovsky and A. E. Vernikovskaya, "Tectonics and Evolution of Granitoid Magmatism in the Yenisei Range," Geol. Geofiz. **47** (1), 35–52 (2006).

120. V. A. Vernikovsky, A. E. Vernikovskaya, A. B. Kotov, et al., "Neoproterozoic Accretionary and Collisional Events on the Western Margin of the Siberian Craton: New Geological and Geochronological Evidence from the Yenisei Ridge," Tectonophysics **375**, 147–168 (2003).

121. H. J. Walderhaug, T. H. Torsvik, and E. Halvorsen, "The Egersund Dykes (SW Norway): A Robust Early Ediacaran (Vendian) Palaeomagnetic Pole from Baltica," Geophys. J. Int. **168**, 935–948 (2007).

122. A. B. Weil, R. Van der Voo, C. MacNiocaill, and J. G. Meert, "The Proterozoic Supercontinent Rodinia: Paleomagnetically Derived Reconstructions for 1100 to 800 Ma," Earth Planet. Sci. Lett. **154**, 13–24 (1998).

123. G. E. Williams, "Late Precambrian Glacial Climate and the Earth's Obliquity," Geol. Mag. **112**, 441–465 (1975).

124. A. P. Willner, T. Ermolaeva, L. Stroink, et al., "Contrasting Provenance Signals in Riphean and Vendian Sandstones in the SW Urals (Russia): Constraints for a Change from Passive to Active Continental Margin Conditions in the Neoproterozoic," Precambrian Res. **110**, 215–239 (2001).

125. M. T. D. Wingate, I.H. Campbell, W. Compston, and G. M. Gibson, "Ion Microprobe U–Pb Ages for Neoproterozoic Basaltic Magmatism in South-Central Australia and Implications for the Breakup of Rodinia," Precambrian Res. **87**, 135–159 (1998).

126. M. T. D. Wingate, F. Pirajno, and P. A. Morris, "Warakurna Large Igneous Province: A New Mesoproterozoic Large Igneous Province in West-Central Australia," J. Geol. **32**, 105–108 (2004).

127. M. T. D. Wingate, S. A. Pisarevsky, and D. A. D. Evans, "Rodinia Connections between Australia and Laurentia: no SWEAT, no AUSWUS?," Terra Nova. **14**, 121–128 (2002).

128. S. Zhang, Z. X. Li, and H. Wu, "New Precambrian Palaeomagnetic Constraints on the Position of the North China Block in Rodinia," Precambrian Res. **144**, 213 (2006).

129. G. Zhao, M. Sun, S. A. Wilde, and S. Li, "A Paleo–Mesoproterozoic Supercontinent: Assembly, Growth and Breakup," Earth Sci. Rev. **67**, 91–123 (2004).