Gondwana Research, V. 5, No. 1, pp. 147-156.
© 2002 International Association for Gondwana Research, Japan.
ISSN: 1342-937X

GR Gondwana Research

Anorthosites, Granulites and the Supercontinent Cycle

Amalbikash Mukherjee[1] and Subhasish Das[2]

[1] *25/1 Subodh Park, Bansdroni, Kolkata – 700 070, India*

[2] *Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur – 721 302, India*

(Manuscript received April 12, 2001; accepted May 31, 2001)



Abstract

The pattern of occurrence of the massif-type anorthosites of the Proterozoic on a Rodinia reconstruction suggests that the geneses of the anorthosites, the associated granulites, and their chief repository- the Grenville age mobile belt - may be interrelated. This relationship has been examined within the broad geodynamic and spatial-temporal framework of the Proterozoic supercontinent. All over the Grenville age mobile belt, approximately within 1500 – 1000 Ma, two successive, back-to-back episodes can be recognized. A continent-continent collisional episode with massive sedimentation, great crustal shortening and thickening with large folds and nappes, metamorphism and calcalkaline magmatism, and accretion of juvenile crust was followed within little over a hundred million years or so by an extensional episode, beginning with large scale mantle-derived basic magma invasion, ponding and differentiation at the base of the thickened orogen, anorthosite diapirism and pervasive thermal overprinting of the lower and middle crust producing granulite belts. Cooling, unroofing and erosion of the orogen coincided with the later stages of the extension, which ended with splitting of the supercontinent. We have argued that the first episode marks the phase of closing in and amalgamation of the converging continental lithospheric plates and the second episode represents the phase of reversal, rifting, plate separation and drifting away of the post-split continental blocks. We believe, the supercontinental closing and opening cycles provide (a) realistic force fields and appropriate spatial-temporal and thermal-tectonic framework for the origin of the Proterozoic massif-type anorthosites and the associated granulites and (b) an explanation for the spatially overlapping but apparently conflicting evidence of both collisional and extensional tectonic signatures in the Grenville age orogenic belts.

Key words: Anorthosites, granulites, Grenville age, orogeny, Proterozoic supercontinent.

Introduction

Partial melting through depressurization of the upper mantle in an extensional set-up has long been known as a potent mechanism for generating large volumes of basaltic magma (Ringwood, 1975; Yoder, 1976; Turcotte and Schubert, 1982). Hot, basic magma underplated at the base of the continental crust has generally been accepted as one probable heat source for deep crustal high grade metamorphism (Bohlen, 1987, 1991; Mukherjee, 1987, 1989; Wickham and Oxburgh, 1987; Fyfe, 1992; Harley, 1992). Basaltic magma accumulated at the base of the continental crust has been preferred as the parent magma for massif-type anorthosites (Bowen, 1917; Emslie, 1985, 1989). What has proved to be a difficult task is to understand how a virtual repository of massif type anorthosites and granulites came to exist at the base of some Grenville age orogens, where enormous compression and crustal shortening have been envisaged through continent-continent collision (Newton, 1983; Wiener et al., 1984; Rivers, 1997).

In this paper, we have tried to examine this problem within the broad geodynamic framework of assembly and dispersal of continental blocks in the Proterozoic (Mukherjee, 2000). Our object is to explore if both collisional and extensional tectonics and their petrogenetic consequences can be accommodated within a realistic sequence of the Grenvillian Events

Massif-Type Anorthosites in the Rodinia Assembly

One of the many intriguing features of the massif-type anorthosites of the Proterozoic is the fact that their locations seem to form belt-like arrays across the continents, when these continents are reset into hypothetical pre-Mesozoic-drift configurations (Herz,

1969; Piper, 1974, 1976). In the northern hemisphere the anorthosite belt begins in Europe in Finland / Ukraine, continues through Sweden and S. Norway, the outer Hebrides, Greenland, Canada and the United States. The southern hemisphere anorthosite belt begins in the west at Capivarita, Brazil, extends eastwards to Angola, Tanzania, Madagascar, Queen Maud Land in Antarctica, the Eastern Ghats of India and possibly into the Musgrave range of Australia (Herz, 1969). Piper (1974, 1976) noted a great circle alignment of massif-type anorthosites (2250–1000 Ma) along a belt across the Proterozoic supercontinent, coinciding with zones of rapakivi granites, alkaline intrusions, thick grabens, and linear mobile belts of 1150 ± 200 Ma age.

Mukherjee (1996) plotted a large number of Proterozoic anorthosites on a supercontinent reconstruction based on the palaeomagnetic and geochronological data from Piper (1974) and Donaldson et al. (1973) and confirmed (a) the anorthosite belt on the elongate ledge-like Proterozoic supercontinent, (b) parallelism of the length of the supercontinent with the Apparent Polar Wander Path (APWP) between two hairpins dated 1300 Ma and 1150 Ma and (c) an anorthosite age progression from well over 1500 Ma in the Baltic-Angara segment to well below this in the Gondwana segment.

Alternative configurations for the Proterozoic supercontinent have been proposed since 1990s (Dalziel, 1991; Hoffman, 1991; Moores, 1991; Rogers, 1996). The one we have adopted here is broadly after Rogers (1996). A diagrammatic representation of this configuration, Rodinia, is given in figure 1. We will not go here into development of the Rodinia concept, its supportive evidence and its sundry variations. The configuration of figure 1 is essentially an agglomeration of three protocontinents, named Ur, Nena and Atlantica by Rogers (1996). A significant difference of the Rodinia assembly from the earlier elongate configuration proposed by Piper (Piper, 1976) is that Rodinia provides for one-to-one amalgamation of the paired margins of several protocontinental blocks. One is between Ur (with a coastal strip of East Antarctica) and Antarctica mainland and the other between the eastern margin of proto-North America (as a part of Nena) and the western margin of Proto-South America (as a part of Atlantica) (Fig. 1). As a result, we have an impressive alignment of a ca. 1000 Ma old Grenvillian mobile belt traceable from the eastern margin of North America through the Namaqua-Natal belt of southern Ur, Dronning Maud Land, Napier and Rayner Complexes, and Vestfold Hills of East Antarctica, Sri Lanka, Eastern Ghats of India and the Albany-Fraser belt of Australia. Extension of this belt to include South China cratonic block has been proposed by Zhang and Piper (1997), though an alternative position for this block is between eastern Australia and western North America (Li et al., 1995). Also, the North China, Kazakhstan and Tarim blocks, shown in figure 1 as close to their Pangean locations, may have been down further south linked to Ur during the Proterozoic and may have shared parts of the Grenvillian belt. Fitzsimons (2000) has drawn attention to small scale age differences in three Grenville age provinces of Maud, Rayner and Wilkes in East Antarctica, correlated with similar rocks in Namaqua-Natal, Eastern Ghats and Albany-Fraser belts respectively, within the overall age bracket: 1200–900 Ma and has recognized three separate collisional orogens within the Grenville belt.

We have plotted 72 major Proterozoic massif-type anorthosite plutons on the Rodinia reconstruction of figure 1. Exact geographic accuracy cannot obviously be achieved in plottings of this type because of the diagrammatic nature of the reconstruction. We believe nevertheless that prominent patterns of occurrence of the anorthosites, if any, may still be brought out in this way. All the plotted anorthosite bodies are labeled and have been identified in the legend for figure 1.

Concentration of massif-type anorthosites in the Grenville age belt along the eastern margin of Baltica, North America and Ur is noteworthy. There is an interesting overall age progression from the Baltic-Ukraine end (well over 1500 Ma) to the Eastern Ghats of India (well below 1500 Ma), although this progression is neither evenly spread out nor monotonic.

The anorthosite occurrences of the Grenville belt do not figure symmetrically in both sides of the opposing cratons, envisaged as amalgamating or colliding during the Grenville Orogeny. In the South American counterpart of the Grenville interface no major anorthosite occurrence has been identified. Similarly, anorthosites are much more numerous in the Eastern Ghats than in the exposed parts of East Antarctica.

At least three other notable concentrations of massif-type anorthosites are in (1) eastern Africa, flanking the eastern margin of the Tanzanian craton (age unknown), (2) Baltic shield, away from the Grenville belt (1500 to 2260 Ma) and (3) the Aldan shield, along the Stanovoy belt (1705 to 2160 Ma).

Some of the Baltic anorthosites on the northwestern side of the Grenville-age thrust limit may be related to the ca. 1.6 ± 0.2 Ga orogenic belts joining Baltica (Baltic-Ukraine shields) with Arctica (North America, Greenland and Siberian shield), forming the protocontinent Nena.

In the Midwest continental United States, the Laramie anorthosite complex (1.43 Ga) and the neighbouring Horse Creek anorthosite complex (1.76 Ga) are believed to have been intruded along or near a Paleoproterozoic suture zone, the Cheyenne belt, where a 1.78 – 1.74 Ga arc-continent collisional event has been recognized (Scoates and Chamberlain, 1997).

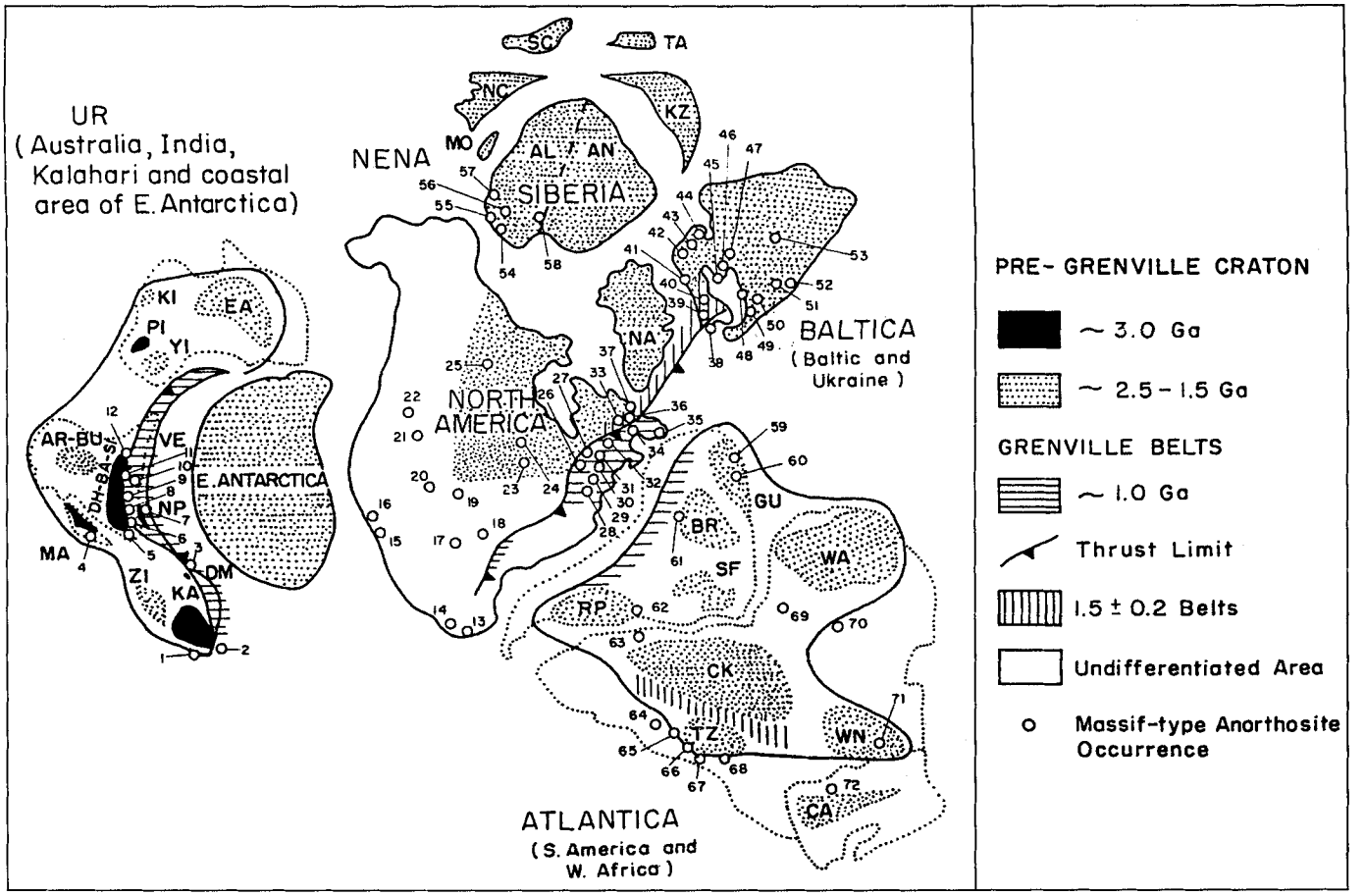


Fig. 1. Approximate locations of massif-type anorthosites on Rodinia. Supercontinent configuration and craton characterizations mainly after Rogers (1996). AL-Aldan; AN-Anabar/Angara; AR-Aravalli; BA-Bastar; BR-Brazil; BU-Bundelkhand; CA-Central Arabia; CK-Congo/Kasai; DH-Dharwar; DM-Western Dronning Maud Land; EA-Eastern Australia; GU-Guyana; KA-Kaapvaal; KI-Kimberley; KZ-Kazakhstan; MA-Madagascar; NA-North Atlantic; NC-North China; NP-Napier; PI-Pilbara; RP-Rio de la Plata; SC-South China; SF-Sao Francisco; SI-Singhbhum; Ta-Tarim; TZ-Tanzania; VE-Vestfold; WA-West Africa; WN-West Nile; YI-Yilgarn; ZI-Zimbabwe. The anorthosite locations (numbered open circles) are taken from the compilation of Ashwal (1993), which should be seen for the source references. The occurrences with a few additional references are as follows: 1-Koperberg, Namaqualand; 2-Plat Sjambok, S.Africa; 3-Amphitheatre L., Enderby Land; 4-Ankafotia, Saririaki, Manambahi, Volovolo (all in Madagascar); 5-Manapparai, Kadavur, Oddanchatram, Palni (all in Tamil Nadu, India); 6-Chinglepet, Tamil Nadu (India); 7-Eliseev, Queen Maud Land; 8-Nellore, Andhra Pradesh (India); 9-Kondapalli, Andhra Pradesh (India); 10-Chilka L.,Orissa (India), 1404 Ma (Sarkar et al., 1981; Mukherjee et al.,1999); 11-Bolangir, Orissa (India), (Mukherjee et al., 1999); 12-Bela, Biwabathan, Dumka,Bankura (all in Bihar, India); 13-Oaxaca, Mexico (1080 Ma); 14-Pluma Hidalgo, Mexico; 15-Orocopia, CA, USA; 16-San Gabriel, CA, USA (1220 Ma); 17-Big Burro, NM, USA; 18-Glen Mts, OK, USA (528 Ma); 19-Cambridge Arch, NB, USA; 20-Laramie, WY, USA (1440 Ma), (Mitchell et al.,1996); 21-Bitterroot, MT, USA; 22-Boehls Butte, ID, USA; 23-Wolf R., WI, USA (1485 Ma); 24-Duluth, MN, USA (1130 Ma); 25-Clearwater, Saskachewan (2000 Ma); 26-Bethoulat, Quebec; 27-Pambrun, Quebec; 28-Marcy, Adirondack (1288, 1130 Ma); 29-Morin, Quebec (1160 Ma); 30-Lac St-Jean,Quebec (1156,1148 Ma), 31-LacTetepisca, Lac Berte, Quebec; 32-Manicouagan, Lac Raudot, Quebec; 33-Michikamau, Labrador (1450 Ma); 34-Romaine R., LacFournier, Quebec; 35-Mecatina R., Lac Minipi, Quebec; 36-Harp L. Labrador (1460 Ma); 37-Nain, Labrador (1305 Ma); 38- Rogaland, Norway (930-1500 Ma); 39-Vossestrand/ Jotun, Norway; 40-Nordringra, Sweden; 41-Lofoten, Norway (1803 Ma), (Markl et al., 1998); 42-Vaskojoki, Finland (1906 Ma); 43-Salno Tundra, Kola Peninsula (1870 Ma); 44-Kolvitsa-Kandalaksha (2260 Ma), Main Range, Kola Peninsula; 45-Turku, Finland; 46-Ahvenisro, Finland (1645 Ma); 47-Salmi, E. European Platform (1500,1566,1552 Ma); 48-Riga, E. European Platform (1600 Ma); 49-Suwalki, Poland (1396 Ma); 50-Mazurskii, Poland; 51-Korosten(1975, 1740 Ma), E. European Platform; 52-Korsun-Novomorgorod (1840 Ma), E.European Platform; 53-Nurlaty,Tuimazi (2570 Ma), Chigiren, Volga-Ural region; 54-Kunmanevsky, Aldan S.; 55-Lavlinsky, Aldan S.; 56-Lantarsky Massif, Udutkansky (2160 Ma), Aldan S.; 57-Sekhtagsky, Chogarsky, Aldan S.; 58-Kalarsky (1850, 1877 Ma), Aldan S.; 59-Sierra Nevada de Santa Marta, Colombia; 60-San Quintin, Venezuela; 61-Ciriquiqui, Brazil; 62-Capivarita, Brazil; 63-Kunene, Angola; 64-Tete, Mozambique; 65-Angonia, Mozambique; 66-Upangwa, Tanzania, Linthipi, Malawi; 67-Uluguru, Tanzania; 68-Ikongwe, Tanzania; 69-Kainya, Nigeria; 70-Aïr, Nigeria (430 Ma); 71-Aswan, Egypt; 72-Muyahil, Saudi Arabia.

Supercontinent Cycles and Geodynamic Implications

Assembly and breakup of supercontinents seem to have a pattern of cyclical episodicity (Hoffman, 1991; Unrug, 1992, 1995). Convergence of at least 3 major protocontinental blocks, Ur, Nena and Atlantica, to form Rodinia around 1100 – 1000 Ma, breakup of Rodinia within ~ 750 Ma, reassembly into Pangea within 300 Ma and once again its breakup between 120 and 40 Ma are cases in point.

Supercontinent assembly and breakup display significant time overlaps in different sections (Unrug, 1995). Such overlaps may cover enormous time scales. For instance, the last phase of Rodinia breakup overlapped in time with the early collision events welding the East Gondwana cratons with the western margin of East Gondwana, although the peaks of the two events: Rodinia breakup and the assembly of East and West Gondwana must have been about 500 Ma apart (Rogers, 1996). These overlaps introduce some imprecision into the overall episodicity but do not make it altogether invalid. In fact, supercontinents appear to have broken apart gradually from one end to the other, following zones close to earlier sutures or interfaces and came together nearly the same way. For instance, the curvilinear zone along which the Australian, Indian, and southern African (mainly Kalahari) protocontinents wrap round East Antarctica in Rodinia is very similar to the zone of amalgamation of Australia, India and parts of southern Africa with East Antarctica in the Pangea set-up. Similarly, the eastern coastline of North America remained broadly comparable in the Rodinia and Pangea assemblies, with the difference that the proto-West Gondwana agglomerate of Rodinia rotated counterclockwise through about 90^0, bringing up northwestern South America and north-eastern Africa against North America in the Pangea assembly (Rogers, 1996).

Apparent polar wander paths in some cases spectacularly register the coming together and drifting away phases of the supercontinent cycle. The nearly 180^0 turnabout of the well constrained North American APWP at the Logan loop (1.15 – 1.20 Ga) and the Grenville loop (~ 1.00 Ga) (Irving and McGlynn, 1981; Idnurm and Giddings, 1995; Idnurm and Radhakrishna, 1999) corresponds well with independently documented large scale supercontinental movements.

Unfortunately, well constrained Proterozoic palaeomagnetic data for all continents are not yet available. In particular, APWP documented from paired and opposing continental blocks in Rodinia, e.g., Ur and East Antarctica or eastern North America and Western South America, should be particularly helpful in bringing out or clearly resolving the collisional and distensional phases of the supercontinent cycle. A partial picture of such movements of paired, opposing blocks is provided by the head-on merging of the Congo APWP and Indian APWP at ca. 683 Ma, registering the initial continent-continent collision within the East Africa Orogen (Meert and Van der Voo, 1997; Meert, 1999).

Movement of continents, often over large distances as registered by palaeomagnetic data (for instance, about 5000 km displacement of the Grenville belt between 1125 and 1000 Ma, Irving and Mcglynn, 1976), must essentially be movement of the lithospheric plate. Since Arthur Holmes (1927), thermal convection in the earth's mantle has remained the favourite causative mechanism for large scale horizontal movement of the continents. A widely accepted model for lithospheric plate movement is based now on a boundary layer theory of thermal convection in an internally heated fluid, in which the lithospheric plate behaves as the thermal boundary layer of mantle convection cells (Turcotte and Schubert, 1982).

Estimated Rayleigh numbers (Ra) for the upper (~700 km) and lower (~2000 km) mantles are considerably larger than the critical Ra ($\sim 10^3$) for convective flow. So, mantle convection may be considered a certainty, irrespective of whether convection is considered separately in the upper and lower mantles or in terms of cells across the entire mantle (Fowler, 1994).

It is generally agreed that there is a close correspondence between the direction of the convective overturn in the upper mantle and the direction of movement of the overriding plate. Beneath a pair of converging and colliding continental lithospheric plates, the mantle convection takes place in pairs of opposing cells, with the cooler material flowing in from both sides and going down. Under a pair of diverging plates of rifting or splitting continental lithosphere, the opposing pairs of mantle convection cells also have diverging current direction, with the hotter material rising and flowing away in both directions (Ziegler, 1993; Fowler, 1994). Also, during the dispersal of continents ridge-push forces may operate in both constructive and destructive interference with shear-traction at the base of the lithospheric plate, depending on their orientation relative to the asthenosphere flow pattern. Whereas the assembly of supercontinents occurs probably in areas of downwelling convection cells, when slab-forces, ridge-push and shear-traction may act in constructive interference (Ziegler, 1993).

Finally, a supercontinent assembly may exercise a pronounced thermal insulating effect on regions over the downwelling convection cells by trapping mantle heat and the radiogenic heat accumulated for a hundred million years or more (Hoffman, 1989; Ziegler, 1993). Mantle heat trapped due to high temperature-caused lowered thermal conductivity of the supercontinent may also be significant (Mukherjee, 1998). These factors may cause major changes in the global mantle convection pattern including decay and reversal.

Absolute time scales for the beginning, sustenance, efficiency, decay and reversal of mantle convection are still largely unconstrained and can be dealt with only speculatively. Runcorn (1980) obtained 30 Ma as the overturn time for a whole mantle-wide convection cell

with the convection current set at 10^{-6} cm.s^{-1}. In a computer-simulated numerical model, in which half of the heat is supplied from below and half supplied internally with Ra set at 1.4×10^6, convection led to vigorous mixing across the upper mantle in 155 Ma (Hoffman and McKenzie, 1985). Scaled results from laboratory experiments with viscous fluids heated from below have yielded interesting estimates for the earth's convecting mantle e.g., current velocity: ~ 3 cm.yr^{-1}, boundary layer thickness: ~ 10^2 km and time between successive thermals or rising plume-like instabilities : ~ 10^8 Ma (Tritton et al., 1980).

To conclude this section, available results and viewpoints suggest that under certain conditions episodicity or cyclicity in the mantle convection pattern may develop with time scales ranging from a few tens to a hundred million years or so. One may only speculate further that under suitable conditions this cyclicity of mantle convection may be transferred to a cyclicity of movement of the overriding continental lithospheric plates.

Proterozoic Anorthosite-Granulite Associations-Genetic Constraints and Time Relations

Massif-type anorthosites and regional granulite belts of the Proterozoic are among the most intensely debated topics of geology (for general coverage see Emslie, 1985; Wiebe, 1992; Ashwal, 1993; Harley, 1992). We will first state our preference and position in these debates straightaway, then follow up with a summary of the already published evidence and arguments (Mukherjee, 1987, 1989, 1996, 1998; Mukherjee et al., 1999) and finally briefly point out how these are relevant as constraints in our present discussion. Unless specially needed, we have refrained from repeatedly citing these references in the following section.

Genetic constraints

Massif-type anorthosites originate from large, slowly cooling layered basic complexes formed from tholeiitic basalt magma ponded at the base of the continental crust. Favourable conditions for extensive partial melting of the upper mantle necessary to generate precursor magma bodies of this nature develop in extensional set-ups beneath zones of (a) intracratonic rifting (without ocean opening) and (b) supercontinental splitting or breakup.

Heat flow from the slowly cooling layered basic complexes and direct mantle heat flow at plate divergences trigger and sustain high grade metamorphism in the continental crust overhead, specially the lower and the middle crust, and produce regional granulite belts, which are invaded by the anorthosite diapirs rising from the same differentiated layered complexes.

While anorthosite volcanism is unknown and anorthosite dykes are rare, transitions between typical anorthosite massifs and layered basic complexes with thick anorthositic layers are well known. Diapirs of very coarse grained anorthosites (1–10 cm, rarely up to 1 m, unzoned/weakly zoned plagioclase, Wiebe, 1992) with circular or quasi-circular internal primary flow structures, strongly discordant with the host rock regional structure, are known to have been intruded at wide-ranging tectonic levels. Darker coloured gabbroic/noritic, oxide-rich varieties are generally more abundant near the border of the diapirs. Block structures, schlieren, fluidal dyke-like bodies and similar structural and petrographic heterogeneities are common in most anorthosite massifs. Protoclastic granulation is universal.

Chemical variations from leucoanorthosites to oxide-rich gabbroic or noritic rocks within a typical anorthosite pluton do not admit of a one-to-one serial magmatic differentiation trend: anorthosite → anorthositic norite / gabbro → Fe-Ti-oxide-rich rocks, because of several reasons, the two most important among them being (1) the forbiddingly high liquidus temperature of the required high Al_2O_3 hyperfeldspathic magma and (2) the theoretical inadmissibility of the required simultaneous increase of both compatible and incompatible elements e.g., Fe, Mn, Mg, Ti, P and REE with decreasing Si, Al and Ca in a truly serial one-to-one differentiation trend. Wide variation in Mg-Fe ratio of the pyroxenes against a comparatively narrowly constrained plagioclase composition is another common intriguing feature of massif-type anorthosites, that does not reconcile with normal fractionation trend of a basaltic magma and suggests syn- or post-crystallization modifications.

The metamorphic rocks invaded by anorthosite diapirs are dominantly (> 70 per cent) of high grade type. These rocks are singularly desiccated (water activity of the order of 0.1 , often much less), almost unzoned with nearly flat isograd surfaces in sharp contrast to the multiply zoned, multifacies Alpine-type belts of the Phanerozoic, and commonly include anatectically melted pockets of felsic granulites. Their high grade metamorphism almost completely postdates the phase of large scale folding and crustal shortening of the belt where they occur. Estimated and measured post-peak metamorphic cooling rates of these rocks are invariably extremely low (estimated rate 12–13^0 C Ma^{-1} in the Eastern Ghats, Mukherjee, 1989, 1996; measured rate 1–2^{0}C Ma^{-1} in Pikwitonei granulites, Mezger et al., 1990 and 3 ± 1^0C Ma^{-1} in the Grenville belt of Ontario and New York, Mezger et al., 1993), for contrast, cooling rates as high as 55°C and 120°C Ma^{-1}

estimated from zoned amphibolite facies garnets in Paleozoic (Acadian) fold belts of southwestern New Hampshire, Muncill and Chamberlain, 1988)

P–T paths of the Proterozoic granulite belts are overwhelmingly of the counterclockwise type in contrast to nearly universally occurring clockwise P–T paths recorded from the Phanerozoic Alpine-type domains. Conductive cooling models are able to reproduce counterclockwise P–T paths characteristic of Proterozoic granulites, when heating is taken to precede loading, or heating and loading are considered as proceeding together. Heat and magma input from the mantle initially perturbs the steady-state geotherm to a transient elevated position. This is followed by or proceeds with loading of the invaded crustal rocks, and later is followed by unroofing and cooling, restoring the transient elevated geotherm to its pre-metamorphic low, steady-state position.

Where massif-type anorthosites have invaded high grade metamorphic rocks as in the Eastern Ghats and similar terrains, the diapir-aureole structural, petrological and thermobarometric relationships lead to an inverted Y-shaped, branched and composite P–T configuration – as the essential topology of the anorthosite-granulite thermal evolution (Mukherjee et al., 1999, Fig. 18).

The single corner-stone of the genetic theory presented above is an enormously amplified scale of size and time of crystallization for the precursor basaltic parent magma body ponded at the base of the continental crust. From this follow all other conditions, namely, layering of the parent magma body, anorthosite diapirism beginning from inside the parent layered complex and in the process juxtaposing the modally sorted anorthosites with the oxide-rich gabbroic-noritic layers of the upper cryptic sequence, and a steeply elevated heat flow gradient making a thermal overprint in the lower and middle crust. (Mukherjee, 1996). This very special combination of genetic constraints and conditions in the Mesoproterozoic requires long protracted thermal perturbation and thermal upwelling along linear zones of a depressurized upper mantle beneath diverging continental lithospheric plates.

Time relationships

Massif-type anorthosites of the Grenvillian belt predate the high grade metamorphism of the belt by a ~0.05–0.1 Ga margin (Emslie and Hunt, 1990). Emslie and Hunt correlate this time lag with conductive heating of thick subcontinental lithosphere, that began with the anorthosite-mangerite-charnockite-granite magmatism and continued till geotherms rose sufficiently to produce granulites in the lower and middle crust. The most detailed geological history preceding and succeeding the anorthosite-granulite associations is available in the Adirondack Mountains of the Grenville Province (Wiener et al., 1984; McLelland and Chiarenzelli, 1990; Bohlen et al., 1992).

Deposition of thick pelitic-arkosic-carbonate sequences, metamorphism, major deformation producing large recline folds and nappes, and intrusion of quartz diorites, tonalites, and leucogranites of calcalkaline affinity characterize a 1300–1280 Ma period, referred to as the Elzevirian Orogeny.

In the next 1170–1130 Ma episode, massif-type anorthosites and the associated charnockites, mangerites, and granites of the Adirondack Highlands were intruded. Approximately synchronous with this stage were a phase of metamorphism in the North-West Lowlands and extremely ductile deformation along the Carthage-Colton zone.

A pervasive high grade metamorphism (ca. 1100 – 1000 Ma) affecting all the pre-existing igneous and metamorphic rocks is the next event. This is considered as the main phase of the Grenville Orogeny and subtitled as the Ottawan Orogeny. Strike-slip motions (1030 – 1000 Ma), followed by normal faulting (~950 Ma) on reactivated shear zones of the Carthage-Colton belt are extensional tectonic processes initiated in this period (Streepey and van der Pluijm, 2000). Detailed U–Pb geochronology of the Grenville region in southern Ontario and New York has identified a collage of crustal segments having distinctive thermal and tectonic histories with small time differences within an overall ~150 Ma period of isotopic resetting (Mezger et al., 1993). This does not invalidate the reality of the Grenville event as a whole, but confirms that the Grenville Orogeny was not switched on and off synchronously all over the region.

The post-1000 Ma period saw uplift and erosion of the Grenville orogen and deposition of Paleozoic sediments on erosional unconformities.

In the Eastern Ghats of India, a massif-type anorthosite event (~ 1404 Ma, Sarkar et al., 1981) predates the major granulite formation at ca. 1000 Ma (Paul et al., 1990; Mezger and Cosca, 1999). But the anorthosites have been shown to have invaded the protoliths of these same granulites (charnockites, khondalites, leptynites) (Mukherjee et al., 1999). The pre-anorthosite sequence in the Eastern Ghats includes massive sedimentary formations (protoliths of khondalites, quartzites and paragneisses), intercalated with calcalkaline magmatic rocks (protoliths of basic charnockites, basic granulites and leptynites) with widespread signatures of arc volcanism (Sarkar et al., 1994; Nanda and Pati, 1994). A rare occurrence of ophiolitic melange has been reported from Nellore (Reddy et al., 1994) The major phases of isoclinal to recline folding also predate the anorthosite

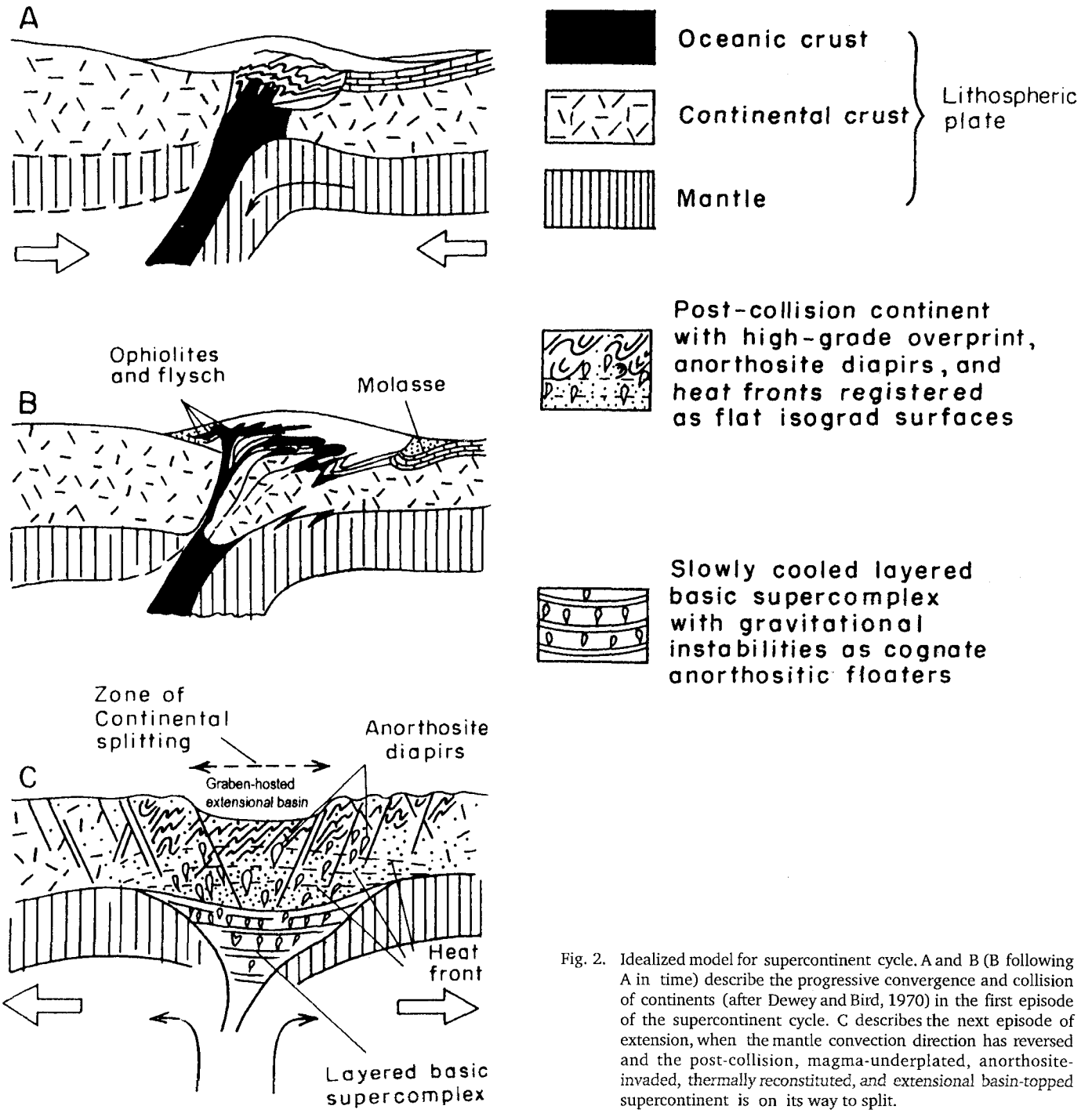


Fig. 2. Idealized model for supercontinent cycle. A and B (B following A in time) describe the progressive convergence and collision of continents (after Dewey and Bird, 1970) in the first episode of the supercontinent cycle. C describes the next episode of extension, when the mantle convection direction has reversed and the post-collision, magma-underplated, anorthosite-invaded, thermally reconstituted, and extensional basin-topped supercontinent is on its way to split.

invasion. A network of 2 – 10 km wide, few hundred km long shear zones showing oblique to strike-ship displacements, possibly initiated in the 1400 – 1000 Ma period, has been reported by Chetty and Murthy (1998). These structures may have overlapped in time with the two later metamorphic heating events (800 and 550 Ma, Shaw et al., 1997) and eventually facilitated the unroofing and extension of the Eastern Ghats belt and its separation from the Grenvillian counterpart in East Antarctica.

Discussion

We believe our review of the massif anorthosite locations on Rodinia (Fig. 1), and the genetic constraints and time relationships of the Proterozoic anorthosite-granulite associations points to (though does not prove) an important relationship between anorthosite-granulite genesis and the supercontinent cycle. The cycle of assembly and breakup of Rodinia provides a discernible

spatial-temporal framework for the Grenville age massif-type anorthosites and granulites. Also, we may at least qualitatively argue that the Rodinia cycle superposed an extensional force field over an earlier compressional field within the same Grenville orogen and created the conditions for origin of the anorthosites and the granulites.

In the Adirondack Mountains, a continent-continent collisional episode with massive sedimentation, great crustal shortening (and therefore thickening) with large folds and nappes, metamorphism, calcalkaline magmatism, and accretion of juvenile crust was followed within little over 100 Ma by an extensional episode, beginning with large scale basic magma invasion, ponding and differentiation at the base of the orogen, anorthosite diapirism, and thermal overprinting of the lower and middle crust producing granulite belts.

The extensional regime, with or without breaks, must have continued through cooling, unroofing, and erosion of the orogen and was eventually terminated by fragmentation of the orogen as the supercontinent split apart.

The Eastern Ghats belt presents more or less the same scenario, but with fewer details and a weaker supportive data-base. All over the Mesoproterozoic circum-East Antarctica mobile belt, an earlier regime of continental margin sedimentation, arc magmatism, recumbent/isoclinal folding and thrusting is known to have culminated in a 1200 – 1000 Ma high grade metamorphic event (Yoshida, 1995). An extensional regime must have taken over after this and continued without any major collisional intervention till the breakup of Rodinia.

A view of the idealized cyclical course of the Grenville age events: convergence → collision → extension → splitting is illustrated in figure 2.

When the supercontinent splits across an orogen and drifts apart on both sides, two important results would be expected: (1) much of the telltale sutures registering the earlier collisional event would be lost through erosion, and (2) the continental margins on both sides of the split would preserve signatures of a passive plate margin (Le Pichon and Sibuet, 1981). One may recall in this context the generally unsuccessful hunt for Proterozoic sutures in the Grenville age belts (Rogers, 1996).

Concluding Remarks

Proper evaluation of a multiple-working hypothesis connecting anorthosites, granulites and supercontinents has to wait till a substantially upgraded data-base, mainly from palaeomagnetic and geochronological investigations, emerges. All our limited analysis has achieved is perhaps a clearer framing of the hypothesis and an assessment of its plausibility and the gaps, where more information is needed.

If there is an essential truth at the core of the hypothesis, then it would be in order here to mention a few closely allied and dependent sub-truths. The mobility of a mobile belt is a two-way process. It begins with collision, but generally ends with extension, each episode possessing unique depositional, magmatic, metamorphic, structural and tectonic signatures. Therefore, in principle, each episode must be separately and independently dated. There may be an error of the order of a hundred million years or more, if the age of isotopic resetting of a granulite metamorphism at the late extensional phase of the Grenville Orogeny is taken to represent the age of the much earlier main collisional event, when the orogen was compressed and thickened. This would lead not only to erroneous history but also to faulty genetic models for massif-type anorthosites and granulites.

Acknowledgments

We are indebted to Dr. John J. W. Rogers and an anonymous reviewer for comments leading to improvement of the manuscript.

References

Ashwal, L.D. (1993) Anorthosites. Springer-Verlag, Berlin-Heidelberg, 422 p.

Bohlen, S.R. (1987) Pressure-temperature-time paths and a tectonic model for the evolution of granulites. J. Geol., v. 95, pp. 617-632.

Bohlen, S.R. (1991) On the formation of granulites. J. Metam. Geol., v. 9, pp. 223-229.

Bohlen, S.R., McLelland, J., Valley, J. and Chiarenzelli, J. (1992) Petrology and geochronology of Adirondack Mountains: a critical look at a classic granulite terrane and its associated anorthosite-mangerite-charnockite-granite (AMCG) suite. IGCP 304 Report , May 16-23, 125p.

Bowen, N.L. (1917) The problem of the anorthosites. J. Geol., v. 25, pp. 209-243.

Chetty, T.R.K. and Murthy, D.S.N. (1998) Regional tectonic framework of the Eastern Ghats mobile belt: a new interpretation. Geol. Surv. India, Spl. Publ., No. 44, pp. 39-50.

Dalziel, I.W.D. (1991) Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology, v. 19, pp. 598-601.

Dewey, J.F. and Bird, J.M. (1970) Mountain belts and the new global tectonics. J. Geophys. Res., v. 75, pp. 2615-2647.

Donaldson, J.A., Irving, E., McGlynn, J.C. and Park, J.K. (1973) Drift of the Canadian Shield. In: Tarling, D.H. and Runcorn, S.K. (Eds.), Implications of continental drift to the earth sciences. Academic Press, London, pp. 3-17.

Emslie, R.F. (1985) Proterozoic anorthosite massifs. In: Tobi, A. and Touret, J.L.R. (Eds.), The deep Proterozoic crust

in the North Atlantic Provinces. NATO ASI Ser. C, 158. Reidel, Dordrecht, pp. 39-60.

Emslie, R.F. (1989) Geology and petrology of the Harp Lake Complex, Central Labrador: an example of Elsonian magmatism. Geol. Surv. Can. Bull., v. 293, pp.1-136.

Emslie, R.F. and Hunt, P.A. (1990) Ages and petrogenetic significance of igneous mangerite-charnockite suites associated with massif anorthosites, Grenville province. J. Geol., v. 98, pp. 213-231.

Fitzsimons, I.C.W. (2000) Grenville-age basement provinces in East Antarctica: evidence for three separate collisional orogens. Geology, v. 28, pp. 879-882.

Fowler, C.M.R. (1994) The solid earth. Cambridge University Press, Cambridge, UK, 472p.

Fyfe, W.S. (1992) Magma underplating of continental crust. J. Volacanol. Geotherm. Res., v. 50, pp. 33-40

Harley, S.L., 1992. Proterozoic granulite terranes. In: Condie, K.C. (Ed.), Proterozoic crustal evolution. Elsevier, Amsterdam, pp. 301-359.

Herz, N. (1969) Anorthosite belts, continental drift, and the anorthosite event. Science, v. 164, pp. 944-947.

Hoffman, P.F. (1989) Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). Geology, v. 17, pp. 135-138.

Hoffman, P.F. (1991) Did the breakout of Laurentia turn Gondwana inside-out? Science, v. 252, pp. 1409-1412.

Hoffman, N.R.A. and McKenzie, D.P. (1985) The destruction of geochemical heterogeneities by differential fluid motions during mantle convection. Geophys. J. Roy. Astro. Soc., v. 82, pp. 163-206.

Holmes, A. (1927) Some problems of physical geology and the earth's thermal history. Geol. Mag., v. 65, pp. 263-278.

Idnurm, M. and Giddings, J.W. (1995) Paleoproterozoic-Neoproterozoic North America–Australia link: new evidence from palaeomagnetism. Geology, v. 23, pp. 149-152.

Idnurm, M. and Radhakrishnan, T. (1999) Australian and Indian APWPs and the time of amalgamation of India and Australia. In: Radhakrishnan, T. and Piper, J.D.A. (Eds.), The Indian Subcontinent and Gondwana: a palaeomagnetic and rock magnetic perspective. Geol. Soc. India, Mem., No. 44, pp. 33-44.

Irving, E. and McGlynn, J.C. (1976) Proterozoic magneto-stratigraphy and the tectonic evolution of Laurentia. Phil. Trans. Roy. Soc. London, Ser. A, 280, pp. 433-468.

Irving, E. and McGlynn, J.C. (1981) On the coherence, rotation and palaeolatitude of Laurentia in the Proterozoic. In: Kröner, A. (Ed.), Precambrian plate tectonics. Elsevier, Amsterdam, pp. 561-598.

Le Pichon, X. and Sibuet, J.C. (1981) Passive margins: a model of formation. J. Geophys. Res., 86(B5), pp. 3708-3720.

Li, Z.X., Zhang, L. and Powell, C.Mc.A. (1995) South China in Rodinia: part of the missing link between Australia-East Antarctica and Laurentia? Geology, v. 23, pp. 407-410.

Markl, G., Frost, B.R. and Bucher, K. (1998) The origin of anorthosites and related rocks from the Lofoten islands, Norhern Norway: I. Field relations and estimation of intrinsic variables. J. Petrol., v. 39, pp. 1425-1452.

Mclelland, J.M. and Chiarenzelli, J. (1990) Isotopic constraints on emplacement age of anorthositic rocks of the Marcy massif, Adirondack Mts., New York. J. Geol., v. 98, pp. 19-41.

Meert, J.G. (1999) Some perspectives in the assembly of Gondwana. In: Radhakrishnan, T. and Piper, J.D.A. (Eds.), The Indian Subcontinent and Gondwana: a palaeomagnetic and rock magnetic perspective. Geol. Soc. India, Mem., No. 44, pp. 45-58.

Meert, J.G. and Van der Voo, R. (1997) The assembly of Gondwana 800-550 Ma. J. Geodyn., v. 23, pp. 223-235.

Mezger, K., Bohlen, S.R. and Hanson, G.N. (1990) Metamorphic history of the Archean Pikwitonei granulite domain and the Cross Lake subprovince, Superior Province, Manitoba, Can. J. Petrol., v. 31, pp. 483-517.

Mezger, K., Essene, E.J., Van der Pluijm, B.A. and Halliday, A.N. (1993) U–Pb geochronology of the Grenville orogen of Ontario and New York: constraints on ancient crustal tectonics. Contrib. Mineral. Petrol., v. 114, pp. 13-26.

Mezger, K. and Cosca, M.A. (1999) The thermal history of the Eastern Ghats Belt (India) as revealed by U–Pb and $^{40}Ar/^{39}Ar$ dating of metamorphic and magmatic minerals: implications for the SWEAT correlation. Precamb. Res., v. 94, pp. 251-271.

Mitchell, J.N., Scoates, J.S., Frost, C.D. and Kolker, A. (1996) The geochemical evolution of anorthosite residual magma in the Laramie anorthosite complex, Wyoming. J. Petrol., v. 37, pp. 637-660.

Moores, E.M. (1991) Southeast U.S.- East Antarctica (SWEAT) connection: a hypothesis. Geology, v. 19, pp. 425-428.

Mukherjee, A. (1987) P–T-time history of a massif anorthosite-granulite interface of the Indian shield (Abst). In: Daly, J.S. (Ed.), Evolution of metamorphic belts, Programmes and Abstracts, Joint Meeting, Sept. 1987, Univ. College, Dublin, p. 16

Mukherjee, A. (1989) P–T-time history and thermal modelling of an anorthosite-granulite interface, Eastern Ghats metamorphic belt, India. In: Daly, J.S., Cliff, R.A. and Yardley, B.W.D. (Eds.), Evolution of metamorphic belts. Geol. Soc. Spl . Publ. No. 43, pp. 265-274.

Mukherjee, A. (1996) Thermal-tectonic evolution of the Proterozoic anorthosites-towards a unified theory. Ind. J. Geol., v. 68, pp. 133-156.

Mukherjee, A. (1998) The Eastern Ghats type metamorphism. Geol. Surv. India, Spl. Publ., No. 44, pp. 137-144.

Mukherjee, A., Jana, P. and Das, S. (1999) The Banpur-Balugaon and Bolangir anorthosite diapirs of the Eastern Ghats, India: implications for the massif anorthosite problem. Int. Geol. Rev., v. 41, pp. 206-242.

Mukherjee, A. (2000) The supercontinent cycles, massif-type anorthosites and granulite belts of the Proterozoic: towards a multiple-working hypothesis (Abst). GSA 2000. Abstracts with Programs, 32(7).

Muncill, G.E. and Chamberlain, C.P. (1988) Crustal cooling rates inferred from homogenization of metamorphic garnets. Earth Planet. Sci. Lett., v. 87, pp. 390-396.

Nanda, J.K. and Pati, U.C. (1994) Mafic granulites and charnockites from Behrampur Jeypore transect in Eastern Ghats of Orissa sector: a petrochemical study, Workshop on Eastern Ghats Mobile Belt, Visakhapatnam, India, (Abst.), Geol. Surv. India, p. 62.

Newton, R.C. (1983) Geobarometry of high-grade metamorphic rocks. Amer. J. Sci., v. 283-A, pp. 1-28.

Paul, D.K., Barman, T.R., Mcnaughton, N.J., Fletcher, I.R., Potts, P.J., Ramakrishnan, M. and Augustine, A.F. (1990) Archean

Proterozoic evolution of Indian charnockites: isotopic and geochemical evidence from granulites of the Eastern Ghats belt. J. Geol., v. 98, pp. 253-263.

Piper, J.D.A. (1974) Proterozoic crustal distribution, mobile belts and apparent polar movements. Nature, v. 251, pp. 381-384.

Piper, J.D.A. (1976) Palaeomagnetic evidence for a Proterozoic super-continent. Phil. Trans. Roy. Soc. London, A., v. 280, pp. 469-490.

Reddy, U.V.W., Narayana, B.L. and Shanti Kumar, C. (1994) Ophiolitic melange from Nellore schist belt – an evidence for Precambrian plate tectonics, Workshop on Eastern Ghats Mobile Belt, Visakhapatnam, India, (Abst.), Geol. Surv. India, p. 21.

Rogers, J.J.W. (1996) A history of continents in the past three billion years. J. Geol., v. 104, pp. 91-107.

Ringwood, A.E. (1975) Composition and petrology of the earth's mantle. McGraw-Hill, Inc. New York, 618p.

Rivers, T. (1997) Lithotectonic elements of the Grenville Province: review and tectonic implications. Precamb. Res., v. 86, pp. 117-154.

Runcorn, S.K. (1980) Some comments on the mechanism of continental drift. In: Davies, P.A. and Runcorn, S.K. (Eds.), Mechanisms of continental drift and plate tectonics. Academic Press, London, pp. 193-198.

Sarkar, A., Bhanumathi, L. and Balasubrahmanyan, M.N. (1981) Petrology, geochemistry and geochronology of the Chilka Lake igneous complex, Orissa state, India, Lithos., v. 14, pp. 93-111.

Sarkar, A., Ghosh, S., Rao, K.N., Bishui, P. K. and Gupta, S.N. (1994) Petrochemistry and Rb–Sr geochronology of the Kommalapadu charnockite: evidence for Mid-proterozoic arc magmatism in the Andhra Pradesh sector of the Eastern Ghats belt, Workshop on Eastern Ghats Mobile Belt, Visakhapatnam, India, (Abst.), Geol. Surv. India, p.68.

Scoates, J.S. and Chamberlain, K.R. (1997) Orogenic to post-orogenic origin for the 1.7 Ga Horse Creek anorthosite complex, Wyoming, USA. J. Geol., v. 105, pp. 331-343.

Shaw, R.K., Arima, M., Kagami, H., Fanning, C.M., Shiraishi, K. and Motoyoshi, Y. (1997) Proterozoic events in the Eastern Ghats granulite belt, India: evidence from Rb–Sr, Sm–Nd systematics, and SHRIMP dating. J. Geol., v. 105, pp. 645-65

Streepey, M.M. and Van der Pluijm, B.A. (2000) Lifting the veil of post-orogenic extension in the metasedimentary belt of the Grenville orogen, Ontario and NewYork. GSA 2000, Abstracts with Programs, 32(7).

Tritton, D.J., Rayburn, D.M. and Forrest, M.A. (1980) Convection of a very viscous fluid heated from below. In: Davies, P.A. and Runcorn, S.K. (Eds.), Mechanisms of continental drift and plate tectonics. Academic Press, London. pp. 267-287.

Turcotte, D.L. and Schubert, G. (1982) Geodynamics. JohnWiley and Sons, New York, 450p.

Unrug, R. (1992) The supercontinent cycle and Gondwana assembly: component cratons and the timing of suturing events. J. Geodyn., v. 16, pp. 215-240.

Unrug, R. (1995) Rodinia and Gondwana: a record of supercontinent configuration change. In: Yoshida, M. and Santosh, M. (Eds.), India and Antarctica during the Precambrian. Geol. Soc. India, Mem., No. 34, pp. 1-9.

Wickham, S.M. and Oxburgh, E.R. (1987) Low pressure regional metamorphism in the Pyrenees and its implications for the thermal evolution of rifted continental crust. Phil. Trans. Roy. Soc. London. Ser. A, 321, pp. 219-242.

Wiebe, R.A. (1992) Proterozoic anorthosite complexes. In: Condie, K.C. (Ed.), Proterozoic crustal evolution. Elsevier, Amsterdam, pp. 215-261.

Wiener, R.W., McLelland, J.M., Isachsen, Y.W. and Hall, L.M. (1984) Stratigraphy and structural geology of the Adirondack Mountains, NewYork: review and synthesis. Geol. Soc. America, Spl. Paper 194, 54p.

Yoder, H.S. Jr. (1976) Generation of basaltic magma. Nat. Acad. Sci.,Washington, D.C., 265p.

Yoshida, M. (1995) Assembly of East Gondwanaland during the Mesoproterozoic and its rejuvenation during the Pan-African period. In: Yoshida, M. and Santosh, M. (Eds.), India and Antarctica during the Precambrain. Geol. Soc. India, Mem., No. 34, pp. 25-45.

Zhang, Q.R. and Piper, J.D.A. (1997) Palaeomagnetic study of Neoproterozoic glacial rocks of the Yangzi Block: palaeolatitude and configuration of South China in the late Proterozoic Supercontinent. Precamb. Res., v. 85, pp. 173-199.

Ziegler, P.A. (1993) Plate-moving mechanisms: their relative importance. J. Geol. Soc. London, v. 150, pp. 927-940.