Pergamon

PII:S0899-5362(00)00016-6

*Journal of African Earth Sciences*, Vol. 30, No. 2, pp. 201–217, 2000

# A commentary on the tectono-sedimentary record of the pre-2.0 Ga continental growth of India *vis-à-vis* a possible pre-Gondwana Afro-Indian supercontinent

RAJAT MAZUMDER[1,*], PRADIP K. BOSE[2] and SUBIR SARKAR[2]
[1]Department of Geology, Asutosh College, Calcutta 700 026, India
[2]Department of Geological Sciences, Jadavpur University, Calcutta 700 032, India

ABSTRACT—An integrated chronicle of major events leading to the growth of the pre-2.0 Ga Indian Craton, which is the aim of this paper, is an essential requirement to constrain the possibility of Neoarchæan unification between Africa and India. The primordial sialic crust that eventually developed into the early Indian Craton segregated from the mantle before 3.8 Ga. Intially there were two seperate Indian blocks, the northern (NIB) and the southern (SIB), and they possibly amalgamated before 2.5 Ga. Rapid and extensive crustal growth at *ca* 3.1, 2.5 and 2.0 Ga, in conjunction with a related rise in relative sea level due to ocean basin volume reduction, kept the continental freeboard at a moderate level. The 2.5 Ga event was the greatest in magnitude and is likely to have led to the formation of an Indian supercontinent. Four sedimentary basins, one in the NIB and three in the SIB, developed on the typical Archæan tonalite-trondhjemite-granodiorite basement, through rifting induced by mantle upwelling. Continental freeboard was lowered as a consequence and transgressions generally followed. Rifting persisted in all the pre-2.0 Ga basins, except one (Bastar) in the SIB, which only underwent a Wilson cycle as the two blocks collided. All the SIB basins were closed by 2.0 Ga, while the basin in the NIB, which only developed at *ca* 2.5 Ga, still persisted. Neoarchæan continuity between the Central Indian Tectonic Zone and the Limpopo Belt appears likely from all major aspects, but for the deformation history, which still remains elusive. © 2000 Elsevier Science Limited. All rights reserved.

RÉSUMÉ—Le but de cet article est de construire le calendrier complet des événements majeurs qui ont conduit à la croissance du craton indien avant 2 Ga. Un tel calendrier est indispensable pour évaluer la possibilité de l'unification de l'Afrique et de l'Inde au Néoprotérozoïque. La croûte sialique primitive qui s'est transformée ensuite en craton indien précoce s'est séparée du manteau avant 3.8 Ga. Au début, il y avait deux blocs indiens séparés, celui du nord (NIB) et celui du sud (SIB), qui ont probablement fusionné un peu avant 2.5 Ga. La marge continentale libre est restée à une altitude basse, à cause de la croissance rapide et intense de la croûte au cours des événements à 3.1, 2.5 et 2.0 Ga, s'ajoutant à l'élévation du niveau de la mer à la suite de la réduction de volume des bassins océaniques. L'événement de 2.5 Ga, le plus important en magnitude, a vraisemblablement abouti à la formation d'un supercontinent indien. Quatre bassins sédimentaires, l'un sur le NIB et les trois autres sur le SIB, se sont développés sur un socle archéen typique de tonalite-trondhjémite-granodiorite par rifting induit par la remontée du manteau. Par conséquent, la marge continentale libre s'est abaissée et des transgressions ont généralement suivi. Le rifting a persisté dans tous les bassins avant 2.0 Ga, à l'exception d'un seul (Bastar) sur le SIB, qui a subi un cycle de Wilson seulement quand les deux blocs sont entrés en collision. Tous les bassins situés sur le SIB se sont fermés il y a 2.0 Ga, alors que le bassin sur le NIB qui s'est développé seulement il y a 2.5 Ga a persisté encore. La continuité au cours du Néoprotérozoïque de la Zone Tectonique de l'Inde Centrale et de la Ceinture du Limpopo semble vraisemblable d'après toutes leurs caractéristiques majeures, à l'exception de la déformation dont l'histoire reste encore mal définie. © 2000 Elsevier Science Limited. All rights reserved.

(Received 7/6/99: revised version received 13/9/99: accepted 13/9/99)

---

*Corresponding author
pradip@jugeo.clib0.ernet.in

## INTRODUCTION

A pre-Gondwana unification of Africa with India, possibly during the Neoarchæan, has been discussed by a number of workers (e.g. Rogers, 1993, 1996; Aspler and Chiarenzelli, 1998; Eriksson *et al.*, 1999). It has been suggested that the Limpopo Mobile Belt (LMB), joining the Kaapval Craton with the Zimbabwe Craton, was contiguous with the Central Indian Tectonic Zone (CITZ), joining the southern and northern blocks (SIB and NIB) of the early Precambrian Indian Craton (e.g. Rogers, 1996). Examination of this postulate is seriously hindered by poor knowledge of the pattern of early growth of the Indian Craton. In addition to a comparision between the LMB and CITZ, this paper explores the possible cause-and-effect relationship between secular changes in crustal thickness, relative sea level and the continental hypsometry with respect to the >2.0 Ga Indian Craton. An integrated chronicle of major episodes of growth of the Indian Craton, even though tentative within existing constraints of relevant data, is the aim of this paper; it may may also provide a guideline to evaluate the Neoarchæan Africa-India unification hypothesis, debated by Eriksson *et al.* (1999).

## LIMPOPO MOBILE BELT AND CENTRAL INDIAN TECTONIC ZONE

Both the LMB and CITZ have an approximately east-west dominant structural grain, roughly parallel to the direction of their elongation. In both cases, a central mobile belt is flanked by rifts. The rifts associated with the LMB are considered as products of plate collision (e.g. impactogenal model of Robb and Meyer, 1995) and the same genesis can be invoked for the CITZ also. Platformal sediments meta-morphosed to lower greenschist- to upper amphibolite-facies, as well as gneisses, constitute both the mobile belts, and they are bordered by granulites on both the north and south (van Reenen *et al.*, 1995; Holzer *et al.*, 1998; Acharyya, 1998; Roy, 1998; Bhowmik *et al.*, 1999). Both the mobile belts have undergone similar crustal-scale ductile shear deformation (van Reenen *et al.*, 1995; Acharyya, 1998). Against these large-scale similarities, there is a considerable difference in the maximum ages of deformation. While it is inferred to be at *ca* 2.68 Ga (Treloar and Blenkinsop, 1995) in the LMB; in the CITZ, it is thought to be at *ca* 1.6 Ga (Radhakrishna and Naqvi, 1986; Radhakrishna, 1989). However, Roy (1998) and Bhowmik *et al.* (1999) recently established a collision-related tectonothermal event of granulite-facies metamorphism that definitely pre-dated the 1.6 Ga orogenic phase in the CITZ.

## CRUSTAL PROVINCES OF INDIA

The Indian Precambrian Craton is intersected, almost at its middle, by the CITZ (Radhakrishna, 1989; Harris, 1993), which runs from the western margin of the craton, eastwards and then northeastwards (Fig. 1). It is divided into the southern (SIB) and northern (NIB) Indian cratonic blocks. Marked differences in character between them have been summarised by Eriksson *et al.* (1999).

## SOUTHERN INDIAN BLOCK

The SIB comprises three crustal provinces, Singhbhum, Bastar (Bhandara) and Dharwar, separated by rifts (Naqvi *et al.*, 1974) (Fig. 1) filled by sediments no older than Proterozoic. The maximum age of the tonalite-trondhjemite-granodiorite (TTG) basement is constrained at 3.8(?) Ga in the Singhbhum Province (Sm-Nd: Basu *et al.*, 1981). The oldest metasedimentary enclaves within the basement are dated at 3.5 Ga in Singhbhum ($^{207}Pb/^{206}Pb$: Goswami *et al.*, 1995) and 3.3 Ga in Dharwar ($^{207}Pb/^{206}Pb$: Peucat *et al.*, 1995). Typically, Archæan komatiitic basalt is locally intercalated with these sediments, which form part of the basement. K-rich granite intrusions in Dharwar indicate cratonisation at *ca* 2.5-2.6 Ga (U-Pb: Friend and Nutman, 1991; Chadwick, 1994). On the other hand, $K_2O$-rich (3.22%) granodiorite with a high initial $^{87}Sr/^{86}Sr$ ratio (0.711: Saha, 1994) in Singhbhum suggests cratonisation at about 3.1 Ga. K-rich granite intrusions suggest cratonisation at *ca* 2.5 Ga (Rb-Sr: Sarkar *et al.*, 1990; U-Pb: Sarkar *et al.*, 1993) in Bastar. Metamorphism in all three provinces is generally low, ranging from greenschist- to lower amphibolite-facies; upper amphibolite-facies with attendant migmatisation is localised. Granulites occur in the southern portion of the Dharwar Province; this granulite belt also covers a large part of Sri Lanka and perhaps also extended through what is now Madagascar (Acharyya, 1998). The structural trend in Dharwar Province is dominantly north-south, while that in Bastar was initially north-south but was rotated later to east-northeast–west-southwest; in Singhbhum the trend is broadly east-west.

## NORTH INDIAN BLOCK

The NIB possibly comprised a single crustal province, known as the Aravalli-Bundelkhand Province. In the Bundelkhand area in the east, early Precambrian sediments are very poorly exposed and very little is known about them; however, the gneissic basement incorporating some TTG enclaves is well-exposed in places. Both the basement and the succeeding volcanosedimentary successions are well-exposed in

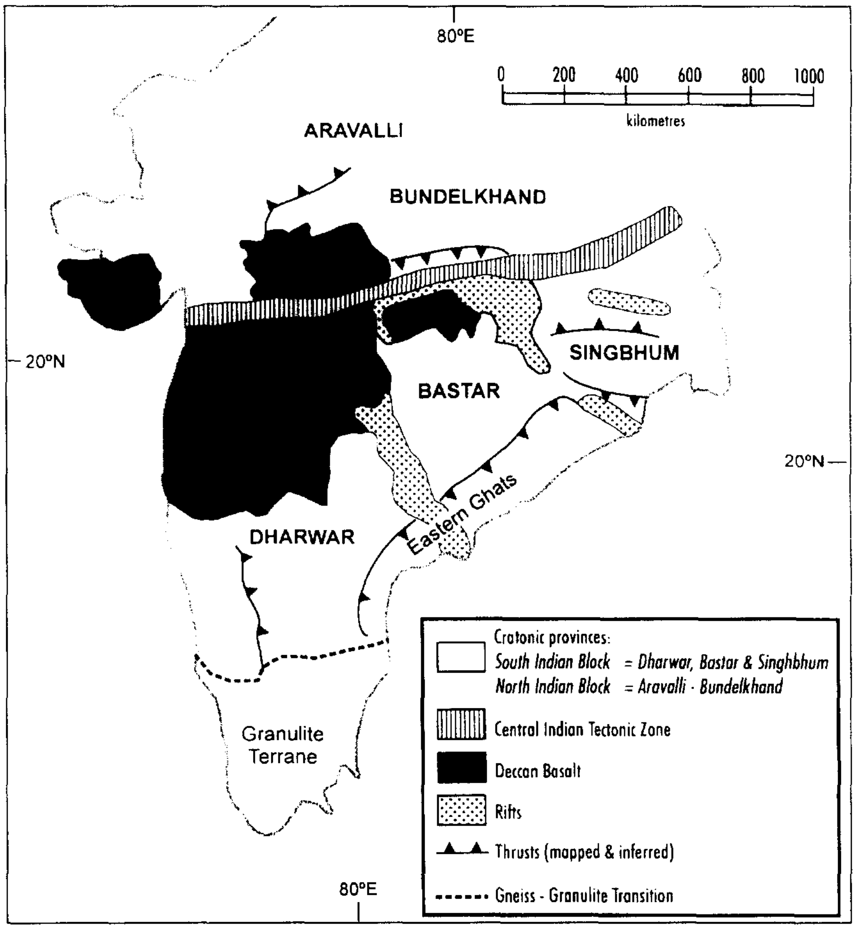

***Figure 1**. The five different crustal blocks constituting the Indian subcontinent.*

the Aravalli Mountains in the west of the province. The basement is as much as 3.5 Ga in age (Sm-Nd: MacDougall *et al.*, 1983; revised to 3.3 Ga: Gopalan *et al.*, 1990; Rb-Sr: Sarkar *et al.*, 1996) and was intruded by granite at 2.9 Ga (Rb-Sr: Choudhary, 1984; Roy, 1990) and 2.5 Ga ($^{207}Pb/^{206}Pb$: Wiedenbeck *et al.*, 1996). Only a few isolated outcrops of supracrustal marble, quartzite and Fe formation are postulated to be Archæan (Roy, 1990; Sahoo and Mathur, 1991; Upadhyaya *et al.*, 1992; Sinha-Roy *et al.*, 1995), although there are no valid data confirming this view. Otherwise, the basement in the Aravalli Mountain Belt is covered by an extensive palæosol (Roy and Paliwal, 1981; Roy *et al.*, 1993). The dominant structural trend in this province is northeast-southwest. Metamorphism in the volcanosedimentary successions of pre-2.0 Ga age remains largely confined to greeenschist-facies, but locally attains granulite-facies within the basement (Sharma, 1995; Dasgupta *et al.*, 1997).

## OTHER PROVINCES

The NIB and SIB with the CITZ constitute the main Indian Precambrian landmass, but there are two smaller provinces as well. One of them is the Eastern Ghats, accreted on to the eastern fringe of the SIB, while the other was accreted on to the northwestern margin of the Aravalli-Bundelkhand Province (Fig. 1). The Eastern Ghats has generally undergone high pressure granulite-facies metamorphism. Geothermobarometric studies reveal pressure and temperature as high as 900–1000°C and 8–10 kbar, respectively (Lal *et al.*, 1987; Sengupta *et al.*, 1990; Dasgupta *et al.*, 1994, 1995; Krause *et al.*, 1996). Khondalites (quartz-perthite-sillimanite-garnet gneisses), charnockites, calc-granulites, leptynites (quartz-plagioclase-garnet-perthite gneisses), quartzites, anorthosites, alkaline rocks and porphyritic granitoids are the major lithotypes. The structural trend in the Eastern Ghats is, more or less, parallel to the elongation of the accreted body, in a north-northeast–south-southwest direction. The Eastern Ghats was thrust on to the Dharawar Province with a west-northwest vergence and on to the Singhbhum Province with a northward vergence, indicating an oblique collision, i.e. transpression (Bhattacharya, 1997). The Eastern Ghats Province in all probablity was fragmented from East Anatartica (Grew and Manton, 1986; Yoshida *et al.*, 1992; Shaw *et al.*, 1997). The oldest metamorphic event documented so far (Mezger *et al.*, 1996) suggests that accretion took place at *ca* 1.6 Ga.

The northwestern province accreted on to the NIB is mostly covered by recent desert sand and little is known about the Precambrian rocks there, which belong to supracrustals of Meso- to Neoproterozoic age. The province was in all probablity fragmented from the Arabian-Iranian Craton and, as for the Eastern Ghats, does not have any known early Precambrian basement. It could not have accreted on to the NIB before 0.9 Ga (Qureshy and Iqbaluddin, 1992). This province, as well as the Eastern Ghats, do not constitute parts of the early Precambrian (pre-2.0 Ga.) Indian Craton and are thus not discussed further.

## SEDIMENTARY SUCCESSIONS AND RELATIVE SEA LEVEL CHANGE

Sedimentary successions in almost all the provinces still await specialist sedimentological analysis, and little more than vertical lithological variations are generally known from them. Palæogeographic inferences are seldom process-related and only a tentative estimation of relative sea level change can thus be made (Fig. 2).

## SINGHBHUM PROVINCE

The earliest supracrustal rocks here, pristine sandstone and shale enclaves within the basement, include some very pure orthoquartzites (Goswami *et al.*, 1995). Such high mineralogical maturity, although exceptional in an Archæan depositional setting (Goodwin, 1996), strongly suggests a shallow marine depositional environment. An Iron Ore Group (IOG) associated with fine siliciclastic rocks immediately overlying the basement, however, indicate transgression and deposition in a deeper shelf setting (Fig. 2a: Beukes, 1983; Beukes and Klein, 1992; Simonson and Hassler, 1996). Metabasalts in this IOG have a tholeiitic trend, while an areally separated younger IOG associated with local shallow water stromatolitic dolostone and conglomerates, includes volcanic rocks with a calc-alkaline character (Sarkar, 1982; Ghosh *et al.*, 1992; Saha, 1994; Sengupta *et al.*, 1997). A highstand systems tract (HST) presumably prevailed during formation of this younger IOG.

The overlying conglomeratic and poorly sorted arkosic terrestrial sediments constituting the ~2.5 Ga Dhanjori Formation (Bose *et al.*, 1997) were possibly deposited as lowstand products. A forced regression (Posamantier and Veil, 1988) and a sequence boundary are envisaged at the base of this formation. Sea level fall was presumably eustatic, as a suspected glacial diamictite (the authors' own unpublished data) locally occurs at the base of the Dhanjori Formation. The diamictite contains multifacetted pebbles (Fig. 3a), dropstones (Fig. 3b) and till balls. This diamictite may be approximately correlatible with similar deposits in North America, Canada, Finland, Scotland and South Africa (Aspler and Chiarenzelli, 1998). Mafic/ultramafic volcanism was profuse during Dhanjori sedimentation.

In contrast, the younger Chaibasa Formation (Fig. 2a), composed of mature quartzite, phyllite and schists, includes only minor volcanic lithologies, suggesting relative tectonic quiescence. Yet, the Chaibasa Formation is almost entirely marine and onlaps the granitic basement across the Dhanjori Formation. A transgressive systems tract (TST), albeit punctuated, is inferred (Bose *et al.*, 1997). Multiple factors might have contributed collectively to this transgression. High atmospheric $CO_2$ build-up, due primarily to restricted weathering under glacial cover, and profuse $CO_2$ emission from subsequent frequent volcanism within the Dhanjori palæoenvironment, presumably resulted in a greenhouse state during Chaibasa sedimentation. In addition, the oceanic crustal floor possibly gradually shrunk due to crustal cooling during depositon of the Chaibasa Formation; an abundance of penecontemporaneous intrastratal thrusts within the Chaibasa Formation is consistent with this hypothesis. The overlying Dhalbhum Formation (Fig. 2a), comprised of poorly sorted gritty quartzites and finer siliciclastics with profuse bimodal volcanic rocks, developed largely in a fluvial and aeolian regime, although pillowed basalts are present locally (Ray *et al.*, 1996; Mazumder, 1996; Singh, 1997, 1998; the authors' own unpublished data). A fall in relative sea level is indicated and the contact between the Chaibasa and Dhalbhum Formations indicates that they are probably separated by a sequence boundary. Frequent slumps and slides suggest at least moderate basin-floor uplift for the Chaibasa.

In the Kolhan Group, the youngest pre-2.0 Ga supracrustal succession in the Singhbhum Province, arkosic and quartzitic sandstones, shales and minor conglomerates of inferred fluvial origin, give way upward to a marine carbonate-dominated lithology; a rise in relative sea level can be presumed (Ghosh and Chatterjee, 1990, 1994; Saha, 1994). Whether the TST was followed by a HST or not is difficult to ascertain from existing data. An enormous stratigraphical gap after deposition of the Kolhan Group was triggered by intrusion of an anorogenic granite around 2.1 Ga (Saha *et al.*, 1988), and there are no Meso- to Neoproterozoic deposits in the Singhbhum Province (Fig. 2a).

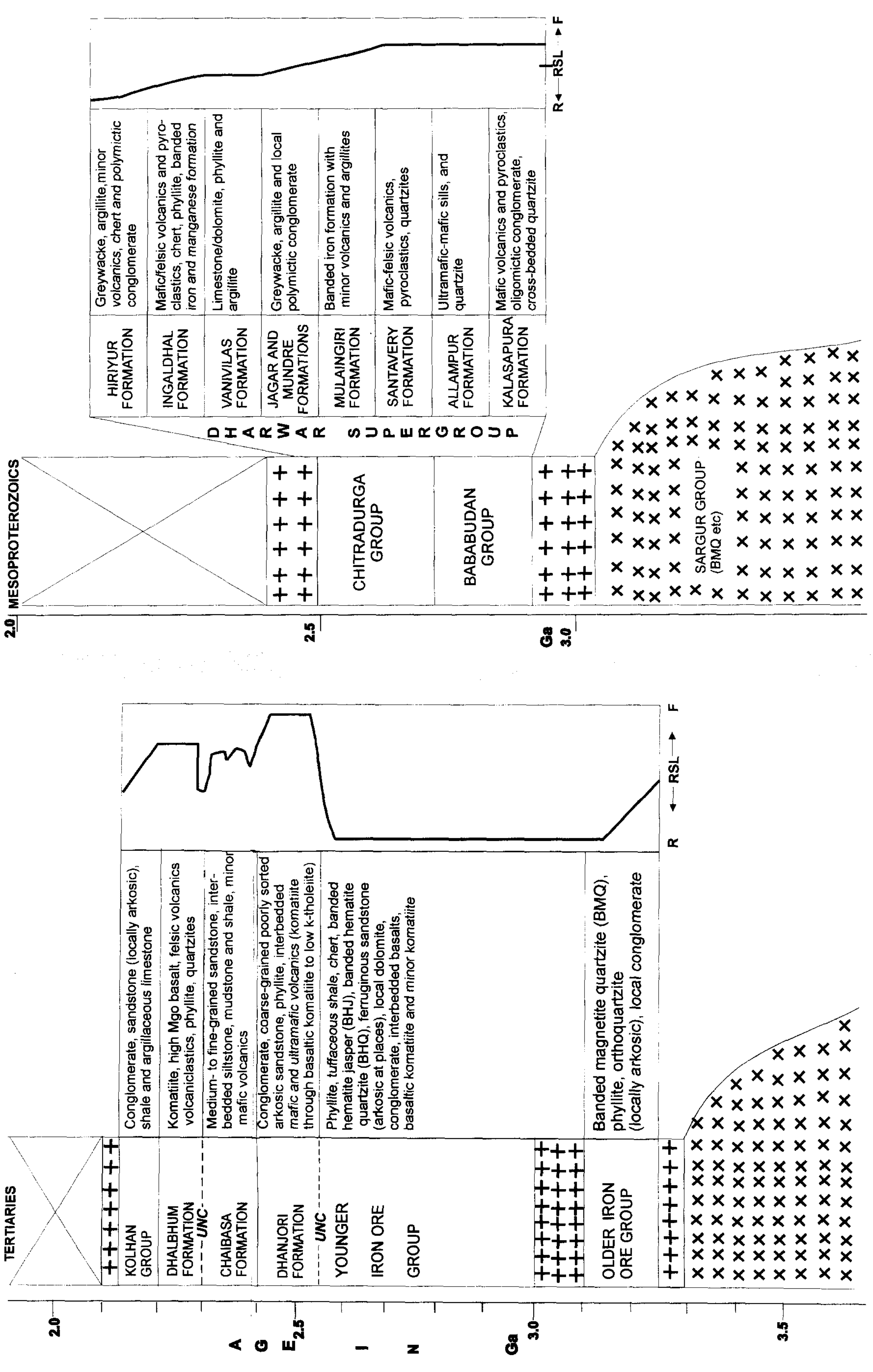

***Figure 2.*** *Pre-2.0 Ga volcano sedimentary succession resting on TTG basement in two of the four different crustal provinces, viz. (A) Singhbhum, (B) Dharwar (modified from Ramakrishnan, 1990; Roy, 1990; Bhaskar Rao et al., 1992; Ghosh et al., 1992; Roy et al., 1993; Saha, 1994; Bandyopadhyay et al., 1995). The inferred rise (R) and fall (F) of relative sea level (RSL) through time has been depicted on the right of each succession.*

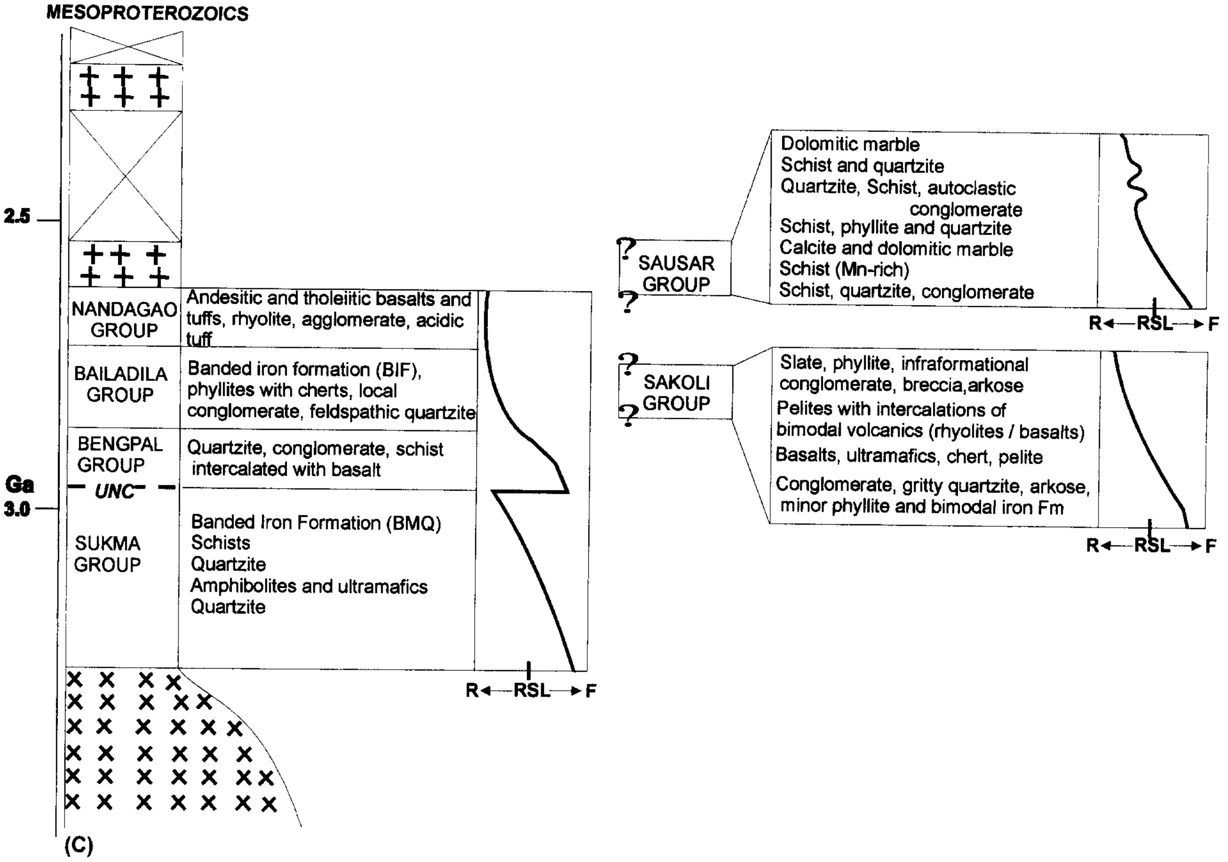

*Figure 2. Pre-2.0 Ga volcano sedimentary succession resting on TTG basement in one of the four different crustal provinces,* viz. *(C) Bastar (modified from Ramakrishnan, 1990; Roy, 1990; Bhaskar Rao* et al.*, 1992; Ghosh* et al.*, 1992; Roy* et al.*, 1993; Saha, 1994; Bandyopadhyay* et al.*, 1995). Inferred rise (R) and fall (F) of relative sea level (RSL) through time have been depicted on the right of each succession.*

## DHARWAR PROVINCE

The oldest supracrustal rocks here, 3.3 Ga volcano-sedimentary basement enclaves collectively known as the Sargur Group, comprise orthoquartzites, micaschists, Fe formation, mafic granulites, komatiites, anorthosites and orthoamphibolites (Radhakrishna, 1983; Naqvi and Rogers, 1987). The depositional setting was, in general, shallow marine, as the maturity of pristine sandstones would indicate; the Fe formation plausibly indicates a phase of transgression. Poor stratigraphical control prevents application of sequence stratigraphy. However, available age data on the Sargur Group (3.3 Ga, $^{207}$Pb/$^{206}$Pb: Peucat *et al.*, 1995) suggest that this Sargur Fe formation broadly corresponds to the older IOG in the Singhbhum Province (Fig. 2b). A regolith cover records exposure of the Dharwar basement at *ca* 3.0 Ga. The overlying Bababudan Group has a basal oligomictic conglomerate and cross-bedded quartzites, inferred to be a fluvial assemblage. Associated mafic volcanics and pyroclastics bear a subaerial imprint (Srinivasan and Ojakangas, 1986). A lowstand origin is indicated for the assemblage. Higher up the Bababudan succession, the volcanics progressively become bimodal with the introduction of felsic components. Overlying banded iron formation (BIF), intercalated with argillite, is broadly correlatable with the younger IOG in Singhbhum and testifies to marine flooding. Greywacke and argillite along with local conglomerates of the Bababudan Group, which succeed the BIF, suggest continuation of the previously established TST, while the immediately overlying succession of phyllite, argillite giving way upward to carbonates of possible shelf origin (Chitradurga Group) suggests a subsequent HST. The following formation is dominantly chemogenic, comprising chert, Mg and Fe deposits intercalated with bimodal volcanics and pyroclastics. Another TST is indicated, which continued during deposition of an uppermost assemblage of graywacke, argillite and chert with local polymictic conglomerate. These rocks represent the top of the Chitradurga Group. The TST terminated abruptly and a huge stratigraphical gap was initiated again with a granite intrusion around 2.5 Ga (Friend and Nutman, 1991; Fig. 2b).

## BASTAR PROVINCE

No sedimentary enclaves are reported from the poorly studied TTG basement of the Bastar Province. The

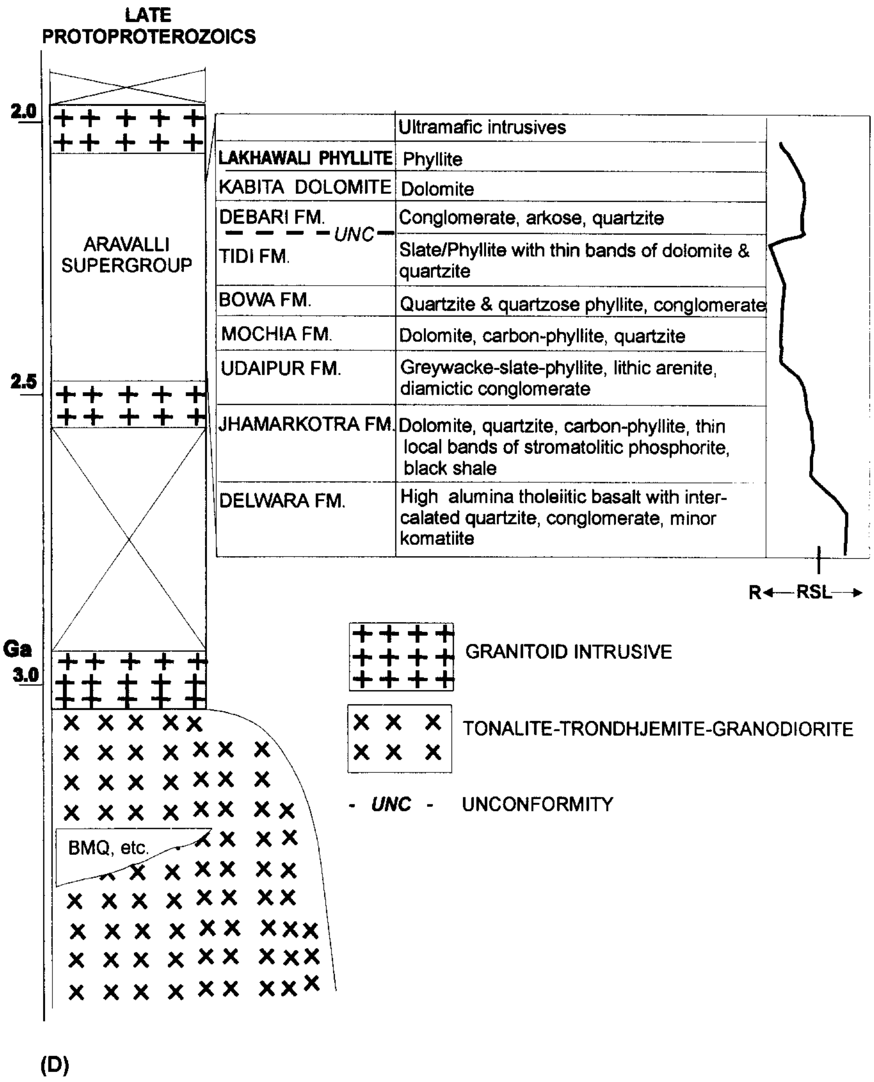

*Figure 2. Pre-2.0 Ga volcano sedimentary succession resting on TTG basement in one of the four different crustal provinces, viz. (D) Aravalli-Bunderkhand in India (modified from Ramakrishnan, 1990; Roy, 1990; Bhaskar Rao* et al.*, 1992; Ghosh* et al.*, 1992; Roy* et al.*, 1993; Saha, 1994; Bandyopadhyay* et al.*, 1995). Inferred rise (R) and fall (F) of relative sea level (RSL) through time have been depicted on the right of each succession.*

Archæan supracrustal sedimentary succession begins with the Sukma Group (Fig. 2c) comprising basal cross-stratified quartzites and para-amphibolites intercalated with mafics/ultramafics, which give way upward to a BIF broadly correlatable with the older IOG of Singhbhum. Marine flooding and a TST following a lowstand systems tract (LST) is indicated. The overlying Bengpal Group consists of a basal conglomerate, quartzites and schists intercalated with metabasites. A forced regression and an unconformity at the base of the formation is inferred (Ramakrishnan, 1990). A BIF with cherts, phyllites, feldspathic quartzites and local conglomerates (Bailadila Group) overlies these regressive deposits, and may be ascribed to a TST, possibly followed by a HST. The BIF is probably an age-equivalent of the younger IOG of Singhbhum Province (Fig. 2c). A thick succession of andesite, basalt, rhyolite and felsic pyroclastics (Nandgaon Group) at the top of the Bailadila Group was intruded by an anorogenic granite around 2.5 Ga (Sarkar *et al.*, 1993), before initiation of a long stratigraphical gap (Fig. 2c).

There are two other 2.5–2.0 Ga groups in this province, whose exact stratigraphical constraints are uncertain. One is the Sakoli Group, with a basal conglomerate and gritty quartzite, followed by arkosic sandstones (Bandyopadhyaya *et al.*, 1995), possibly of lowstand alluvial fan origin. The overlying Fe formation with minor phyllite suggests transgression (Fig 2c). The inferred TST most likely continued, as the meta-

***Figure 3**. (A) Multi-faceted pebbles and (B) dropstone from the suspected glacial conglomerate occurring at the base of the Dhanjori Formation, Singhbhum Province.*

sediments overlying the Fe formation are slates and phyllites with only minor sandy lithologies. The relatively younger Sausar Group has conglomerate and quartzite at its base, and is again possibly a lowstand product. Dominance of argillaceous sediments, calcitic/dolomitic marbles and manganese ore deposits in the overlying formation (Dasgupta *et al.*, 1992; Bandyopadhyaya *et al.*, 1995) would suggest a TST, possibly punctuated, as suggested from an internal asymmetric facies packaging (Fig 2c).

## ARAVALLI-BUNDELKHAND PROVINCE

In the Aravalli Mountain Belt, a Palæoproterozoic relatively shallow depositional domain in the east gave way to a deep water regime in the west, in a pericontinental setting (Roy and Paliwal, 1981). The succession that formed therein is the Aravalli Supergroup. The products of the shallower domain are chosen for scrutiny with the anticipation that palæogeographic shifts would be better reflected in them. A widespread palæosol on the basement suggests extensive exposure. A 2.5 Ga formation of paraconglomerate, clean quartzite and local arkoses, in association with high alumina tholeiitic basalt, komatiite and picrite as well as ash beds, overlies the palæosol (Roy *et al.*, 1993; Ahmad and Rajamani, 1991; Ahmad and Tarney, 1994) and is possibly fluvial in origin (Heron, 1953). It would appear to be a lowstand assemblage, a contention corroborated by red beds on top of the formation. The overlying assemblage, of phosphatised stromatolitic dolomite along with orthoquartzite and carbonaceous phyllite (black shale), clearly suggests a transgression (TST) (Fig. 2d). However, an exposure surface associated with laterite termi-nates this assemblage, so a HST might have preceded the implied emergence. The next younger formation, consisting of graywacke, slate, phyllite, litharenite and paraconglomerate, suggests another TST. Obviously the base of the formation is an E/T surface (*cf.* Plint *et al.*, 1986), where a transgressive surface merges with an exposure surface. The following formation consists of dolomite, phyllite and quartzite, and suggests a progradational HST (Fig. 2d). Lenticular conglomerates, cross-bedded quartzite and quartzose phyllite on top of it suggest continuation of the HST, building up in the terrestrial regime, possibly under fluvial conditions. Repeated fining-upward cycles (Roy *et al.*, 1993) corroborate the latter contention. The next younger formation contains slates and phyllites with interbeds of dolomite and quartzite, and suggests a moderate rise in relative sea level (Fig. 2d). The overlying conglomerate, followed upward by cross-bedded arkose and quartzite interbedded with red coloured quartz-sericite schist, points to simple pro-gradation and eventual emergence and may indicate a HST. Alternatively, some workers envisage an uncon-formity at the base of the conglomerate (Roy *et al.*, 1993). A suggested glacial origin for the conglomerate (Sinha-Roy *et al.*, 1993) would support the suggested uncon-formity. A locally cross-bedded dolomite overlies the previous HST succession and a fining-upward phyllite follows. Development of a TST can be suggested.

## CRUSTAL THICKNESS, CONTINENTAL FREEBOARD AND TECTONICS

Crustal thickness is a direct reflection of crustal growth and can be estimated on the basis of various geochemical parameters (Condie, 1973; Windley, 1977; Taylor and McLennan, 1985). Rubidium versus Sr contents in volcanic rocks and plutons, and $K_2O$ contents normalised against 60% $SiO_2$ in calc-alkaline volcanic rocks and plutons (Condie and Potts, 1969; Condie, 1973) have been used because of their ready availability (Table 1; see also Fig. 4). Continental freeboard change is almost the reverse of the temporal trend of relative sea level and its estimation helps to visualise the continental hypsometry in response to changes in the crustal growth rate. Temporal shifts in palæogeography in conjunction with lithological variations help assessment of local continental freeboard.

During Palæo- to Mesoarchæan times, TTG basements achieved almost similar crustal thickness (~30 km) in all the Indian provinces; only in Bastar was it comparatively higher (~42 km; Table 1). The SIB basement was exposed early, as the 3.5–3.3 Ga sedimentary enclaves within the Singhbhum and Dharwar basement rocks suggest. Suspected Archæan sediments in the Aravalli-Bundelkhand Province include Fe formations which may be age-equivalents of the older IOG of Singhbhum, of the BIF of the Sargur Group of the Dharwar Province (Sahoo and Mathur, 1991; Upadhyaya *et al.*, 1992) and of the older BIF in the Bastar succession, as all of them are magnetite-rich in contrast to the younger Fe formations that are hematite-rich. It is thus possible that the SIB basement emerged about the same time in all three provinces. The nature of these Archæan sedimentary assemblages, however, indicates that the continental freeboard on the exposed crusts was low. No sedimentary enclave is reported from the relatively less well-known Bastar basement.

The granitoid intrusive bodies dated at 3.3–3.1 Ga, 3.0 and 2.9 Ga in the basement of the Singhbhum, Dharwar and Aravalli- Bundelkhand Provinces indicate an increase in crustal thickness to about 48 km, 38 km and 73 km, respectively (Table 1). Significantly, the

**Table 1.** Crustal thickness (in km) computed from Rb-Sr distribution in volcanics and plutons (TRb) and silica normalised $K_2O$ content of calc-alkaline rocks (Tk)

| CRUSTAL PROVINCE | TRb | Tk | INTERVAL | DATA SOURCE |
|---|---|---|---|---|
| **DHARWAR** | | | | |
| TTG basement | 0–30 | 30 | Palæo- to Mesoarchæan | Bhaskar Rao *et al.*, 1983 |
| Granodiorite Pluton | 20–30 | 38 | Mesoarchæan | Taylor *et al.*,1984; Stroh *et al.*, 1983 |
| Bababudan Volcanics | 15–20 | 16 | Neoarchæan | Bhaskar Rao *et al.*, 1992 |
| Chitradurga Volcanics | 15–20 | 20 | Neoarchæan | Bhaskar Rao *et al.*, 1992; Bhattacharyya *et al.*, 1988 |
| Granite Pluton | >30 | 65 | Neoarchæan | Bhaskar Rao *et al.*, 1992; Jayananda *et al.*, 1993;<br>Jayananda *et al.*, 1995 |
| **SINGBHUM** | | | | |
| TTG basement | >30 | 25 | Palæo-archæan | Saha, 1994; Sharma *et al.*, 1994 |
| Granodiorite Pluton | >30 | 49 | Mesoarchæan | Saha, 1994 |
| Older Fe Ore Gr Volcanics | 15-20 | | Mesoarchæan | Sengupta *et al.*, 1997 |
| Granodiorite Pluton | >30 | 48 | Mesoarchæan | Saha, 1994 |
| Younger Fe Ore Gr. Volcanics | 15–20 | | Neoarchæan | Sengupta *et al.*, 1997 |
| Dhanjori Volcanics | 15–20 | 13 | Palæoproterozoic | Alvi and Raza, 1992 |
| Dalma Volcanics | <15 | | Palæoproterozoic | Bose *et al.*, 1989; Bose and Chakrabarti, 1994 |
| Granite Pluton | >30 | 65 | Palæoproterozoic | Saha, 1994 |
| **BASTAR** | | | | |
| TTG basement | >30 | 42 | Palæo-archæan | Sarkar *et al.*, 1993 |
| Basic Volcanics | | 11 | Neoarchæan | Sarkar *et al.*, 1994 |
| Nandgao Volcanics | >30 | 52 | Neoarchæan | Neogi *et al.*, 1996 |
| Granite Pluton | >30 | 73 | Neoarchæan | Sarkar *et al.*, 1990 |
| **ARAVALLI-BUNDELKHAND** | | | | |
| TTG basement | 20–30 | 27 | Palæo-archæan | Sarkar *et al.*, 1996 |
| Granite Pluton | | 73 | Neoarchæan | Sastry, 1992 |
| Granite Pluton | >30 | 82 | Palæoproterozoic | Sastry, 1992; Mondal and Zainuddin, 1996 |
| Basal Aravalli Volcanics | 15–20 | | Palæoproterozoic | Ahmad and Tarney, 1994; Raza and Khan, 1993 |
| Upper Aravalli Volcanics | 15–20 | | Palæoproterozoic | Abu-Hamatteh and Ahmad, 1994 |
| Granite Pluton | | 95 | Palæoproterozoic | Sastry, 1992 |

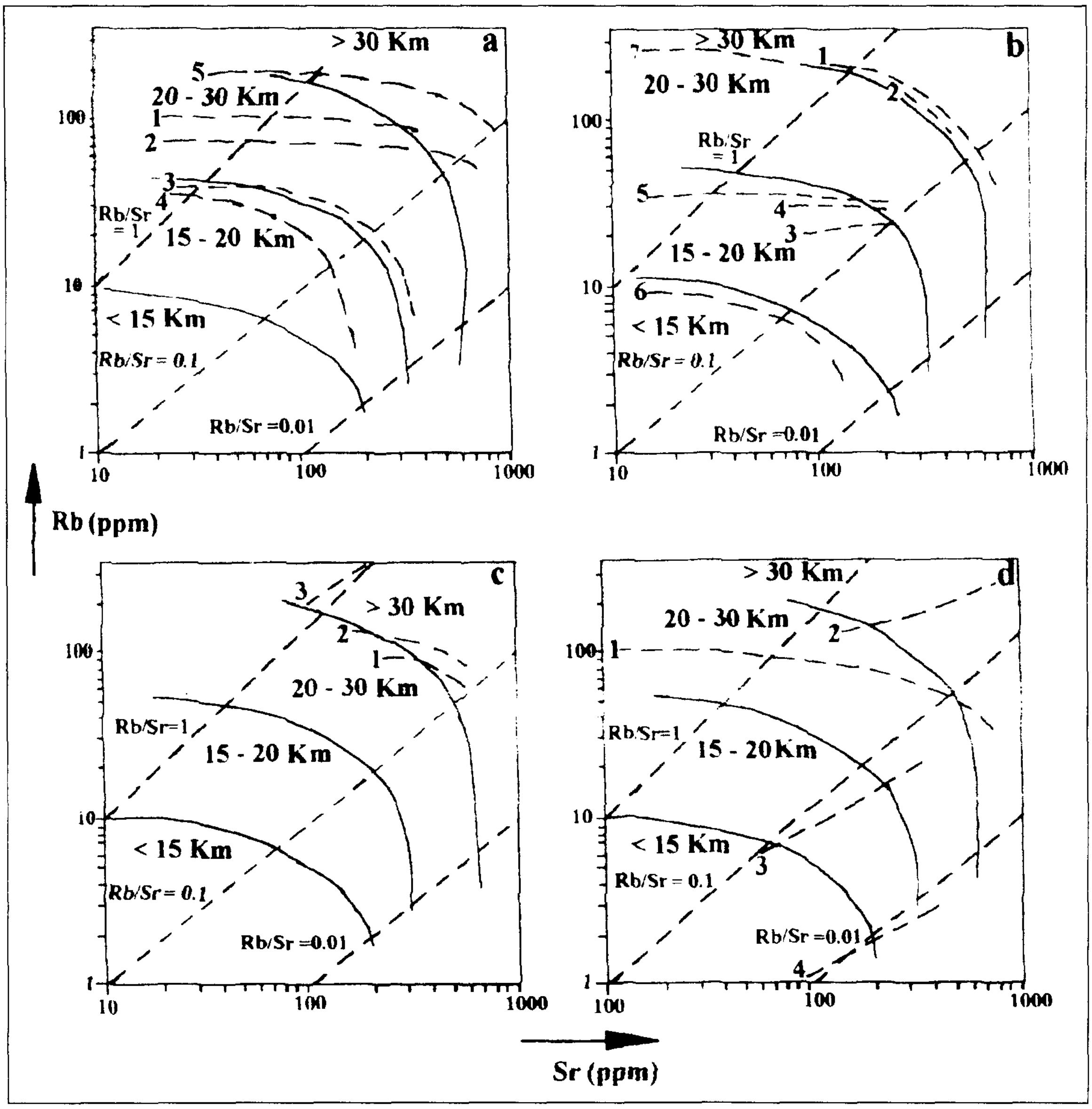

*Figure 4. Crustal thickness computed from Rb-Sr distribution in volcanic rocks and plutons in Dharwar. (a) 1: TTG basement; 2: granodiorite pluton; 3: Bababudan volcanic rocks; 4: Chitradurga volcanic rocks; 5: basin-closing granite pluton (2.5 Ga). (b) Singhbhum 1: TTG basement; 2: granodiorite pluton; 3: older IOG volcanic rocks; 4: younger IOG volcanic rocks; 5: Dhanjori volcanic rocks; 6: Dalma volcanic rocks; 7: basin-closing granite pluton (2.1 Ga). (c) Bastar 1: TTG basement; 2: Nandgao volcanic rocks; 3: basin-closing granite pluton (2.5 Ga). (d) Aravalli-Bundelkhand 1: TTG basement; 2: granite pluton; 3: basal Aravalli volcanic rocks; 4: upper Aravalli volcanic rocks. Following Condie (1973). For data source see Table 1.*

intrusions are granodioritic in the SIB provinces, but comprise K-rich granite in the Aravalli-Bundelkhand Province (Naqvi and Rogers, 1987; Roy, 1990; Saha, 1994). The enormous thickness of the Aravalli-Bundelkhand crust was possibly responsible for granitic intrusion (Goodwin, 1996). Crustal reworking may be envisaged, but the low initial $^{87}Sr/^{86}Sr$ ratio in these granites suggests a differentiated mantle source (Choudhary, 1984; Roy, 1990).

Profuse volcanism, partly komatiitic and picritic, followed the growth of the TTG basement in all the provinces, though diachronously. The volcanic rocks within the older and younger IOG in the Singhbhum Province indicate a drastic thinning of the crust and favour a rift-origin for the basin (~20 km)(Fig. 4b: Bhattacharji and Saha, 1990; Mukhopadhayay, 1994; Sengupta *et al.*, 1997). The tectonic setting thus seems to be plume-related (Sharma *et al.*, 1994). Similarly, the Dharwar crust was also thinned to ~16 km (Fig. 4a: Rajamani, 1990; Arora *et al.*, 1995). In the Bastar Province, the volcanic rocks associated with the younger BIF also indicate thinning of the crust, to ~11 km (Table 1). Persistence of the younger BIF in all the SIB provinces suggests generally low continental freeboard throughout the SIB during Neoarchæan times (Fig. 2). The freeboard was possibly at a minimum in the Dharwar Province, as carbonate sediments are more commonly associated with the BIF there. Products of the preceding lowstand are still preserved on the Dharwar basement, but were possibly eroded from the Bastar and Singhbhum basements during the Neoarchæan transgression. The Dharwar facies succession (Fig. 2b) indicates almost continuous lowering of the continental freeboard after the initial marine flooding, although crustal thickness did not alter significantly (Fig. 4a). In contrast, in the Bastar Province, around the same time (2.5–2.6 Ga), calc-alkaline volcanic rocks indicate considerable crustal thickening (53 km; Fig. 4c). In both the Dharwar and Bastar provinces a large hiatus in sedimentation up to the Mesoproterozoic began at *ca* 2.5 Ga, when another K-rich granite intrusion event enhanced crustal thickness substantially, to ~65 km in Dharwar and 73 km in Bastar (Table 1). In the NIB also, similar anorogenic granite intrusion took place at about the same time (2.5 Ga) and the crustal thickness increased to ~82 km (Table 1). A moderate rise in continental freeboard and a wide expanse of continental surface area can be suggested. This was possibly a period of large supercontinent formation (Aspler and Chiarenzelli, 1998).

Suspected glacial conglomerates at the base of the Dhanjori Formation in the Singhbhum Province suggest that the widespread crustal stability achieved at the end of the Archæan was followed by Palæoproterozoic glaciation and still higher continental freeboard. The absence of associated granite intrusions indicates that crustal heat flow was comparatively low in the Singhbhum Province. Heat flow later increased enormously as is evident from the abundance of volcanic rocks, including komatiite above the base of the Dhanjori Formation. Crustal thickness decreased to ~15 km (Fig. 4b). Continental freeboard was lowered and its progressive lowering is indicated in the upward transition to the Chaibasa Formation; climatic amelioration and crustal shrinking together possibly contributed to this as well. During formation of the overlying Dhalbhum Formation (including the Dalma lavas), crustal heat flow became very high again. The crustal thickeness was reduced further (Fig. 4b). Despite this, the facies assemblage indicates relatively high continental freeboard. Mantle plume upwelling and resumption of rifting is consistent with these observations. The youngest Precambrian unit in this province, the Kolhan Group, apparently formed in a half-graben setting, with lowering of the continental freeboard again, at least, locally.

The very thick 2.5 Ga crust in the Aravalli-Bundelkhand Province must have emerged signi-ficantly, as the extensive palæosol cover on the basement would suggest. The basal Aravalli volcanic rocks, however, again indicate drastic crustal thinning, to ~20 km (Fig. 4d); very high heat flow is suggested by the presence of komatiite and picrite. This inference supports rifting due to mantle plume upwelling (Ahmad and Tarney, 1994). The TST that overlies the basal fluvial Aravalli assemblage suggests lowering of continental freeboard. The general trend of intraformational transgressions punctuated by intervening unconformities points to intermittent increase in continental freeboard. The forcing mechanism most probably was eustatic sea level change. Conglomerates with granite fragments or other labile clasts, litharenites and arkoses in association with the unconformities would suggest significantly high continental freeboard. Abundance of chemogenic sediments in close association with these lithologies, however, indicates general starvation of the sedimentary basin. In conjunction with laterite and red bed occurrences, these observations are consistent with an arid climate during the Palæo-proterozoic period, for the NIB province. The ultramafic volcanic rocks at the top of the succession point to further crustal thinning, to about <15 km (Fig. 4d). Association of a nepheline syenite pluton also sup-ports continental rifting (Roy and Dutt, 1995).

A K-rich granite intrusion event at *ca* 2.0 Ga terminated the Aravalli Supergroup (Fig. 2d), as well as the Palæoproterozoic succession in the Singhbhum Province. Crustal thickness increased to ~65 km in the Singhbhum Province and to *ca* 95 km in the Aravalli-Bundelkhand Province (Table 1). Continental freeboard rose and an unconformity terminated the Palæoproterozoic succession in both the provinces.

## DISCUSSION

The sialic crust that eventually developed into the Indian Craton segregated from the mantle before 3.8 Ga. The three basic aspects of the early Precambrian crustal growth pattern in Peninsular India are:

***i)*** rapid thickening during granitoid intrusions and calc-alkaline volcanism;

***ii)*** rapid thinning when ultramafic rocks and tholeiitic basalts, with or without felsic components, erupted; and

***iii)*** all the sedimentary basins appear to have been initiated by rifting. The rate of crustal growth became accentuated, particularly at ~3.1 Ga, 2.5 Ga and 2.0 Ga.

Deposition of Fe formations coincides with crustal thinning and it is tempting to correlate them with tectonics. However, after 2.5 Ga, with similar conditions prevalent, Fe formations did not develop. Thus, in consequence, neither crustal thinning nor concomitant transgression were the sole cause of BIF dpeosition (e.g. Cloud, 1983).

The crustal growth rate was apparently considerably higher in the NIB, implying higher and prolonged crustal heat flow there. Crust emerged above sea level at *ca* 3.5 Ga. Reduction in ocean basin volume, as a consequence of widespread crustal development, induced a rise in relative sea level and maintained the continental freeboard only at moderate levels. Prolonged weathering on exposed continents produced mature quartz-rich sands, siliciclastic muds, carbonates and Fe-rich deposits, even when the granitoid basement was still in the process of growing. Granite intrusion events between 3.3 Ga and 2.9 Ga caused a widespread enhancement in crustal growth rate.

There is still uncertainty about the timing of amalgamation of the two initially separated northern and southern Indian blocks. Dominant signals in the CITZ, in between the two blocks, are in favour of amalgamation at *ca* 1.6 Ga (Radhakrishna and Naqvi, 1986; Radhakrishna and Ramakrishna, 1988; Radhakrishna, 1989). The present analysis, however, suggests a different hypothesis. Rifting had been the primary mechanism in creating all the sedimentary basins on the Archæan basement; the process was diachronous, and was much delayed in the NIB. The common association of mafic-ultramafic volcanic rocks, including komatiite and picrite, suggests that the rifting was caused by mantle plume upwelling (Rajamani, 1990; Sharma *et al.*, 1994; Ahmad and Tarney, 1994). This rifting prevailed throughout all the pre-2.0 Ga sedimentary basins, except that in the Bastar Province. Only the Bastar Basin, closest to the NIB, shows evidence of a Wilson cycle in association with enormous thickening of crust, in conjunction with calc-alkaline volcanism, immediately prior to 2.5 Ga. The time of closure of the Bastar Basin may well have been the time of SIB-NIB amalgamation. The 2.5 Ga and 2.0 Ga granite bodies intruded both the blocks. A supercontinent possibly developed. Pertinently, some 2.5 Ga granite bodies in the Bundelkhand area, on the northern side of the CITZ, are interpreted to be arc-related (Mondal and Zainuddin, 1996). If this is valid, the two blocks might have collided with possibly limited subduction. The pre-2.5 Ga amalgamation is further corroborated by deflection of structural elements parallel to those of the CITZ in the top part of the Bastar succession.

Consistent with the global scenario, evidence from Peninsular India suggests that 2.5 Ga was the time of maximum crustal growth and extensive granite intrusion (Taylor and McLennan, 1985; Eriksson, 1995; Goodwin, 1996; Condie, 1997). However, there were multiple phases of growth enhancement. Depositional surfaces in the Dharwar and the Bastar Basins emerged above base level and basin-wide unconformities formed, thereby delimiting mega-sequences. However, sedimentation continued in the Singhbhum Basin despite the contemporary relative sea level fall there. The Aravalli-Bundelkhand Basin developed only after 2.5 Ga. Enormous expansion of crustal surface area and amalgamation between the two blocks considerably reduced the rate of sedimentation. Younger siliciclastic deposits are thus generally fine-grained and carbonates became important associated lithologies.

While the NIB was probably unitary, the SIB was divided in three provinces. Many workers have postulated that the SIB provinces were the initial nuclei for crustal growth and later amalgamated (e.g. Radhakrishna and Naqvi, 1986; Rogers, 1986). However, there is no evidence for such amalgamation and only intracratonic rifts filled by post-2.0 Ga sedimentary rocks occur in between the three provinces. Proponents of the above-mentioned hypothesis suggest that the rifts formed on the overthickened crusts that developed along orogenic belts between the three provinces (Rogers, 1986; Naqvi and Rogers, 1987). There are some workers who have challenged this hypothesis (Srinivasa Rao, 1987; Sreenivasa Rao, 1994; Mahadevan, 1994). Against this background, one should also consider the possibility that the three SIB Archæan-Palæoproterozoic sedimentary basins formed on a single craton and that the rifts between them only developed later. The difference between the three provinces in terms of dominant structural trends may merely be due to superimposition of Mesopreterozoic (CITZ) deformation that obliterated the initial north-south trend, still largely visible in Singhbhum (Bhattacharya, 1997; Acharyya, 1998), and partially so in Bastar. In the CITZ also there was, at least, one deformation event that predated the Mesoproterozoic deformation (Roy, 1998). Clearly, there is a need for a lot more data of good quality to resolve many such key questions about the pre-2.0 Ga history of the Indian Craton, and its possible Neoarchæan unification with cratons in present-day Africa.

## ACKNOWLEDGEMENTS

This paper is an outcome of a research project (ESS/CA/A9/13-92) on the Singhbhum Province sponsored by the Department of Science and Technology, Government of India. RM acknowledges financial support from the University Grants Commission, Government of India. PKB and SS are also indebted to the Department for financial support. Infrastructural facilities were provided by the Department of

Geological Sciences, Jadavpur University. The authors also thank Pat Eriksson for reviewing an earlier version of the manuscript. They are deeply indebted to K.K. Roy, ex-director, Geological Survey of India for inspiring the authors with stimulating discussion. The contribution of Snehasis Chakrabarty in the field of computer graphics is gratefully acknowledged.

*Editorial handling - P. Eriksson*

## REFERENCES

Abu-Hamatteh, Z.S.H., Ahmad, T., 1994. Geochemistry of early Proterozoic mafic and ultramafic rocks of the Jharol Group, Rajasthan, Northwestern India. Journal Geological Society India 44,141–156.

Acharyya, S.K., 1998. Tectonic setting and nature of the Gondwanic Indian crust. Extnded Abstracts International Seminar on Precambrian Crust in Eastern and Central India, Bhubaneswar, UNESCO-IUGS-IGCP-368, 1–5.

Ahmad, T., Rajamani, V., 1991. Geochemistry and petrogenesis of basal Aravalli volcanics near Nathdwara, Rajasthan, India. Precambrian Research 49, 185–204.

Ahmad, T., Tarney, J., 1994. Geochemistry and petrogenesis of late Archæan Aravalli volcanics, basement enclaves and granitoids, Rajasthan. Precambrian Research 65, 1–23.

Alvi, S.H., Raza, M., 1992. Geochemical evidence for the volcanic arc tectonic setting of the Dhanjori volcanics, Singhbhum Craton, eastern India. Geological Magazine 129, 337–348.

Arora, M., Govil, P.K., Charan, S.N., Uday Raj, B., Balaram, V., Manikyamba, C., Chatterjee, A.K., Naqvi, S.M., 1995. Geochemistry and origin of Archæan Banded Iron Formation from Bababudan Schist Belt, India. Economic Geology 90, 2040–2057.

Aspler, L.B., Chiarenzelli, J.R., 1998. Two Neoarchæan supercontinents? Evidence from the Palæoproterozoic. Sedimentary Geology 120, 75–104.

Bandyopadhyay, B., Roy, A.B., Huin, A.K., 1995. Structure and tectonics of a part of the central Indian Shield. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental crust of northwestern and central India. Memoir Geological Society India, pp. 433–467.

Basu, A.R., Ray, S.L., Saha, A.K., Sarkar, S.N., 1981. Eastern Indian 3800 million-year-old crust and early mantle differentiation. Science 212, 1502–1506.

Beukes, N.J., 1983. Palæoenvironmental setting of iron formations in the depositional basin of the Transvaal Supergroup, South Africa. In: Trendall A.F., Morirs, R.C. (Eds.), Iron Formations: Facts and Problems. Elsevier, Amsterdam, pp. 131–209.

Beukes, N.J., Klein, C., 1992. Models for iron formation deposition. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere: a multidiciplinary study. Cambridge University Press, Cambridge, pp. 147–151.

Bhaskar Rao, Y.J., Beck, W., Ram Murthy, V., Nirmal Charan, S., Naqvi, S.M., 1983. Geology, geochemistry and age of metamorphism of Archæan grey gneiss around Channarayapatna, Hassan District, Karnataka, South India. In: Naqvi, S.M., Rogers, J.J.W. (Eds.), Precambrian of south India. Memoir Geological Society of India, pp. 309–328.

Bhaskar Rao, Y.J., Sivaraman, T.V., Pantulu, G.V.C., Gopalan, K., Naqvi, S.M., 1992. Rb-Sr ages of late Archæan metavolcanics and granites, Dharwar Craton, South India and evidence for Early Proterozoic thermotectonic event(s). Precambrian Research 59, 145–170.

Bhattacharji, S., Saha, A.K., 1990. A thermal model for the evolution of the Singhbhum Iron-Ore Basin of the Indian Shield. In: Naqvi, S.M. (Ed.), Precambrian Continental Crust and It's Economic Recsources. Developments in Precambrian Geology 8. Elsevier, Amsterdam, pp. 47–61.

Bhattacharya, S., 1997. Evolution of the Eastern Ghats granulite belt of India in a compressional tectonic regime and juxtaposition against Iron Ore Craton of Singhbhum by oblique collision-transpression. Proceedings Indian Academy Science (Earth Planetary Sciences) 106(3), 65–75.

Bhattacharyya, P.K., Bhattacharya, H.N., Mukharjee, A.D., 1988. The Chitradurga greenstone succession in south India and evolution of the late Archæan basin. Geological Magazine 125, 507–519.

Bhowmik, S., Pal, T., Roy, A.B., Pant, N.C., 1999. Evidence for Pre-Grenvillian high-pressure granulite metamorphism from the northern margin of the Saussar Mobile Belt in central India. Journal Geological Society India 53, 385–399.

Bose, M.K., Chakrabarti, M.K., 1994. Geochemical changes in basalts across the Archæan-Proterozoic boundary - an evaluation of Dalma Basalts from eastern Indian Shield. Journal Geological Society India 43, 281–293.

Bose, M.K., Chakrabarti, M.K., Saunders, A.D., 1989. Petrochemistry of the lavas from Proterozoic Dalma Volcanic Belt, Singhbhum, eastern India. Geologie Rundshau 78, 633–648.

Bose, P.K., Mazumder, R., Sarkar, S., 1997. Tidal sandwaves and related storm deposits in the transgressive ProtoProterozoic Chaibasa Formation, India. Precambrian Research 84, 63–81.

Chadwick, B., 1994. Book review of Yoshida, M., India and Antarctica during Precambrian, Precambrian Research 82, 173–174.

Choudhary, A.K., 1984. Precambrian Geochronology of Rajasthan, Western India. Ph.D thesis (unpubl.), Gujrat University, Ahmedabad, 109p.

Cloud, P.E., 1983. Iron-formation - A gradualist's dilemma. In: Trendall A.F., Morris, R.C. (Eds.), Iron Formations: Facts and Problems. Elsevier, Amsterdam, pp. 401–416.

Condie, K.C., 1973. Archæan magmatism and crustal thickening. Geological Society America Bulletin 84, 2981–2992.

Condie, K.C., 1997. Plate Tectonics and Crustal Evolution, Fourth edition. Butterworth-Heinemann, Oxford, 282p.

Condie, K.C., Potts, M.J., 1969. Calc-alkaline volcanism and the thickness of the early Precambrian crust in North America. Canadian Journal Earth Sciences 6, 1179–1184.

Dasgupta, S., Guha, D., Sengupta, P., Miura, H., Ehl, J., 1997. Pressure-temperature-fluid evolutionary history of the polymetamorphic Sandmata granulite complex, Northwestern India. Precambrian Research 83, 267–290.

Dasgupta, S., Roy, S., Fukuoka, M., 1992. Depositional models for the manganese oxide and carbonate deposits of the Precambrian Sausar Group, India. Economic Geology 87, 1412–1418.

Dasgupta, S., Sanyal, S., Sengupta, P., Fukuoka, M., 1994. Petrology of granulites for Anakapalle-evidence for Proterozoic decompression in the Eastern Ghats, India. Journal Petrology 35, 435–459.

Dasgupta, S., Sengupta, P., Ehl, J., Raith, M., Bardhan, S., 1995. Reaction Textures in a Suite of Spinel Granulites, India: evidences for polymetamorphism, a partial Petrogenetic Grid in the system KFMASH and the roles of ZnO and $Fe_2O_3$. Journal Petrology 36, 435–461.

Eriksson, K.A., 1995. Crustal growth, surface processes and atmospheric evolution on the early Earth. In: Coward, M.P., Rice, A.C. (Eds.), Early Precambrian Processes. Special Publication Geological Society London 95, 11-25.

Eriksson, P.G., Mazumder, R., Sarkar, S., Bose, P.K., Altermann, W., van der Merwe, R., 1999. The 2.7-2.0Ga. volcano-sedimentary record of Africa, India and Australia: evidence for global and local changes in sea level and continental freeboard. Precambrian Research 97, 269-302.

Friend, C.R.L., Nutman, A.P., 1991. SHRIMP U-Pb geochronology of Closepet granite and Peninsular gneiss, Karnataka, South India. Journal Geological Society India 38, 357-368.

Ghosh, S.K., Chatterjee, B.K., 1990. Palæoenvironmental reconstruction of the Early Proterozoic Kolhan siliclastic rocks, Keonjhar District, Orissa, India. Journal of the Geological Society India 35, 273-286.

Ghosh, S.K., Chatterjee, B.K., 1994. Depositional mechanism as revealed from grain-size measures of the Palæoproterozoic Kolhan Siliciclastics, Keonjhar District, Orissa, India. Sedimentary Geology 89, 181-196.

Ghosh, S.K., Chatterjee, D., Sarkar, A.N., 1992. An approach towards time-stratigraphical classification of the Indian Precambrians. Indian Minerals 46, 191-216.

Goodwin, A.M., 1996. Principles of Precambrian Geology. Academic Press, London, 327p.

Gopalan, K., MacDougall, J.D., Roy, A.B., Murali, A.V., 1990. Sm-Nd evidence for 3.3 Ga old rocks in Rajasthan, northwestern India. Precambrian Research 48, 287-297.

Goswami, J.N., Mishra, S., Wiedenbeck, M., Ray, S.L., Saha, A.K., 1995. 3.55 Ga old zircon from Singhbhum-Orissa Iron Ore craton, eastern India. Current Science 69, 1008-1011.

Grew, E.S., Manton, W.I., 1986. A new correlation of sapphirine granulites in the Indo-Antarctic metamorphic terrain: Late Proterozoic dates from the Eastern Ghats Province of India. Precambrian Research 33, 123-137.

Harris, L.B., 1993. Correlation of tectonothermal events between the central Indian Tectonic Zone and the Albany Mobile Belt of Western Australia. In: Findlay, R.H., Unrug, R., Banks, M.R., Veevers, J.J. (Eds.), Gondwana Eight: Assembly, Evolution and Dispersal. Balkema, Rotterdam, pp. 165-180.

Heron, A.M., 1953. The geology of central Rajputana. Memoir Geological Survey India 79, 339p.

Holzer, L., Frei, R., Barton, J.M., Kramers, J.D., 1998. Unraveling the record of successive high-grade events in the Central Zone Limpopo Belt using Pb single phase dating of metamorphic minerals. Precambrian Research 87, 87-115.

Jayananda, M., Martin, H., Mahabaleswar, B., 1993. The mechanisms of recycling of the Archaean continental crust: example of the Closepet Granite, southern India. In: Radhakrishna, B.P. (Ed.), Continental Crust of South India. Memoir Geological Society India 25, 119-134.

Jayananda, M., Martin, H., Peucat, J.J, Mahabaleswar, B., 1995. Late Archæan crust-mantle interactions: geochemistry of LREE enriched mantle derived magmas, Example of the Closepet batholith southern India. Contribution Mineralogy Petrology 119, 314- 329.

Krause, O., Mezger, K., Raith, M., Bhattacharya, A., 1996. First petrogenetical conclusions on megacrystic S-type granitoids from the Eastern Ghats Belt (India). Journal Conference Abstracts 1 (1), 334.

Lal, R.K., Ackermand, D., Upadhyaya, R., 1987. P-T-X relationships deduced from corona textures in sapphirine-spinel-quartz assemblages from Paderu, southern India. Journal Petrology 28, 1139-1168.

MacDougall, J.D., Gopalan, K., Lugmair, G.W., Roy, A.B., 1983. The banded gneissic complex of Rajasthan, India, early crust from depleted mantle at 3.5 AE. Transactions American Geophysical Union 64 (18), 351p.

Mahadevan, T.M., 1994. Deep continental structure of India: A review. Memoir Geological Society India 28, 569p.

Mazumder, S.K., 1996. Precambrian geochronology of peninsular India - a selective review. Indian Minerals 50 (3), 139-174.

Mezger, K., Cosca, M.A., Raith, M., 1996. Thermal history of the Eastern Ghats Belt (India) deduced from U-Pb and $^{40}$Ar-$^{39}$Ar dating of metamorphic minerals. Journal of Conference Abstracts 1, p. 400.

Mondal, M.E.A., Zainuddin, S.M., 1996. Evolution of the Archæan-Palæoproterozoic Bundelkhand Massif, central India-evidence from granitoid geochemistry. Terra Nova 8, 532-539.

Mukhopadhayay, D., 1994. Evolution of the Precambrian terrane of Singhbhum. Extended Abstract Symposium Mantle Dynamics and its relation to Earthquake and Volcanism, Calcutta, pp. 45-48.

Naqvi, S.M., Divakara Rao, V., Narain, H., 1974. The Proto- Continental growth of the Indian Shield and the antiquity of its rift valleys. Precambrian Research 1, 345-389.

Naqvi, S.M., Rogers, J.J.W., 1987. Precambrian Geology of India. Oxford University Press, New York, 223p.

Neogi, S., Miura, H., Hariya, Y., 1996. Geochemistry of the Dongargarh volcanic rocks, central India: implications for Precambrian mantle. Precambrian Research 76, 77-91.

Peucat, J.J., Bouhallier, H., Fanning, C.M., Jayananda, M., 1995. Age of Holenarsipur Greenstone Belt, relationships with the surrounding gneisses (Karnataka, South India). Journal Geology 103, 701-710.

Plint, A.G., Walker, R.G., Bergman, K.M., 1986. Cardium Formation 6: Stratigraphic framework of Cardium Formation in subsurface. Bulletin Canadian Petroleum Geology 34, 213-225.

Posamantier, H.W., Veil, P.R., 1988. Eustatic controls on clastic deposition 1. Sequence and systems tract models. In: Wilgus, C.K., Stings, B.S., Kendall, C.G.St.C., Posamantier, H.W., Ross, C.A., van Wagoner, J.C, (Eds.), Sea Level Changes: An Integrated Approach. Society of Economic Palæontologists and Mineralogists Special Publication 42, 109-124.

Qureshy, M.N., Iqbaluddin, 1992. A review of the geophysical constraints in modelling the Gondwana crust in India. Tectonophysics 212, 141-151.

Radhakrishna, B.P., 1983. Archæan granite-greenstone terrain of the south Indian Shield. In: Naqvi, S.M., Rogers, J.J.W. (Eds.), Precambrians of South India. Memoir Geological Society India, pp. 1-46.

Radhakrishna, B.P., 1989. Suspect tectono-stratigraphic terrane elements in the Indian sub-continent. Journal Geological Society India 34, 1-24.

Radhakrishna, B.P., Naqvi, S.M., 1986. Precambrian continental crust of India and its evolution. Journal of Geology 94, 145-166.

Radhakrishna, B.P., Ramakrishnan, M., 1988. Archæan-Proterozoic Boundary in India. Journal Geological Society India 32, 263-278.

Rajamani, V., 1990. Petrogenesis of metabasites from the Schist belts of the Dharwar Craton: Implications to Archæan mafic magmatism. Journal Geological Society India 36, 565-587.

Ramakrishnan, M., 1990. Crustal development in southern Bastar Central Craton. Geological Survey India Special Publication 28, 44-66.

Ray, K.K., Ghosh-Roy, A.K., Sengupta, S., 1996. Acid volcanic rocks between the Dalma volcanic belt and Chhotanagpur gneissic complex, east Singhbhum and Purulia districts of Bihar and West Bengal. Indian Minerals 50, 1-8.

Raza, M., Khan, M.S., 1993. Basal Aravalli volcanism: Evidence for an abortive attempt to form Proterozoic Ensialic Greenstone Belt in northwestern part of the Indian Shield. Journal Geological Society India 42, 493-512.

Robb, L.J., Meyer, F.M., 1995. The Witwatersrand Basin, South Africa: geological framework and mineralization processes. Ore Geology Review 10, 67-94.

Rogers, J.J.W., 1986. The Dharwar Craton and the assembly of Peninsular India. Journal Geology 94, 129-143.

Rogers, J.J.W., 1993. India and Ur. Journal Geological Society India 42, 217-222.

Rogers, J.J.W., 1996. A history of continents in the past 3 billion years. Journal Geology 104, 91-107.

Roy, A.B., 1998. Tectonothermal history of the Proterozoic Supracrustal Belt and their implication on the crustal evolution in the central Indian Precambrian Shield. Extended Abstracts International seminar on Precambrian crust in Eastern and Central India, Bhubaneswar, UNESCO-IUGS-IGCP-368, pp. 30-35.

Roy, A.B., 1990. Evolution of the Precambrian crust of the Aravalli Mountain Range. In: Naqvi, S.M. (Ed.), Precambrian Continental crust and its Economic Resources. Developments in Precambrian Geology 8, Elsevier, Amsterdam, pp. 327-347.

Roy, A.B., Dutt, K., 1995. Tectonic evolution of the Nepheline Syenite and associated rocks of Kishengarh, District Ajmer, Rajasthan. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Memoir Geological Society of India, pp. 231-257.

Roy, A.B., Paliwal, B.S., 1981. Evolution of Lower Proterozoic epicontinental deposits: stromatolite-bearing Aravalli rocks of Udaipur, Rajasthan, India. Precambrian Research 14, 49-74.

Roy, A.B., Sharma, B.L., Paliwal, B.S., Chauhan, N.K., Nagori, D.K., Golani, P.R., Bejarniya, Bhu, H., Sabah, M.Ali, 1993. Lithostratigraphy and tectonic evolution of the Aravalli Supergroup - A protogeosynclinal sequence. In: Casshyap, S.M. (Ed.), Rifted Basins and Aulacogens. Ganodaya Prakashan, Nainital, pp. 73-88.

Saha, A.K., 1994. Crustal Evolution of Singhbhum-North Orissa, eastern India. Memoir Geological Society India 27, 341p.

Saha, A.K., Ray, S.L., Sarkar, S.N., 1988. Early history of the Earth: evidence from the Eastern Indian Shield. In: Mukhopadhyaya, D. (Ed.), Precambrians of the Eastern Indian Shield. Memoir Geological Society of India 8, 13-38.

Sahoo, K.C., Mathur, A.K., 1991. On the occurrence of Sargur type Banded-Iron-Formation in Banded Gneissic complex of south Rajasthan. Journal Geological Society India 38, 299-302.

Sarkar, A.N., 1982. Precambrian tectonic evolution of eastern India: a model of converging microplates. Tectonophysics 86, 363-397.

Sarkar, A.N., Paul, D.K., Potts, P.J., 1996. Geochronology and geochemistry of mid-Archæan Trondhjemitic Gneisses from the Bundelkhand Craton, Central India. In: Saha, A.K. (Ed.), Recent Researches in Geology and Geophysics of the Precambrian. Hindustan Publisers, New Delhi, pp. 76-92.

Sarkar, G., Paul, D.K., McNaughton, N.J., de Laeter, J.R., Mishra, V.P., 1990. A geochemical and Pb, Sr isotopic study of the evolution of granite gneisses from the Bastar Craton, central India. Journal Geological Society India 35,480-496.

Sarkar, G., Corfu, F., Paul, D.K., McNaughton, N.J., Gupta, S.N., Bishui, P.K., 1993. Early Archæan crust in Bastar Craton, central India - a geochemical and isotopic study. Precambrian Research 62, 127-137.

Sarkar, S.N., Sarkar, S.S., Ray, S.L., 1994. Geochemistry and genesis of the Dongargarh Supergroup precambrian rocks in the Bhandara-Durg region,central India. Indian Journal Earth Science 21,117-126.

Sastry, C.A., 1992. Geochronology of the Precambrian rocks from Rajasthan and northwestern Gujrat. Geological Survey India Special Publication 25, 96p.

Sengupta, P., Dasgupta, S., Bhattacharyya, P.K., Fukuoka, M., Chakraborty, S., Bhowmik, S., 1990. Petro-tectonic imprints in sapphirine granulites from Anantagiri, Eastern Ghats Mobile Belt. Journal Petrology 31, 971-996.

Sengupta, S., Acharyya, S.K., Desmeth, J.B., 1997. Geochemistry of Archæan volcanic rocks from Iron-Ore Supergroup, Singhbhum, eastern India. Proceedings Indian Academy Science (Earth Planetary Science) 106, 327-342.

Sharma, M., Basu, A.R., Ray, S.L., 1994. Sm-Nd isotopic and geochemical study of the Archæan tonalite-amphibolite association from the eastern Indian Craton. Contributions Mineralogy Petrology 117, 45-55.

Sharma, R.S., 1995. An evolutionary model for the Precambrian crust of Rajasthan: some petrological and geochronological considerations. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Memoir Geological Society India, pp. 91-115.

Shaw, R.K., Arima, M., Kagami, H., Fanning, C.M., Shiraishi, K., Motoyoshi, Y., 1997. Proterozoic events in the Eastern Ghats Granulite Belt, India: evidence from Rb-Sr, Sm-Nd systematics and SHRIMP dating. Journal Geology 105, 645-656.

Simonson, B.M., Hassler, S.W., 1996. Was the deposition of large Precambrian Iron Formations linked to major marine transgressions? Journal Geology 104, 665-676.

Singh, S.P., 1997. Geochemistry of Acid volcanics of the Dalma Group, Singhbhum, Eastern India. Journal Geological Society India 49, 437-441.

Singh, S.P., 1998. Precambrian startigraphy of Bihar - an overview. In: Paliwal, B.S. (Ed.), The Indian Precambrian. Scientific Publishers, Jodhpur, India, pp. 1-45.

Sinha-Roy, S., Mohanty, M., Malhotra, G., Sharma, V.P., Joshi, D.W., 1993. Conglomerate horizons in southcentral Rajasthan and their significance on Proterozoic stratigraphy and tectonics of the Aravalli and Delhi fold belts. Journal Geological Society India 44, 331-350.

Sinha-Roy, S., Malhotra, G., Guha, D.B., 1995. A transect across Rajasthan Precambrian terrain in relation to geology, tectonics and crustal evolution of south-central Rajasthan. In: Sinha-Roy, S., Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Memoir Geological Society India, pp. 63-89.

Sreenivasa Rao, T., 1996. The Godavari Valley, a Rift or Raft. Gondwana Nine, New Delhi, pp. 855-863.

Srinivasan, R., Ojakangas, R.W., 1986. Sedimentology of quartz- pebble conglomerates and quartzites of the Archæan Bababudan Group, Dharwar Craton, south India: evidence of early crustal stability. Journal Geology 91, 99-214.

Stroh, P.T., Monard, J.R., Fullagar, P.D., Naqvi, S.M., Hussain, S.M., Rogers, J.J.W., 1983. 3.0 Halekote Trondhjemite: a record of stabilization of the Dharwar Craton. In: Naqvi, S.M., Rogers, J.J.W. (Eds.), Precambrian of South India. Memoir Geological Society India, pp. 365-376.

Taylor, P.N., Chadwick, B., Moorbath, S., Ramakrishnan, M., Viswanatha, M.N., 1984. Petrography,chemistry and isotopic ages of Peninsular geeiss,Dharwar acid volcanic rocks and the Chitradurga granite with special reference to the late Archaean evolution of the Karnataka Craton, Southern India. Precambrian Research 23, 349–375.

Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: Its Composition and Evolution. Blackwell, Oxford, 312p.

Treloar, P.J., Blenkinsop, T.G., 1995. Archæan deformation pattern in Zimbabwe: true indicators of Tibetan-style crustal extension or not? In: Coward, M.P., Rice, A.C. (Eds.), Early Precambrian Processes. Geological Society of London Special Publication 95, 87–108.

Upadhyaya, R., Sharma, B.L. Jr, Sharma, B.L. Sr, Roy, A.B., 1992. Remnants of greenstone sequence from the Archæan rocks of Rajasthan. Current Science 63, 87–92.

Van Reenen, D.D, McCourt, S., Smit, C.A., 1995. Are the southern and northern marginal zones of the Limpopo related to a single continental collisional event? South African Journal Geology 98, 498–504.

Wiedenback, M., Goswami, J.N., Roy, A.B., 1996. Stabilization of the Aravalli Craton of northwestern India at 2.5 Ga: an ion microprobe zircon study. Chemical Geology 129, 325–340.

Windley, B.F., 1977. Timing of continental growth and emergence. Nature 270, 426–427.

Yoshida, M., Funaki, M., Vitanage, P.W., 1992. Proterozoic to Mesozoic east Gondwana: the juxtaposition of India, Sri Lanka and Antarctica. Tectonics 11, 381–391.