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Cratons and Fold Belts of India

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Chapter 2
Cratons of the Indian Shield

2.1 Introduction

The Indian shield is made up of a mosaic of Precambrian metamorphic terrains that exhibit low to high-grade crystalline rocks in the age range of 3.6–2.6 Ga. These terrains, constituting the continental crust, attained tectonic stability for prolonged period (since Precambrian time) and are designated *cratons.* The cratons are flanked by a fold belt, with or without a discernible suture or shear zone, suggesting that the cratons, as crustal blocks or microplates, moved against each other and collided to generate these fold belts (Naqvi, 2005). Alternatively, these cratons could be the result of fragmentation of a large craton that constituted the Indian shield. In either case, rifting or splitting of cratons is documented by the presence of fold belts that are sandwiched between two neighbouring cratons. The cratons or microplates collided and developed the fold belts that occur peripheral to the cratonic areas of the Indian shield. The rocks making up the fold belts were the sediments derived from crustal rocks and volcanic material derived from the mantle, all deformed and metamorphosed during subsequent orogeny(s) brought about by collision of crustal plates (cratonic blocks) that are now flanking the fold belts. There are six cratons in the Indian shield with Mid- to Late- Archaean cores or nucleus (Fig. 2.1). These cratons are: the Dharwar or Karnataka craton, Bastar (also called Bhandara) craton, Singhbhum (-Orissa) craton, Chhotanagpur Gneiss Complex (which is arguably a mobile belts of some workers), Rajasthan craton (Bundelkhand massif included), and Meghalaya craton. The last named craton is located farther east and is shown separately (see Fig. 2.10). The name Rajasthan craton is more appropriate than the term Aravalli craton used by some authors, because the term Aravalli is used for the Proterozoic Aravalli mountain belt made up of the supracrustals rocks of the Aravalli Supergroup and Delhi Supergroup, both of which were laid upon the Archaean basement—the Banded Gneissic Complex (BGC), including the Berach granite. The Bundelkhand granite located a few hundred kilometers in the east in the adjoining State of Madhya Pradesh is similar in age and petrology to the Berach granite, despite their separation by Vindhyan basin. These three Archaean domains of the BGC, Berach and Bundelkhand granites are, therefore, considered a single Protocontinent (named here Rajasthan craton) to the north of the Son-Narmada lineament (SONA Zone). To the south of this E-W trending lineament, there are

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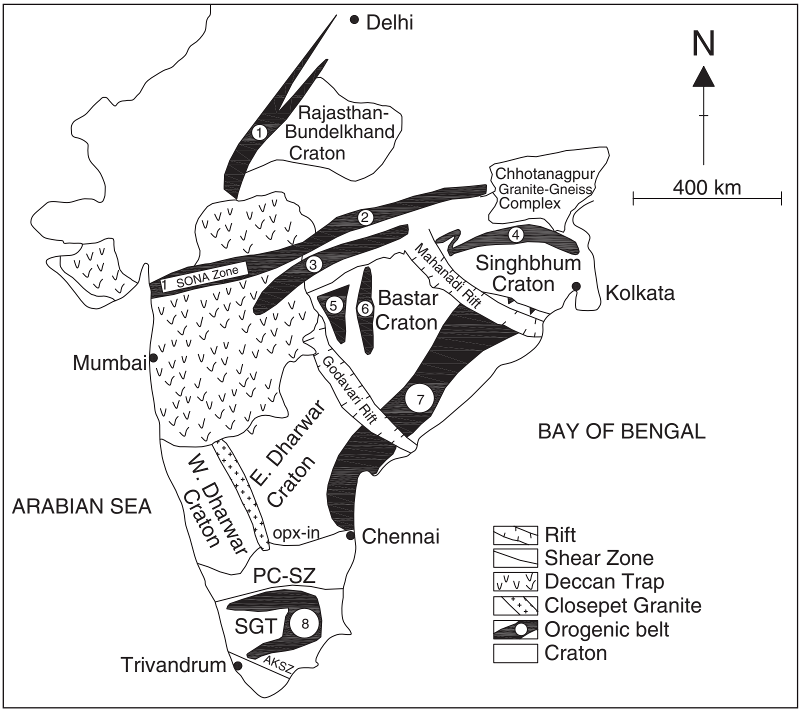


Fig. 2.1 Outline map of the Indian shield showing the distribution of cratons, including Chhotanagpur Granite Gneiss Complex, Rifts and Proterozoic fold belts. Megahalaya craton (formerly Shillong Plateau) is not outlined here but is shown in Fig. 2.10. The fold belts are: 1 = Aravalli Mt. belt, 2 = Mahakoshal fold belt, 3 = Satpura fold belt, 4 = Singhbhum fold belt, 5 = Sakoli fold belt, 6 = Dongargarh fold belt, 7 = Eastern Ghats mobile belt, 8 = Pandyan mobile belt. Abbreviations: Opx-in = orthopyroxene-in isograd; AKS = Achankovil shear zone; PC-SZ = Palghat Cauvery Shear Zone; SGT = Southern Granulite Terrain; SONA Zone = Son-Narmada lineament

three other cratonic regions, namely the Bastar craton, the Dharwar craton, and the Singhbhum craton (SC) which collectively constitute the southern Protoconinent of the Indian shield (Radhakrishna and Naqvi, 1986). The Chhotanagpur Gneiss Complex (CGC) is located to the north of the Singhbhum craton (Fig. 2.1) and the North Singhbhum fold belt or simply called Singhbhum fold belt (SFB) sandwiched between the Singhbhum craton and CGC in all probability is the outcome of the collision of SC and CGC (discussed later).

Each of these six cratons shows different geological characteristics. In this chapter, we enquire into the age, composition, and structural architecture of these cratonic masses to which the fold belts had accreted. In general, the cratons are dominated by granite and metamorphic rocks, mainly gneisses, which imply a series of intense mountain making episodes (deformation and metamorphism) in the Precambrian time before the stable conditions set in. A common feature of these cratonic regions is the occurrence of greenstone-gneiss association, as found in other

Archaean cratons of the world. Geochronological data have disclosed that rocks, especially the grey tonalitic gneisses, range in age from 3.4 to 2.6 Ga old, which may be taken to indicate that all these regions contain continental nucleus (cf. Mukhopadhyay, 2001). Another feature of these cratons is that they are often bordered by a shear zone or a major fault system and the intervening fold belt is composed of metamorphosed, deformed Proterozoic rocks. This implies that the stable Archaean cratons subdivided by mobile belts or fold belts had split or rifted during the Proterozoic and the resulting basin was wholly ensialic, with no rock associations that could be equated with ancient ocean basins. In most fold belts, as shown in subsequent chapters, one observes that gneiss-amphibolite-migmatites are exposed as the dominant cratonic rocks, suggesting that the supracrustals sequences rested upon the Archaean gneissic rocks of the cratons and that both basement and cover rocks were deformed and recrystallized in the subsequent orogeny.

In the following pages, these cratonic blocks are described with respect to their lithology, geology, geochronology, and structural characteristics in the given order:

(1) Dharwar craton (also called Karnataka craton) in the south
(2) Bastar craton (also called Bastar-Bhandara craton) in the central part
(3) Singhbhum craton (also called Singhbhum-Orissa craton) in the northeast
(4) Chhotanagpur Gneiss Complex in eastern India
(5) Rajasthan (-Bundelkhand) craton in the north
(6) Meghalaya craton in far east Indian shield

The following account is highly variable for each craton because all the cratons of the Indian shield have not been studied with equal intensity and the available geochronological and structural data are meager for some but sufficient for other cratonic regions, depending upon various reasons.

2.2 Dharwar Craton

2.2.1 Introduction

The Archaean Dharwar craton (also called Karnataka craton) is an extensively studied terrain of the Indian shield. It is made up of granite-gneiss-greenstone (GGG trinity) belts. The craton occupies a little less than half a million sq. km area. It is limited in the south by the Neoproterozoic Southern Granulite Belt (SGT) or Pandyan Mobile belt of Ramakrishnan (1993); in the north by the Deccan Trap (late Cretaceous); in the northeast by the Karimnagar Granulite belt (2.6 Ga old) which occupies the southern flank of the Godavari graben; and in the east by the Eastern Ghats Mobile Belt (EGMB) of Proterozoic age (Fig. 2.2 inset). The boundary between the Craton and the SGT is arbitrarily taken as Moyar-Bhavani Shear (M-Bh) Zone (Fig. 2.2) while the boundary between the Craton and the EGMB is demarcated by the Cuddapah Boundary Shear Zone. Besides these shear zones at the contact between the craton and the stated terrains/belts, there are many sub-parallel

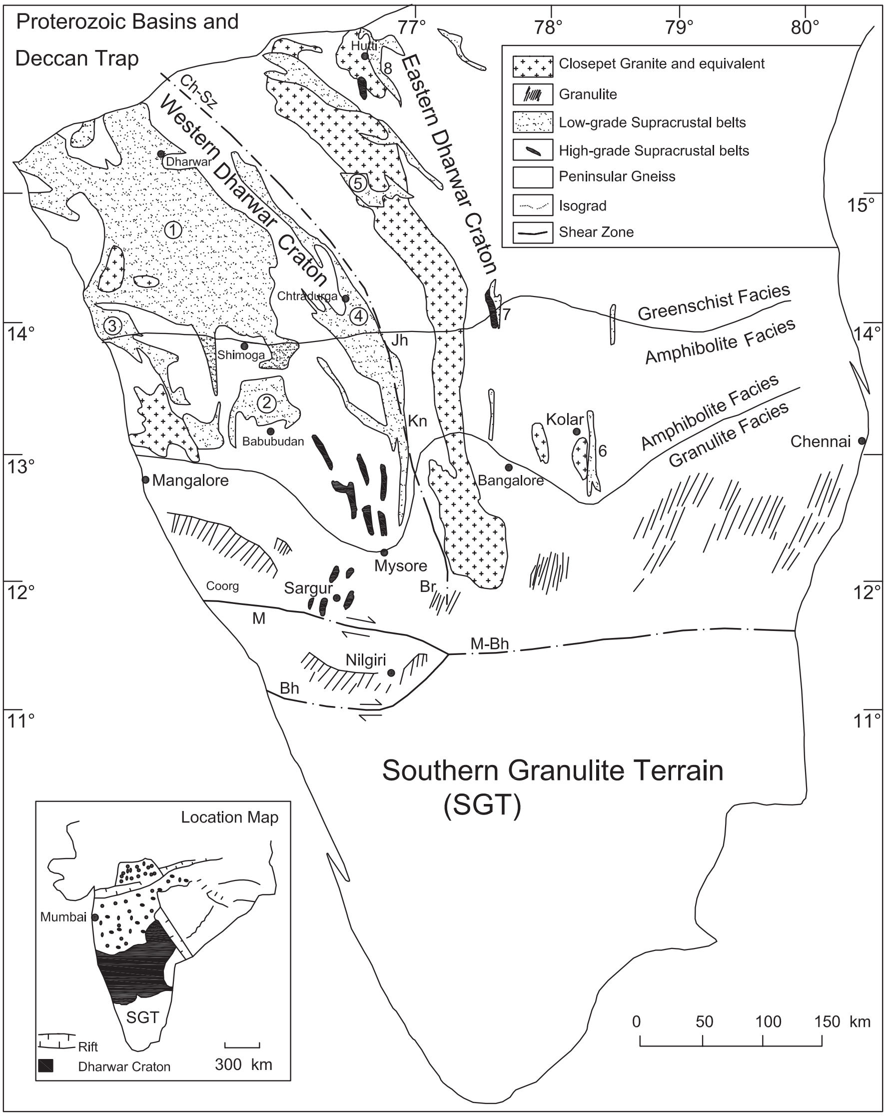


Fig. 2.2 Simplified geological map of the southern Indian shield (after GSI and ISRO, 1994) showing the Dharwar (-Karnataka) craton and its Schist belts, Southern Granulite Terrain (SGT) and shear zones. Metamorphic isograds between greenschist facies and amphibolite facies and between amphibolite and granulite facies (i.e. Opx-in isograd) are after Pichamuthu (1965). Greenstone (Schist) belts in the Dharwar craton (Eastern and Western blocks) are: 1 = Shimoga, 2 = Bababudan, 3 = Western Ghats, 4 = Chitradurga, 5 = Sandur, 6 = Kolar, 7 = Ramagiri, 8 = Hutti. Locality: BR = Biligiri Rangan Hills, Ch = Chitradurga, Cg = Coorg, Dh = Dharwar, Jh = Javanahalli, Kn = Kunigal, S = Shimoga. Shear zones: Bh = Bhavani; Ch-Sz = Chitradurga Shear Zone, M = Moyar; M-Bh = Moyar-Bhavani

NNW to N-S trending shear zones within the main Dharwar Craton, mostly at the eastern boundaries of major schist belts. Although the relationship between these nearly N-S shear zones and the E-W shear zones is uncertain, the shear zones should throw significant light on the crustal evolution of the southern Indian shield (Vemban et al., 1977).

Early studies on the Dharwar craton were ambiguous and controversial in regard to the status of gneisses and schistose (greenstone belts) rocks of "Dharwar System" (see review in M.S. Krishnan, 1982). In the early nineteenth century, Bruce Foote stated that crystalline granitoid gneiss was Fundamental gneiss and the schistose rocks of Dharwar System unconformably overlie the gneiss. This view was opposed in 1915–1916 by W.F. Smeeth who suggested that the gneisses were intrusive into the schists and hence not the Fundamental Gneiss. Smeeth designated the Fundamental Gneiss of Bruce Foote as Peninsular gneiss in view of its vast development in Peninsular India. The controversy continued for over three decades until geochronological data were generated along with relationships of rocks of the Dharwar craton. Detailed field work by the team of Geological Survey of India backed with large scale maps (1: 50,000) finally established that the Peninsular gneiss in western craton is the basement (infracrystalline) for the schist belts and that the intrusive relationship was due to re-melting of the Pre-Dharwar granite gneiss (for details see Ramakrishnan and Vaidyanadhan, 2008). The discovery of a regional unconformity defined by the presence of quartz-pebble conglomerate by the GSI confirmed the given conclusion. The Dharwar schists in western part of the craton was also divided into two Groups, the older Sargur Group (3.1–3.3 Ga) and the younger Dharwar Supergroup (2.6–2.8 Ga) because the Sargur and Dharwar successions are separated by angular unconformities at several localities in western Dharwar craton.

Dharwar craton, as the northern block of southern Indian shield (Fig. 2.2, inset), is a dominant suite of tonalite-trondhjemite-granodiorite (TTG) gneisses which are collectively described under the familiar term Peninsular gneisses. The TTG suite is believed to be the product of hydrous melting of mafic crust and a last stage differentiates of mantle, accounting for crustal growth, horizontally and vertically. The available geochronological data indicate that the magmatic protolith of the TTG accreted at about 3.4 Ga, 3.3–3.2 Ga and 3.0–2.9 Ga (see Meen et al., 1992). The Pb isotope data of feldspar suggests near Haedian (>3.8 Ga) juvenile magmatism (cf. Meen et al., 1992). The second category of rocks in the Dharwar craton is greenstones or schist belts with sedimentary associations. The greenstones are mainly voluminous basalts with subordinate fine clastics and chemical sediments and in certain areas with basal conglomerate and shallow water clastics (e.g. ripple-bedded quartzites) and shelf sediments (limestone and dolomite). In the Dharwar craton, both volcanics and sediments as supracrustal rocks were laid upon the basement of Peninsular gneiss (>3.0 Ga). During Dharwar Orogeny (2500 Ma) the volcanics have been metamorphosed into greenschist (chlorite schist) and amphibolite and even higher grade basic granulites while the associated sediments have recrystallized into quartzite, crystalline marbles, metapelites with index minerals denoting a particular metamorphic grade (Ramiengar et al., 1978).

The greenstone belts together with the intercalated metasediments designated as the *Dharwar Schist Belts* have N-S trend and show a gradual increase of metamorphic grade from N to S. The N-S trending compositional layering in the belts are transected by east-west running isograds (Fig. 2.2), suggesting that conductive/thermal relaxation of the superposedly deformed Dharwar supracrustals (along with their basement gneisses) occurred when their regional foliation (axial plane S2) had a steep disposition with respect to the rising isotherms during regional metamorphism. This is in contrast if the structurally duplicated (or tectonically thickened) crust at depth had gentle inclination of the compositional layering or dominant foliation and subject to uprising isotherms during thermal relaxation. In the latter situation the metamorphic isograds would be nearly parallel to the compositional layering and the small obliquity between them is considered to suggest that regional metamorphism outlasted deformation as in the Swiss Alps and other fold belts.

The metamorphic isograd between greenschist facies (low grade) to amphibolite facies (medium grade) is defined by a line (outcome of intersection of isothermal surface with the ground surface) on a regional geological map, shown in Fig. 2.2. The Opx-in isograd between the amphibolite and granulite facies is not a line but a zone of up to 30 km wide in which mineral assemblages of both amphibolite facies and granulite facies (characterized by the presence of hypersthene (a mineral of orthopyroxene group) are found together. This zone is called the Transition Zone (TZ). It is in this zone that excellent outcrops of "charnockite in-making" (Pichamuthu, 1960; Ravindra Kumar and Raghavan, 1992, 2003) or arrested charnockite (also called incipient charnockite) are seen to have formed from gneisses due to reduced water activity at same prevailing P and T conditions (Peucat et al., 1989). From the disposition and wavy nature of the isograds, it is inferred that the isothermal surfaces had gentle inclination towards north. Further south of the TZ occurs the main granulite terrane, called the Southern Granulite Terrane (SGT) (Fig. 2.2), where massive charnockite-enderbite rocks dominate amidst high-grade supracrustals.

In the Dharwar craton, the Peninsular Gneisses are found to contain tonalitic gneisses of 3.56–3.4 Ga age and enclaves of older metavolcanic-metasedimentary rocks categorized under name Sargur Group (3.2–3.0 Ga). Thus, it is likely that the Peninsular gneiss with its enclaves of older tonalitic gneiss and Sargur Group of rocks served as the basement upon which the Dharwar supracrustals were deposited.

Swami Nath and Ramakrishnan (1981) divided the Dharwar Craton into two blocks—the *Western Block* and the *Eastern Block*, separated by the Chitradurga Shear Zone (ChSz) (Fig. 2.2). Later, Naqvi and Rogers (1987) designated these blocks as Western and Eastern Dharwar Cratons. According to Ramakrishnan (2003), the Chitradurga shear zone, separating the Eastern and Western blocks of the Dharwar craton, extends via Javanahalli (Jh) through the layered mylonite of Markonahalli near Kunigal (Kn) and the western margin of the BR Hills into the Moyar Bhavani (M-Bh) shear zones (Fig. 2.2). The stated shear zone occurs all along the western margin of the 2.5 Ga old Closepet Granite. It is interesting to note that the schist belts in both cratonic blocks show the same N-S trend with almost constancy of strike and dip of the foliation (regional foliation).

However, the greenstone belts of the Western Block are characterized by mature, sediment-dominated supracrustals with subordinate volcanism and are recrystallized in intermediate pressure (kyanite-sillimanite type) Barrovian metamorphism. On the other hand, the greenstone belts of the Eastern block are often gold bearing and show low-pressure (andalusite-sillimanite type) metamorphism, perhaps due to profuse granite intrusions (2600–2500 Ma old) that invade the schists and metasediments of the Eastern block. Geophysical work (see, for example, Singh et al. 2003) revealed that the Western Block has a thicker crust of 40–45 km while the Eastern Block has a thinner crust of 35–37 km (Srinagesh and Rai, 1996). These differences between the two blocks, as well as the occurrence of lower crustal rocks (charnockite-enderbite) along the Western Ghats, suggest that the southern Indian shield had tilted towards the east in addition to generally accepted northward tilt which gave rise to huge exposure of granulite rocks (see Mahadevan, 2004).

The Western Block is characterized by the presence of 3000 Ma old TTG (tonalite-trondhjemite-granodiorite) gneisses—the Peninsular Gneiss Complex. As stated earlier, the Peninsular Gneisses contain 3400–3580 Ma old basement tonalitic gneiss enclaves (Nutman et al., 1992). From a careful fieldwork, Swami Nath and Ramakrishnan (1981) showed that the Peninsular gneisses also enclose relics of older supracrustals in form of narrow belts and enclaves or synclinal keels that show amphibolite facies mineral assemblages. They were called Ancient Supracrustals by Ramakrishnan (1990) and later designated by the term *Sargur Group* (3000–3200 Ma old) by Swami Nath and Ramakrishnan (1990) who also considered them equivalent to Waynad Group in Kerala. The metamorphic fabric of these Ancient Supracrustals (the Sargur Group rocks) and the surrounding gneiss complex is truncated by the low-grade Dharwar Schists (Bababudan Group) and both the former rocks are unconformably overlain by the main schist belts of the Dharwar Supergroup (2600–2800 Ma). Because of these features Swami Nath and Ramakrishnan (1990) proposed an orogeny (Sargur orogeny) before the deposition of the Dharwar supracrustals. The type Sargur Group, developed around Hole Narsipura, is represented by high-grade pelitic schists (kyanite-staurolite-garnet-mica schists), fuchsite quartzite, marble and calc-silicate rocks, besides mafic and ultramafic bodies. The mafic rocks (amphibolites) show typical tholeiitic trend and are essentially low K-tholeiites with normative olivine and hypersthene. The ultramafic rocks appear to be komatiite flow. Detrital zircons from metapelites yielded ~3.3 Ga evaporation age) and 3.1–3.3 Ga (SHRIMP U-Pb age). Ultramafic-mafic rocks yielded Sm—Nd model age of ~3.1 Ga.

The main Dharwar Schist Belts of the Western Block are: (1) Shimoga-Western Ghat-Babubudan, and (2) Chitradurga (Fig. 2.2). Their western margin preserves the depositional contact marked by basal quartz-pebble conglomerate and abundance of platform lithologies, whereas the eastern contact is tectonized and marked by mylonitic shear zones. Besides Chitradurga shear zone, other prominent shear zones are Bababudan and Balehonnur. The metabasalts of Bababudan Group are low-K tholeiites, showing flat HREE and moderate LREE enrichment to indicate mantle source. The negative Eu anomalies in these rocks suggest plagioclase fractionation (see in Naqvi, 2005). The regional stratigraphy of the WDC (after Swami Nath and Ramakrishnan, 1981) is given below:

Proterozoic mafic dykes
Incipient charnockites (2.5–2.6 Ga)
Younger Granites (Closepet etc.) (2.5–2.6 Ga)
Dharwar- {Chitradurga Group: alluvial and shallow marine sedim. and volcanics
Supergroup {Bababudan Group: shallow marine sedim. and basaltic volcanics
-------Deformed angular unconformity-----
Peninsular gneiss, TTG (>3.0 Ga)
------------Intrusive/Tectonic contact-----
Sargur Group (3.1–3.3 Ga)
-----Intrusive/Tectonic contact---------
Basement Gorur Gneiss (3.3–3.4 Ga)

The *Eastern Block* consists mainly of volcanic (greenstone) belts of Dharwar group (2600–2800 Ma old) that are contemporaneous with the volcano-sedimentary schist belts of the Western Block. The prominent schist belts of the Eastern Block are Sandur, Kolar, Ramagiri, and Hutti (see Fig. 2.2). These volcanic belts have a narrow platformal margin marked by orthoquartzite-carbonate suite (e.g. Sakarsanhalli adjacent to Kolar belt, which is intruded by 2500–2600 Ma old granites. This caused dismembering of the supracrustals as screens and enclaves at the contact. These screens render it difficult to recognize pre-Dharwar (Sargur) enclaves in this block. The eastern margins of these schist belts are extremely sheared but could not be shown in geological maps for want of systematic geological mapping. There is no recognizable basement to these schist belts because these belts are engulfed on all sides by 2500–2600 Ma old granites and gneisses. The prominent meridional *Closepet Granite* occurring close to the boundary between the Eastern and Western blocks is one such younger granite, running parallel to the trend of the schist belts. According to Narayanaswami (1970), there are numerous elongated granites running parallel to the schist belts of the Eastern Block but they have not been fully delineated on geological maps. These granites occur in a series of parallel plutonic belts which have been collectively designated as Dharwar Batholith (Chadwick et al., 2000) in order to distinguish them from the widely used term Peninsular gneiss, scarcely exposed in the EDC. The TTG suite gneisses in the EDC show LREE enrichment and negative Eu anomaly. The gneisses span the age from 2.7 to 2.8 Ga (SHRIMP U—Pb and Rb—Sr methods). The protolith ages are >2.9 Ga, corresponding to the main thermal event of WDC. Amongst the younger granites, the Closepet Granite is an elongated (600 × 15 km) body intruding the Bababudan schist belts as well as the basement gneiss. It is a biotite granite or granodiorite to quartz monzonite composition. Recent studies by Chadwick et al. (2007) have shown that the granite splits into two segments near Holekal and has possibly emplaced as a sheet. The granite yielded well-defined Pb—Pb and Rb—Sr isochron of ∼2.6 Ga which is also the U—Pb zircon age of the granite (see Chadwick et al., 2007). The involvement of gneissic basement in the generation of the Closepet Granite and other late to post-tectonic granites (Arsikere, Banovara, Hosdurga) of Dharwar craton is evident from Sm—Nd model ages (T_{DM}) of the granite at ∼3.0 Ga.

Deformation of Dharwar Schist Belts show superpose folding wherein the N-S trending folds superposed on an older E-trending recumbent folds, giving rise to the prevalent NNW to NNE Dharwar Trend with convexity toward the east. But this view became untenable because the older E-W folds superposed by N-S folds could not be found on a regional scale. Recent structural studies show that the N-S trending tight to isoclinal upright folds have been coaxially refolded during D2 deformation. D3 phase produced more open folds. Crustal-scale shear zones at the eastern margin of most schist belts are now considered as the outcome of sinistral transpression in the late stage of tectonic evolution. Structural studies of Dharwar craton by Naha et al. (1986) showed that the Sargur, Dharwar and Peninsular gneiss (and Dharwar Batholith) have similar style, sequence, and orientation of folding (named Structural Unity). This view, however, overlooked the fact that "Peninsular Gneiss, where exposed in areas of less intense regional strain, preserves the original angular unconformable relations with the Dharwar schists. In areas of intense deformation, the Dharwar folds and fabric are superposed on Sargur folds and fabric, resulting in apparent parallelism as a result of rotation of earlier Sargur fabric into parallelism during the younger Dharwar deformation" (Ramakrishnan and Vaidyanadhan, 2008, p. 172).

Progressive regional *metamorphism* is convincingly documented in the Dharwar craton, especially in WDC (Fig. 2.2) where greenschist facies, amphibolite facies and finally granulite facies are noticed from N to S direction. The different isograds run nearly parallel and transect the compositional layering (S2 foliation) at high angle, suggesting that metamorphism outlasted deformation D2. Geothermobarometry along with fluid inclusion studies demonstrated that the P-T conditions in the low grade rocks in the north are 500°C/4 kb which increases to 600°C/5–7 kb in middle grade and 700–750°C/7–8 kb in the granulite grade rocks of the Dharwar craton. The regional metamorphism of EDC also occurred in a similar way, but is of low-pressure facies series. P-T conditions of EDC range from 670°C/3 kb in the Sandur belt in the north through 710°C/4–5 kb in the middle to 750°C/6–7 kb in the Krishnagiri-Dharmapuram area in the south (Jayananda et al., 2000). The low-pressure metamorphism of EDC is caused by the abundance of younger granites that seem to have supplied advective heat. The younger granites are almost absent in the WDC.

As stated already, the *Dharwar Schist Belts* are Late Archaean (age range of 2.8–2.6 Ga). They occupy a vast terrain of the Dharwar craton and are geologically significant for their linear occurrences like in other Precambrian fold belts of India (Gopalkrishnan, 1996). The Dharwar Schist belts appear to have evolved in ensialic intracratonic basins, subsequently subjected to regional compressions resulting in the deformation and recrystallization of these rocks, finally exposed by erosion in the present form. These Schist belts can thus be compared to the Proterozoic fold belts found in ancient shield areas of Canada, Africa, and Australia. One may also think that the Dharwar schist belts initially existed as mafic lava, like the Deccan Trap, covering a vast area of peneplaned Archaean gneisses. This basement-cover association, along with their eroded sediments, was involved in superposed folding, resulting into different schist belts that now characterize the Dharwar craton. Structural data suggest that the Dharwar craton deformed into tight to upright folds of two generations (with or without kinematic interval). Before we discuss evolutionary models for the origin of these greenstone belts of the Dharwar Supergroup, we need to know the agreed observations and facts about these Schist Belts. They are stated as follows:

1. The Dharwar Schist Belts (familiarly known as greenstone belts) rest on the Archaean gneisses with an unconformity, denoted by basal quartz-pebble conglomerate.
2. The Schists belts extend over a length of 600 km and width of 250 km or less.
3. The entire Dharwar succession is $\sim$10 km in thickness.
4. The Eastern greenstone belts have larger volumes of mafic to ultramafic flows and intrusives at the base; fine clastic and chemical sediments are subordinate.
5. The Dharwar greenstone belts of Western Block have oligomictic conglomerate overlain by mafic, orthoquartzite-carbonate (platform)-cum-iron ore deposits which became geosynclinal (graywacke-argillite-mafic volcanics) in the upper succession.
6. The Dharwar Schist Belts are in the age range of 2.8–2.6 Ga.
7. The Eastern block shows profuse granite intrusions.
8. The Eastern schist belts are gold-bearing and show low-pressure regional metamorphism (andalusite-sillimanite type), whereas the Western schist belts show intermediate regional metamorphism (kyanite-sillimanite type).
9. The Schist belts record two major deformation events out of which the first event (Dh1) is most widespread and responsible for the regional NWN-SES trend of the greenstones (Roy, 1983).
10. The belts show an arcuate N-S or NWN-SES trend with convexity towards the east, which is due to later tectonic event (Dh2) (Roy, 1983).
11. The regional foliation in the Peninsular gneisses and schist enclaves (of Sargur rocks) is largely parallel to the trend of the Dharwar schist belts, attributed to rotation of earlier structures in these pre-Dharwar rocks (Mukhopadhyay, 1986).
12. The schist belts are wide in north and taper down to the south, with younging direction towards north, perhaps due to northward tilt of the southern Indian shield
13. Banded iron formation (BIF) is a characteristic component of these schist belts.
14. Regional metamorphism related to the Dharwar orogeny affecting these schist belts is post-tectonic with respect to Dh1 (Mukhopadhyay, 1986) and is progressive from N to S and ranges from greenschist, amphibolite to granulite facies (Pichamuthu, 1953).
15. The second deformation, Dh2, is older than 2500–2600 Ma (Mukhopadhyay, 1986).

2.2.2 Evolution of Dharwar Schist Belts

Considering the foregoing account, we can infer that the Dharwars are the remains of a great supracrustal sequence that once had covered a very large area of the southern Indian shield. Because of different lithology of the schist belts of the two blocks we shall consider the Western and Eastern greenstone belts separately for their evolution.

The depositional environment for the *Western Dharwar Schist Belts* was marine and shallow. Moreover, since the Dharwar succession comprises basic flows and sediments, the original attitude was mainly horizontal. The deposition was evidently on a peneplaned basement of the Peninsular Gneiss (with its older enclaves) because of the supermature basal quartz-pebble conglomerate of the Dharwar schists. It is proposed that the Archaean crust of the Western Dharwar craton rifted to give rise to linear ensialic intra-continental basins. In these basins, the supracrustals were deposited, not necessarily continuously. Because of rifting and thinning of the crust/lithosphere, the underlying mantle underwent decompression melting, pouring out basaltic lavas which intervened the rift-sedimentation. Sagging of the basin allowed further accumulation of volcanic material and sediments, especially graywacke in northern parts of the rifts. These Dharwar supracrustals along with their infracrystallines (i.e. basement) were subsequently involved in the Dharwar orogeny that produced superposed folds in the Dharwar Schist Belts characterized by N-S regional foliation. Field evidence suggests that post-Dh1 recrystallization affected both cover and basement rocks that at depth were also remobilized to generate granites (2600 Ma old) which intruded the overlying rocks of the Dharwar Supergroup. Later, faulting and erosion caused the present isolation of the schist belts. The Dharwar greenstone belt of Western block cannot be considered to have formed in a marginal basin because the depositional margin represents an ancient shoreline and a more stable environment with a proximal sialic crust. Consequently, the Western Block schist belts seem to have evolved in a rifted continental margin containing abundant detritus from the stabilized continental crust of 3000 Ma age and progressed through an unstable shelf to an ocean basin.

The *Eastern Block schist belts,* on the other hand, are likely to have developed away from the continental influence, and their development conforms to the marginal basin model. The metabasics (amphibolites) of the Eastern Block, are enriched in LIL and LREE, compared with the marginal basin basalts of the Scotia arc (Anantha Iyer and Vasudevan, 1979). The possible cause of interlayered komatiitic amphibolites and tholeiitic amphibolites (2700 Ma old) is attributed to melting of asthenosphere (>70 km depth) and subcontinental lithosphere ($\sim$50 km depth) respectively (Hanson et al., 1988). The schist belts in the Eastern Dharwar craton are narrow and elongated and are dominated by volcanics with subordinate sediments. The Kolar schist belt is similar to other schist belts of the Eastern Block, and the gneisses on its E and W sides are dated at 2632, 2613, and 2553 Ma (Fig. 2.3). These are interpreted to have inherited zircons from an older sialic basement (Peninsular Gneiss and/or older basement gneiss) that was subjected to spreading and served as a basement in the marginal basin region. Chadwick et al. (2000) correlated the greenstone succession of the Eastern Dharwar craton with the Chitradurga Group. Their age data range from 2.7 to 2.55 Ma (Krogstad et al., 1991; Balakrishnan et al., 1999; Vasudevan et al., 2000). The Eastern Block has been profusely intruded by granites which could have been originated from partial melting of the continental crust during subduction (that caused secondary spreading) or during

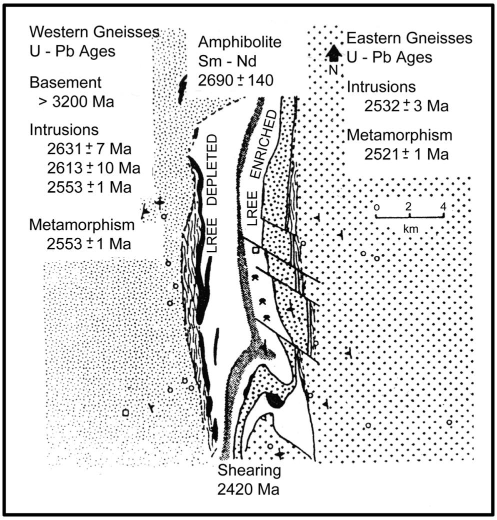


Fig. 2.3 Geological sketch map of central part of the Kolar Schist Belt (after Hanson et al., 1988)

rise of mantle plume, resulting in the heating and rifting of the overlying continental crust (Jayananda et al., 2003). The profuse granite intrusion may also be the cause of andalusite-sillimanite type metamorphism found in the rocks of the Eastern Block. Rogers et al. (2007) have presented SHRIMP U—Pb zircon ages together with whole-rock geochemical data for granitoid adjacent to Hutti-Muski schist belt in the EDC. They show two phase of intrusion into the belt; the syntectonic porphyritic Kavital granitoid of 2543 ± 9 Ma, followed by post-tectonic fine grained Yelagat granite defining minimum age of 2221 ± 99 Ma.

2.2.3 Geodynamic Models for the Evolution of Dharwar Craton

As stated already, the basement for the schist belts was sialic, because basal conglomerate defines the angular unconformity (deformed) between the Archaean gneisses and the supracrustals of Dharwar (formerly basic lavas and sediments). An important implication of this observation is that the geodynamic models for the evolution of Dharwar greenstone belts must have started with continental rifting. Furthermore, the occurrence of Closepet Granite between WDC and EDC of the Dharwar craton probably indicates a geosuture (Ramakrishnan and Vaidyanadhan, 2008). The different models need to consider the following geological-geochemical characteristics.

1. The basement of the greenstone was continental and hence Peninsular Gneiss.
2. Geochemistry suggests that the greenstone volcanics are not the source for the surrounding granites.

3. The Closepet Granite is late to post-tectonic body at the boundary of WDC and EDC.
4. Western margin of most schist belts has thin marine sediments.
5. The NNW trend of the schist belts is the result of superposed deformation of the schist belts which originally had nearly E-W orientation.
6. The progressive metamorphism in both WDC and EDC increases from N to S and the E-W running isograds are unbroken in the entire Dharwar craton.

With these facts and observations, we now evaluate different geodynamic models.

Model 1 (Newton, 1990)

This model considers that the greenstone belts are back-arc marginal basins formed as a result of E-W rifting of Archaean continental gneisses (i.e. Peninsular gneiss). The marginal basin was developed by N-verging subduction of an oceanic plate (now vanished). The subduction zone was located at the contact of Dharwar craton and the Neoproterozoic Pandyan mobile Belt (non-existent then at present location). The contact is now marked by a crustal-scale shear zone, the Palghat-Cauvery shear zone. The oceanic subduction toward north caused rifting in the overlying continental crust, generating the E-W greenstone belts. A reference to Fig. 1.11 will help the reader to understand this model. The E-W trending greenstone belts were later deformed (by E-W compression or transpression) to produce the present N-S configuration of the schist belts.

The model fails to explain the origin of low pressure greenstone belts of the EDC and cannot also explain the paucity of the Archaean gneisses in the EDC.

Model 2 (Chadron et al. in Ramakrishnan and Vaidyanadhan, 2008)

Non-uniformitarian "sagduction" model which involves gravitational sinking of greenstone pile into the gneissic basement together with tectonic slides at the margin.

This model cannot account for the large-scale top-to-SW overthrusting reported in many schist belts. The model requires a huge amount of lava to be extruded and then superposedly folded to acquire the present orientation.

Model 3 (Chadwick et al., 2000)

It is a convergence model of schist belt evolution, like the Andes. It can be easily followed if Fig. 1.11 is referred to. The WDC is regarded the foreland which was subject to secondary spreading due to subduction of an oceanic crust beneath it. This resulted into marginal basins and a continental arc (Dharwar Batholith) that later accreted onto the craton around 2750–2510 Ma. The EDC greenstone belts are considered to have developed as intra-arc basins. Later, as a result of arc-normal compression there occurred NE-SW shortening which resulted in the sinistral transpressive shear system at the margin of most schist belts. The oblique convergence of an oceanic plate (subducting toward WNW) resulted in the Archaean plate tectonic evolution of the Dharwar craton. The Closepet Granite in this model is regarded as a part of the Dharwar Batholith

There are, however, some objections to this model. It fails to identify the forearc accretionary prism in the east. It also cannot account for the marginal marine stable continental sediment along the western margin of many schist belts. It is also a question as to how did the convergence occur for the amalgamation of the WDC and EDC when the foreland of WDC and the Arc of EDC were drifting apart during the formation of marginal basin.

Model 4 (Rajamani, 1988; Hanson et al., 1988; Krogstad et al., 1989)

Based on the observations that the Eastern Block is characterized by low-pressure high-temperature metamorphism (unlike the kyanite-sillimanite type of Western Block) and is devoid of older basement, Rajamani (1988) proposed a tectonomagmatic model from the geochemical and geochronological data on the gneisses and amphibolites of the Eastern Block. The gold-bearing schist belts or Kolar-type belts of the Eastern Block are predominantly metamorphosed basalts with no exposure of gneissic basement. However, they are surrounded by reworked gneisses and migmatites containing their (greenstones) enclaves or tectonic slices. The schist belts show diapiric intrusion of granites along their margins. The absence of clastic sediments and the presence of pillowed and variolitic structures of the mafic rocks/schist belts led Rajamani (ibid) to propose a tectonic setting (i.e. oceanic) for them, different from the model given above for the well-defined Western Dharwar-type schist belts. He named them “Older greenstone” or Kolar-type greenstone belts—representing pieces of oceanic crust welded together to form composite schist belts. Being host rocks for gold, as at Kolar and Hutti at the southern and northern ends of the belts, the schist belts are also named Gold -bearing Schist Belts of Eastern Karnataka (Radhakrishna and Vaidyanadhan, 1997).

A detailed petrological and geochemical study, particularly of the Kolar schist belt, shows that the metabasic rocks (amphibolites) are characterized by four textural types viz. schistose, granular, massive and fibrous. The study of Rajamani (1988), Hanson et al. (1988), and Krogstad et al. (1989) suggests that the Kolar Schist Belt, as a type belt, is divisible into an E and W part with respect to a central ridge made up of a fine-grained metavolcanic unit (Fig. 2.3). To the west of the belt, granodioritic gneisses are found to have ages of 2631 ± 7, 2613 ± 10, and 2553 ± 1 Ma. These gneisses are found to have inherited zircons of 3200 Ma age or older, suggesting that an older basement gneiss existed >3200 Ma ago. To the east of the schist belt, the gneisses were emplaced at 2532 Ma ago. According to Hanson et al. (1988), these gneisses have mantle-like signatures, as revealed by Pb, Sr and Nd isotope data.

The age difference of about 100 Ma between the western and eastern gneisses is taken to indicate existence of two gneissic terranes, presumably with a separate evolutionary history, with metamorphic ages of 2521 ± 1 Ma for the eastern terrane and 2553 ± 1 Ma for the western terrane. Within the gneissic terranes, there are komatiitic amphibolites that to the east are LREE enriched whereas those of the west-central part are LREE depleted. The komatiitic amphibolites of the west-central part give Sm/Nd age of 2690 ± 140 Ma (Fig. 2.3). The interlayered tholeiitic amphibolites are older having Pb—Pb isochron age 2733 ± 155 Ma, suggesting that some of the amphibolites of the Kolar Schist Belt are older than the 2530–2630 Ma old gneisses to the E and W of the belt. Furthermore, the other two types of amphibolites from west-central part also have different Pb isotope ratios, suggesting that the parental magmas of the tholeiitic amphibolites derived from sources with a different U—Pb history than the parental magmas of the komatiitic amphibolite. Their depth of melting was also considered different, about 150 km for the komatiitic and about 80 km for the tholeiitic amphibolites (cf. Rajamani, 1988). It is proposed that the tholeiitic and komatiitic amphibolites were tectonically interlayered (Rajamani et al., 1985). The eastern amphibolites have not been dated, but from their Nd and Pb isotope characteristics, Hanson et al. (1988) suggest an age of 2700 Ma. Because of the REE characteristics and the geological setting, these authors argue that the eastern amphibolites formed in different tectonic settings from that of the west-central amphibolites. The authors (Hanson et al., 1988) propose a tectono-magmatic evolutionary model for the Kolar Schist belt in light of plate tectonics. This model is enumerated below and shown in block diagram (Fig. 2.4), after Hanson et al. (1988).

1. Initially the western terrane consisted only of 3200 Ma or older basement; the eastern terrane did not exist (Fig. 2.4a).
2. At about 2700 Ma, the parental rocks of the eastern and west-central parts of the Kolar schist belt developed in widely separated environments (Fig. 2.4b). The parental rocks of the schist belt of west-central part are believed to have formed either as Mid-Oceanic Ridge basalts (komatiites due to high heat flow), or as back-arc basin basalts (if both tholeiitic and komatiitic basalts were formed at the same time and place).

   The parents for the eastern komatiitic amphibolites could be oceanic island basalts or island arc basalts.
3. Westward subduction of the ocean floor brought the komatiitic-tholeiitic basalts in juxtaposition (as they developed in separate environments) (Fig. 2.4c) and developed a magmatic arc on the eastern edge of a continent, supported from the characters of plutonic rocks of the western gneisses and their setting upon an older basement. The eastern gneisses with mantle signatures are similar to many Archaean granitoids, but their tectonic setting remains unexplained.
4. Around 2550 Ma the gneisses to the west and east of the Kolar schist belt were welded together. The accreted terranes were subsequently involved in superposed isoclinal folding due mainly to E-W subhorizontal shearing, followed by longitudinal shortening.
5. The last event is the N-S left-lateral shearing found in all rocks of the Kolar schist belt (Fig. 2.4d). The age of shearing is about 2420 Ma, as deduced by Ar-Ar plateau age for muscovite developed in the shear zones.

The model of Hanson, Rajamani and coworkers would be challenged if gneisses of 3.3 Ga or older age could be found in the eastern terrain of the Kolar area. In this situation, a more viable model proposed for the schist belts of the Western Block may also be applicable for evolution of the Eastern Block. Whether or not >3.2 Ga old gneisses existed in the eastern part, the low pressure- high temperature

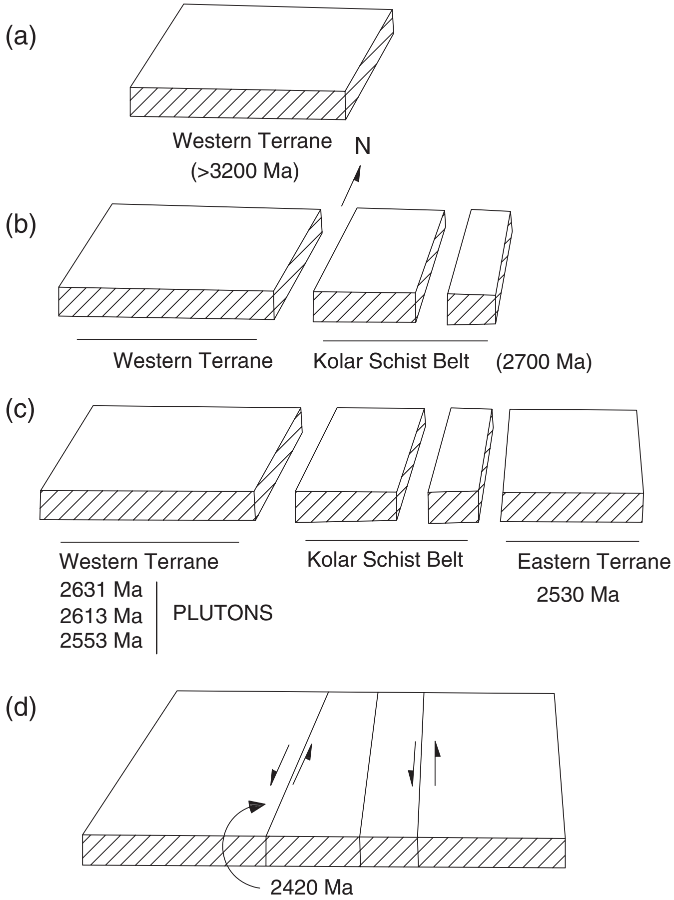


Fig. 2.4 Block diagram showing the crustal evolution in the Kolar area (after Hanson et al., 1988). See text for details

metamorphism of 2550 Ma for the Kolar area corresponds with the age of regional metamorphism (2.5 Ga) that affected both supracrustals and the infracrystallines (Archaean gneisses) of the Dharwar craton and developed the E-W trending isograds Pichamuthu, (1953, 1961). The E-W disposition of the regional metamorphic isograds is not compatible with the Westward subduction model of Hanson et al. (1988). The andalusite-sillimanite type metamorphism in the Eastern Block seems to be the result of profuse granite intrusions emplaced following peak metamorphism during which the Eastern Block was subjected to a greater upliftment relative to the Western Block. In support of this proposition, a more careful petrography could enable one to find kyanite relics in suitable compositions of the so-called andalusite-sillimanite type terrane of the Eastern Block. As stated earlier, the variation of facies series between the Western and Eastern Blocks is the outcome of eastward tilting of the southern Indian shield. This is manifested in the thicker crust in the Western Block compared to the Eastern Block and in the occurrence of vast exposures of charnockites (as lower crustal rocks) in Western Ghats.

We must now examine what light does the Late Archaean granite intrusions throw in regard to the geohistory of the two blocks, since granites have important bearing on crustal evolution. As we know, the granite intrusions represent a larger part of the EDC, since Peninsular Gneiss is absent or scantly reported from this Block. The granites are similar to those of the Western Block due to the similarity of outcrop pattern, relationship with the country rocks, geochemical characteristics and their isotopic ages (2.5 Ga, Friend and Nutman, 1991). Again, studies by Moyen et al. (2001) show that the granite intrusions of the E and W blocks were emplaced in the same transcurrent tectonic setting as the main phase of the Closepet Granite further south. The granites are clearly formed by anatexis of crustal rocks (Peninsular gneisses!) at depth, but the basement rheology was responsible for the upward movement of this low-viscosity magma to fill deformation-controlled pockets in the upper crust (Moyen et al., 2001). These considerations lead us to believe that the evolution of the E and W Blocks witnessed similar granite activity during the Late Archaean, presumably by their similar evolutionary history.

Finally, the model of Hanson et al. (1988), Rajamani (1988) and Krogstad et al. (1989) does not get support from a regional tectonic framework of southern India in terms of plate tectonics, given for the first time by Drury and Holt (1980) and Drury et al. (1984), based mainly on the Landsat imagery. They suggested that the Southern Granulite Terrain (SGT) underthrusted the Dharwar Craton along the E-W shear zone in Proterozoic. In light of the plate tectonic model, the 2663 or 2613 Ma old granites intruding the metavolcanics are considered to represent a magmatic arc (see Hanson et al., 1988). Nevertheless, it is a question whether the entire period starting from rifting to collision was an isolated event in the Eastern Block, not connected with the rifting of the crust in the Western Block of the Dharwar craton. It needs to be explained as to how both schist belts were affected by the same progressive regional metamorphism of Dharwar time ($\sim$2550 Ma) if they had developed separately in space and time. Ramakrishnan (2003) observes that preservation of the platformal margin and the sheared eastern margins of the schist belts in both blocks favour the view that all the Dharwar Schist Belts were evolved nearly contemporaneously on a continental crust but with different tectono-sedimentary environments. If so, the proposition by Chadwick et al. (2000) that the Western schist belts are foreland basins situated on a granitic crust and that the Eastern schist belts are intra-arc basins within the Dharwar batholith, is untenable. Also, the lack of fore-arc accretionary prism and the absence of suture zone to the east of Dharwar batholith do not support the proposed model of Chadwick et al. (ibid.) that is akin to Mesozoic-Cenozoic convergent setting (cf. Ramakrishnan, 2003, p. 12). It must be recalled that the greenstone belts from both E and W blocks are parallel and have similar structural styles, despite having different geotectonic settings. The structural similarity between the Peninsular gneiss, Sargur and Dharwar Schists is interpreted either as a single post-Dharwarian deformational episode or as due to rotation of older structures into parallelism with the younger Dharwar structures during the Dharwar orogeny.

The above account is thus helpful to answer critical questions whether the greenstone belts evolved diachronously or several cycles of greenstone belts occurred before Dharwar craton stabilized.

2.3 Bastar Craton

2.3.1 Introduction

The Bastar craton (BC) is also called Bastar-Bhandara craton. It lies to ENE of the Dharwar craton (DC), separated from the latter by the Godavari rift (see Fig. 2.1). Located to the south of the Central Indian Tectonic Zone (CITZ) the Bastar craton is limited by three prominent rifts, namely the Godavari rift in the SW, the Narmada rift in the NW and the Mahanadi rift in the NE. Its southeastern boundary is marked by the Eastern Ghats front. The western limit of the Eastern Ghats mobile belt overlying the Bastar craton is demarcated by a shear zone, which in fact is a terrain boundary shear zone (Bandyopadhyay et al., 1995). The Bastar craton is essentially formed of orthogneisses with enclaves of amphibolites, vestiges of banded TTG gneisses of 3.5–3.0 Ga, and low- to high-grade metasediments as supracrustals. Ancient supracrustals consisting of quartzite-carbonate-pelite (QCP) with BIF and minor mafic-ultramafic rocks, collectively called Sukma Group in the south and Amgaon Group in the north, occur as scattered enclaves and narrow belts within Archaean gneisses and granites. The succeeding metasedimentary belt is called Bengpal Group. The sequence is intruded by Archaean granites and the Bengpal Group is therefore considered Neoarchaean (2.5–2.6 Ga). Unconformably overain on the Bengpal Group Schists are BIF (Bailaddila Group). The next succession is felsic and mafic volcanics with pyroclastics (Nandgaon Group) intruded by 2.3–2.1 Ga old granites (Dongargarh, Malanjkhand etc.). The Nandgaon Group is overlain unconformably by basalts alternating with sediments, classed under Khairagarh Group.

H. Crookshank and P.K. Ghosh mapped the geology of southern Bastar during 1932–1938. Ghosh described the charnockites of Bastar. Recent geological summaries of Bastar craton is by individual workers, viz. Chatterjee, Ramakrishnan, Abhinaba Roy, Basu, Ramchandra, Bandyopadhya et al. (see in Ramakrishnan and Vaidyanadhan, 2008). S.N. Sarkar worked the geology of Kotri-Dongargarh belt.

The gneiss/migmatites and amphibolites, constituting the early crustal components of the Bastar craton, are grouped under the *Amgaon gneiss* that resembles the Peninsular Gneiss Complex of the Dharwar craton. It ranges in composition from tonalite to adamellite. Amgaon gneisses occur in the north of Bastar craton and south of Central Indian Shear zone (CIS). They were geochemically studied by Wanjari et al. (2005) who showed high Al_2O_3 trondhjemite along with cal-alkaline and peraluminous granites, similar to the 2.5 Ga old granites of Dharwar craton (Sarkar et al., 1981). The tonalite gneisses of Bastar craton yielded interesting age data. Geochronology of single grain U–Pb zircon ages gave 3580 ± 14 and 3562 ± 2 Ma for tonalite gneisses to the east and west of Kotri-Dongargarh linear belt (Ghosh, 2003, 2004). These ages represent the oldest Archaean crust not only in

Bastar craton but also in the Archaean cratonic regions of the Indian shield. The basement complex also contains granulite facies rocks and intrusion of granites of different ages.

The TTG gneisses enclose rafts of continental sediments (QCP facies) together with minor BIF and mafic-ultramafic rocks (Sukma Group of Bastar and Amgaon Group of Bhandara), as stated already (Wanjari and Ahmad, 2007). Large bodies of younger granites intruding the gneisses and supracrustals are notable components in the craton. Enclaves of granulites and high-grade metasediments also occur in the craton.

In *Bastar craton* the gneisses are classified into 5 types. These are: the Sukma granitic gneiss (Group 1), Barsur migmatitic gneiss (Group 2), leucocratic granite (Group 3) occurring as plutons with migmatitic gneiss, pegmatoidal or very coarse granite (Group 4), and fine-grained granite (Group 5) occurring amidst the Sukma gneisses. The gneisses of Groups 1 and 2 are chemically and mineralogically similar to the Archaean TTG, while the gneisses of Groups 3, 4 and 5 are of granitic nature.

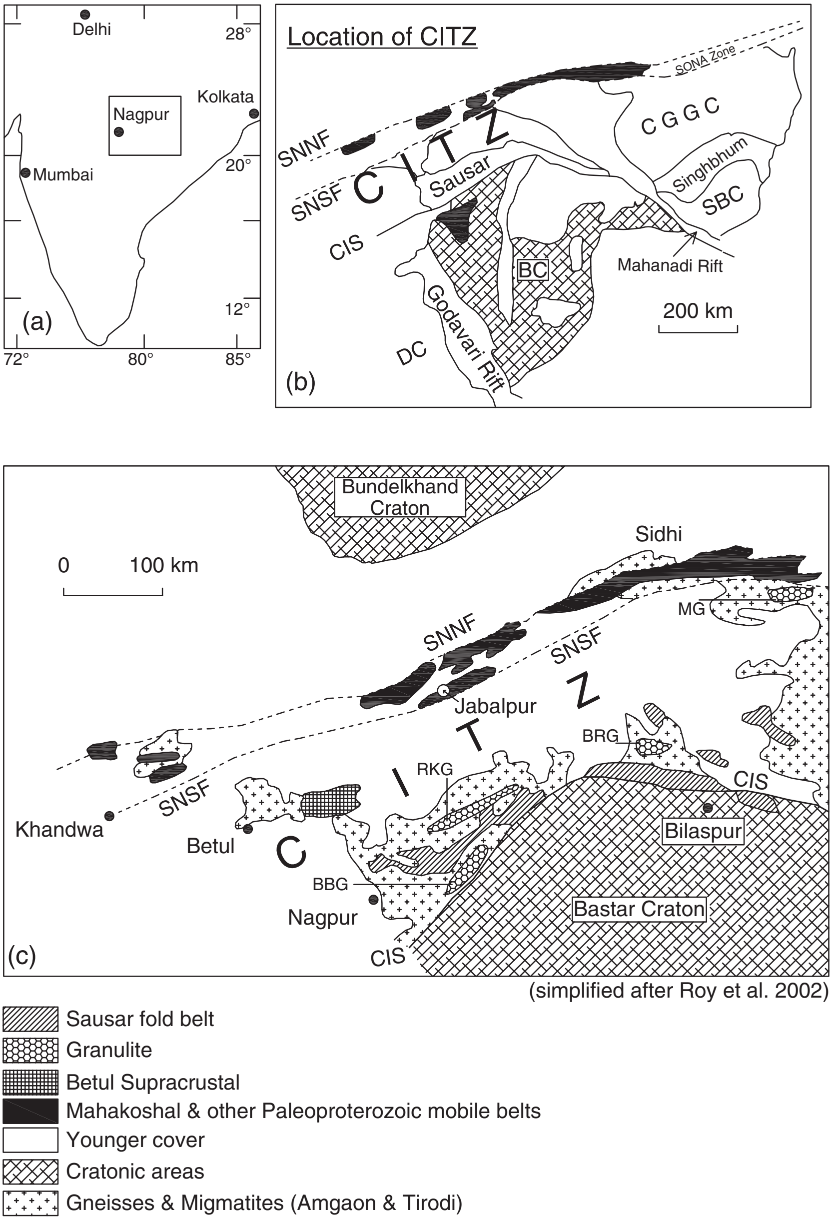
Pb-Pb isotope dating of Group 1 gneisses yielded 3018 ± 61 Ma age. The intrusive granites, particularly the leucocratic granite of Group 3 yielded 2573 ± 139 Ma (Stein et al., 2004). However, Rb/Sr age of this granite is 2101 ± 32 Ma with initial Sr ratios = 0.7050. The fine-grained granite (Group 5) gave Rb/Sr age of 2610 ± 143 Ma with initial Sr ratios = 0.7056 (Sarkar et al., 1990). It must be noted that most of these ages are errochrons but they definitely point to the presence of >3000 Ma old gneissic rocks in the Bastar craton. Also, high alumina trondhjemite gneisses, occurring as enclaves within the granite of Bastar craton near Markampura, yielded U—Pb zircon age of 3509 Ma, which is considered as the age of crystallization of tonalitic magma (Sarkar et al., 1995).

In the Bastar craton, three Archaean supracrustal units are recognized (Ramakrishnan, 1990), as stated already. First is Sukma metamorphic suite consisting of quartzites, metapelites, calc-silicate rocks, and BIF with associated metabasalt and ultramafic rocks. Second is Bengpal Group which is also characterized by the similar rock association as that of the Sukma unit. Hence, no distinction can be made between the two groups except that the Sukma suite shows a higher grade of metamorphism characterized by cordierite-sillimanite in the metapelites. These two rock groups, with associated granite-gneiss, have a general strike of WNW-ESE to NW-SW and appear to form a synclinorium in the west where the Third Group, the Bailadila Group is seen to overlie them. This Group contains BIF, grunerite-quartzite, and white quartzites. Migmatitic leucosomes from the Bengpal Group rocks yielded an errochron of 2530 ± 89 Ma with initial Sr ratio = 0.70305 (MSWD = 18.61) (Bandyopadhyay et al., 1990; Sarkar et al., 1990). The granites and associated pegmatites from Kawadgaon, intruding the Archaean Sukma and Bengpal formations of Bastar craton yielded whole rock Rb—Sr isochron of 2497 ± 152 Ma (Singh and Chabria, 1999, 2002; Sarkar et al., 1983).

On the NW of the Bastar craton there also occurs a vast exposure of gneissic complex, known in literature as *Tirodi gneiss*, which is a two-feldspar gneiss with biotite and occasionally garnet. Accessory minerals are zircon, apatite magnetite and sphene. Straczek et al. (1956), while mapping the Central Indian manganese belt, recognized biotite gneisses of all varieties surrounding the Proterozoic Sausar belt, which are often intercalated with amphibolites and hornblende gneiss (Subba Rao et al., 1999). They named this stratigraphic unit as Tirodi biotite gneiss and provisionally placed it at the base of the Sausar Group. Narayanaswami et al. (1963) considered the Tirodi gneiss as the basement to the Sausar Group. Although the contact between the Tirodi gneiss complex and the Sausar is mostly tectonized at most places, recently a polymictic conglomerate has been reported at the contact of Sausar and Tirodi gneiss from the locality of Mansar (Mohanty, 1993), confirming that the Tirodi gneiss is a basement to the Proterozoic Sausar Group. This rejects the hypothesis of some workers (Fermor, 1936; Roy et al., 2001) who proposed the Tirodi gneiss as migmatized Sausar Group rocks. Since the metasediments of the Sausar Group attained upper amphibolite facies (Brown and Phadke, 1983), the basement Tirodi gneiss should have equal or higher grade than sillimanite-almandine-orthoclase subfacies of the amphibolite facies. This accounts for the intermingling of granulites and gneisses so often seen in the Tirodi gneiss complex of the Bastar craton (cf. Bhate and Krishna Rao, 1981). Because of the occurrence of two or more phases of migmatization the Tirodi gneiss complex is considered a reworked Amgaon basement complex. It is in this context that the Rb/Sr isochron age of 1525 ± 70 Ma for the Tirodi gneiss and its mineral ages around 900 Ma (Sarkar et al., 1988) need to be considered. The Tirodi gneiss, although occurs to the north of the Central Indian Shear zone, abbreviated CIS (Fig. 2.5), is considered equivalent to the Amgaon gneiss described above. Both the Tirodi gneiss complex and the Sausar Group rocks are intruded by granite pegmatite and quartz veins of different generations. A detailed mapping showed that the Tirodi gneiss terrain contains mafic granulite, porphyritic charnockite, cordierite granulite and amphibolites—all occurring as rafts and lenses within the migmatized and banded gneisses of the Tirodi biotite gneiss complex (Bhowmik et al., 1999; Bhowmik and Roy, 2003). Considering the nature of the occurrences of the granulites, it seems quite probable that the granulite pods or lenses are the restites formed as a result of partial melting of the Tirodi gneiss during the Proterozoic Sausar (Satpura) orogeny. Alumina-rich pelites yielded garnet-cordierite-sillimanite gneisses, while normal metapelites and gneisses yielded hypersthene from biotite-involving dehydration melting reactions. The possible reactions are:

Biotite + sillimanite + quartz = garnet + cordierite + K feldspar + H_2O;
Biotite + quartz = hypersthene + K feldspar + H_2O ± garnet;
Hornblende + quartz = hypersthene + clinopyroxene + plagioclase + H_2O.

The Tirodi gneiss complex shows different periods of crustal melting which produced different types of migmatites, mostly felsic migmatites (Bhowmik and Pal, 2000). Some authors consider the granulites within the Tirodi gneiss as mylonitized and deformed tectonized rock in view of their occurrence as lensoidal and sigmoidal shape two-pyroxene granulites and their marginal retrogression. Due to this occurrence, the granulite is mistakenly interpreted as the remnant oceanic crust or the obducted tectonic slices/mélanges while the Tirodi basement gneiss as the Crustal block had subducted under the Bastar craton along the CIS (cf. Yedekar et al., 1990, 2000). It is interesting to observe that the boundary between the granulites and



(simplified after Roy et al. 2002)

Fig. 2.5 Central Indian fold belts and cratons. (**a**) Location of central Indian fold belts. (**b**) Geological setting of Bastar Craton in relation to adjacent cratons and Central Indian Tectonic Zone (CITZ). Abbreviations: BC = Bastar craton, CGGC = Chhotangapur Granite Gneiss Complex, CIS = Central Indian shear zone, DC = Dharwar craton, SBC = Singhbhum craton, SONA ZONE = Son-Narmada Lineament zone bounded by Son-Narmada North Fault (SNNF) and Son-Narmada South Fault (SNSF). (**c**) Simplified geological map (*bottom sketch*) shows the CITZ sandwiched between Bastar craton in the south and Bundelkhand craton in the north. The four localities of granulites described in the Satpura fold belt are: BBG = Bhandara-Balaghat granulite, BRG = Bilaspur-Raipur granulite, MG = Makrohar granulite, and RKG = Ramakona-Katangi granulite gneisses is lined up with sheet-like bodies of younger granitoids, suggesting that genesis of granulites is the outcome of partial melting phenomenon that produced the associated granitic bodies in the terrain.

There are four main occurrences of the granulites within the basement gneiss complex. (1) Ramakona-Katangi granulite domain (RKG) in the NW of the Bastar craton; (2) the Bilaspur-Raipur granulite (BRG) domain in the middle; (3) Makrohar granulite domain (MG) further east of the Satpura belt, near the SONA zone (Fig. 2.5c). These occurrences are in the form of boudins and pods within the Tirodi gneiss complex. The fourth occurrence of the granulite is the Bhandara-Balaghat Granulite belt (BBG). The granulite belt (4) is near the Central Indian shear Zone (CIS) and has a controversial location with respect to the shear zone. In geological maps, some workers (e.g. Bhowmik et al., 1999) show the BBG granulite within the Tirodi gneiss complex to the north of the CIS, whereas others (e.g. Abhijit Roy et al., 2006) place it within the Amgaon gneiss complex of the Bastar craton, south of the CIS.

The Ramakona-Katangi granulite domain (RKG) is dominated by basic type that includes mafic granulites and amphibolites. The host gneisses also experienced high-grade metamorphism and the garnet-amphibolites are not considered as retrogressed granulites. Bhowmik and Roy (2003) deduced a metamorphic history from garnet amphibolite and mafic granulites from this belt. The peak metamorphism (M1) for garnet-amphibolite has been estimated at 9–10 kbar/750–800°C while lower P-T value (8 kbar/675°C) was obtained for amphibolites. The M1 event in the rocks was followed by isothermal decompression phase (M2), estimated at 6.4 kbar/700°C, after which the rocks underwent isobaric cooling (M3) at 6 kbar/650°C (Bhowmik and Roy, 2003). The authors argue that the decompression in the mafic granulites is not continuous, but punctuated by a distinct heating event (prograde). The event is related to an extension phase marked by emplacement of mafic dykes. The combined P-T path is clock-wise. A near clock-wise P-T loop has also been established from studies of pelitic granulites of the RKG domain (Bhowmik and Spiering, 2004). On the consideration of growth zoning preserved in garnets and based on heterogeneous distribution of diverse inclusions of mineral assemblages in the porphyroblasts of pelitic granulites from RKG, Bhowmik and Spiering (2004) deduced a clockwise P-T path. The path is claimed to have started with an early prograde amphibolite facies metamorphism (identified by staurolite-biotite-quartz ± kyanite), followed by peak metamorphism (M1) at ~9.5 kbar/~850°C, documented by dehydration melting of biotite and formation of pelitic migmatite. The path terminated by isothermal decompression (M2) at 6 kbar/~825°C documented by plagioclase corona and spinel-plagioclase-cordierite symplectite around garnet. The final P-T trajectory, according to the authors (Bhowmik and Spiering, 2004), was marked by isobaric cooling (M3) which terminated at 5 kbar/600°C. From this depth, the rocks were possibly emplaced in the shallower depth (equivalent to the depth of the Al-silicate triple point) by upthrusting along the CIS to be later acted upon by erosion to expose them in the present state. According to these authors, the deduced P-T loop is consistent with a model of crustal thickening due to continental collision, followed by rapid vertical thinning.

However, there is considerable debate on the extent of the collision event. Bhowmik et al. (1999) considered the collision orogeny to be related to an older pre-Sausar tectono-thermal event. The overprint of an amphibolite facies event was taken by these authors as evidence for the younger Sausar event (Mesoproterozoic). Bhowmik and Spiering (2004) derived 880 Ma age for the monazite included within a garnet of RKG domain. This age is close to the 860 Ma Rb/Sr mineral isochron age from the basement of Tirodi gneiss (Sarkar et al., 1986), but nearly 70 Ma lower than the $^{40}Ar/^{39}Ar$ age for cryptomelane derived from Ramakona granulite area (Lippolt and Hautmann, 1994). Bhowmik and Dasgupta (2004) consider this age to mark the timing of post-decompression cooling history in the RKG domain. These authors claim that the timing of the collision and peak metamorphism is likely to be older and the metamorphic history of the RKG domain is an outcome of a single Grenville-age tectonothermal event (Bhowmik and Dasgupta, 2004).

The Bilaspur-Raipur granulite domain (BRG) occurs in the eastern extremity of the CITZ bordering the Bastar craton (Jain et al., 1995; Bhattacharya and Bhattacharya, 2003). This domain represents an ensemble of supracrustals, granite, gneisses, and granulites, each separated by tectonic contacts. Jain et al. (1995) reported mafic granulites from Ratanpur area. The granulites are boudin type. The geological history of this belt is poorly understood.

The Makrohar granulite domain (MG) occurs to the south of the low-grade Mahakoshal supracrustal belt. Previous workers have identified three distinct lithologies in the MG (Pascoe, 1973; Solanki et al., 2003). These are: (a) felsic gneiss-migmatite, (b) supracrustal lithopackage of sillimanite, quartzite, meta-BIF, calc-silicate gneiss, calcite marble, pelitic schists, garnetiferous metabasics, including amphibolites and hornblende schists, (c) metaigneous rocks comprising gabbro-anorthosites and porphyritic granitoid. The latter intruded the supracrustal rocks. Solanki et al. (2003) have documented garnet-cordierite-biotite-sillimanite assemblage in pelitic granulites and garnet-hornblende-plagioclase-epidote-rutile-sphene assemblage in metabasic rocks. Pitchai Muthu (1990) previously reported corundum-bearing sillimanite schists from the same area. Based on textural, mineral-chemical and geothermobarometric studies, Solanki et al. (2003) established P-T conditions of three stages in the development of pelitic granulites and garnet-metabasic rocks. These stages are: (1) 9 kbar/800°C for peak metamorphic condition, (2) 6.5 kbar/740°C for early stage of retrogression, and (3) 685°C for final re-equilibration. The granulite events, however, remain isotopically undated.

The lithological ensemble of the Bhandara-Balaghat granulite (BBG) domain is subdivided into 4 distinct components: (i) a large migmatitic felsic gneiss terrain, locally with garnet, (ii) enclaves or isolated bands of garnet-cordierite gneiss, BIF, quartzite, corundum-bearing and felsic granulite within the Tirodi gneisses, (iii) a mafic-ultramafic magmatic suite of metagabbro-metanorite and gabbro metanorite-metaorthopyroxenite, occurring as concordant sheets in the felsic gneisses, and (iv) metabasic dykes and amphibolites. The gabbroic suite of rocks is particularly dominant in the southern part of the BBG domain where it is interlayered with felsic and aluminus granulites. By contrast, norites and meta-orthopyroxenites are quite common in the northern part where they are associated with garnet-cordierite gneiss.

Bhowmik et al. (2005) recognized 5 phases of deformation, D1 to D5. The D1 has caused banding demarcated by alternate light and dark migmatitic layers. D2 is a foliation parallel to banding. This was followed by a strong ductile shear zone that produced south-verging isoclinal folds, D3, and a strong mylonitic foliation S3. This phase deformed mafic dykes that were emplaced in the felsic granulites. The σ-type asymmetrical orthopyroxene porphyroclasts indicate that the southerly tectonic transport was a high T phase during D3. Subsequent deformation produced narrow steep ductile shear zone fabrics that affected the amphibolites. The D1 to D3, according to Bhowmik et al. (2005), pre-date the Sausar orogeny and the cross folds in the granulites due to D5 are also found in the Sausar Group rocks.

The granulite facies metamorphism is dated at 2040–2090 Ma by Bhowmik and Dasgupta (2004). Ramchandra and Roy (2001) have reported Sm/Nd and Rb/Sr ages from charnockitic gneisses and two-pyroxene granulites from BBG domain. They show three distinct age clusters, at 2672 ± 54 Ma; 1416 ± 59 to 1386 ± 28 Ma; and 973 ± 63 to 800 ± 16 Ma. These ages are correlated with two temporally separated phases of granulite facies metamorphism of Archaean and Mesoproterozoic ages, finally overprinted by the Sausar orogeny (Ramachandra and Roy, 2001). However, in the absence of detailed information on the type of rocks and mineralogy being dated and the methodology being used, it is difficult to use these dates to constrain tectono-thermal events in the Sausar mobile belt (see Chap. 5).

Petrological work by Bhowmik et al. (1999) showed that mafic granulite (metagabbro) is the dominant component of the BBG that also has enderbite gneiss, charnockite, cordierite gneiss and meta-ultrabasites (gabbro-norite-pyroxenite). P-T estimates by the authors revealed an anti-clockwise path characterized by heating and isobaric cooling. Charncokites from the BBG are found to show peak metamorphism at ∼10.5 kbar/775°C and a lower P-T (∼5 kbar/700–650°C), which are considered to correspond to Pre-Sausar and Sausar orogeny (Bhowmik et al., 199 l; Roy et al., 2006). Recent geochronological data given by Roy et al. (2006) reveal quite interesting ages on the charnockites and mafic granulites from BBG. Sm—Nd isochron of charnockite whole rock (WR) and its three mineral separates gave an age of 2672 ± 54 Ma but Rb—Sr isotope systematics yielded an age of 800 ± 171 Ma. The high error in age and higher MSWD of the samples are attributed to limited spread among Rb—Sr ratios of mineral phases and whole rock, besides high Rb/Sr ratios. Again, the garnet-bearing as well as garnet-free mafic granulites yielded WR and mineral separates Rb/Sr and Sm/Nd isochron ages in the range 1400–1420 ± 70 Ma. The coincidence of Sm/Nd and Rb/Sr ages indicate the crystallization ages of these mafic bodies. Rb/Sr isochron for two of the analyzed samples of mafic granulites from BBG, however, gave an age of about 970 Ma which Roy et al. (2006) consider as re-set ages by a thermal imprint.

Two more granulite belts are reported in the Bastar craton (Ramakrishnan and Vaidyanadhan, 2008). One is the Bhopalpatnam granulite belt at the northern shoulder of Godavari graben that conceals the actual contact between Dharwar craton and Bastar craton. Zircon U—Pb dating report 1.6–1.9 Ga for the granulites (Santosh et al., 2004). Another belt is the Kondagaon granulite belt which occurs in the middle of the craton. Here, charnockites and leptynites dominate the western part of the granulite belt. The Kondagaon granulite belt indicates ages around 2.6 Ga, similar to those of Karimnagar granulite belt on the southern flank of the Godavari graben.

Recently, Srivastava et al. (1996) have identified three sets of mafic dyke swarms in the southern Bastar craton. Two sets are sub-alkaline tholeiitic whereas the third set is boninite-like mafic rock (high SiO_2 and high MgO). The earliest dyke (D-1) is an amphibolite, mostly intruding Archaean granite gneisses but not the Proterozoic granites since it is cut by 2.3 Ga old granite. The second set of dyke cuts all rock-types, including the 2.3 Ga old granite. The age of this latter dyke (D-2) collected from Bastanar gave an age of 1776 ± 13 Ma (Srivastava and Singh, 2003). French et al. (2008) have carried out U–Pb (zircon and Baddeleyite) dating of two NW-SE trending mafic dykes from southern Bastar that gave 1891 ± 0.9 Ma and 1883 ± 1.4 Ma ages.

Geodynamic Evolution of Bastar crtaon cannot be modeled for want of thermo-tectonic and sufficient geochronological data on the rocks of the craton. However, the following account would form the foundation for future attempt in this direction.

The grey gneiss complex of Bastar craton contains relicts of early continental rocks of 3.5–3.6 Ga. The Archaean crust of Bastar craton seems to have witnessed rifting in the Neoarchaean time for the supractrustals of Sukma and Amgaon Groups (∼3.0 Ga) which now occur as enclaves in the basement TTG gneisses of the craton. With deposition of the supracrustals the craton was presumably stabilized. On the stabilized crust, a WNW-ESE rift was formed and subsequently filled with amygdule basalt in association with clastics of Bengpal Group. The Bengpal Group witnessed widespread granite activity at the Arcchaean-Proterozoic transition (2.5–2.6 Ga). After Bengpal event, there occurred another continental rifting for the deposition of N-S trending Kotri-Dongargarh fold belt (Sect. 5.5). After a break in sedimentation, a new cycle of felsic and mafic volcanics (Nandgaon Group) occurred, with a basal conglomerate and quartzite. A major granite pluton (Dongargarh), perhaps comagmatic with the felsic volcanics, intruded Nandgaon Group at about 2.3 Ga ago. Thereafter there was another volcanic-clastic cycle (Khairagarh Group) which seems to have concluded the main felsic to mafic volcanism in this stage of continental rifting. Finally, the younger succession of dominantly fine clastic plus chemical sediments (Chilpi Group) occurred which were subsequently involved in the Proterozoic orogeny (Satpura fold belt). Bastar craton was completely stabilized by about 1800 Ma to have deposition of the Purana basins of central Indian region.

2.4 Singhbhum Craton

The Singhbum craton (SBC) is also called Singhbhum-Orissa craton in eastern India. It is made of Archaean rocks that are exposed in an area of ∼40,000 km^2 in Singhbhum district of Jharkhand (formerly Bihar) and northern part of the State of Orissa. The craton is bordered by Chhotanagpur Gneissic Complex to the north, Eastern Ghats mobile belt to the southeast, Bastar craton to the southwest, and alluvium to the east. Much of the geological information about Singhbhum craton (SC) or Singhbhum Granite Complex (SGC) is due to Saha (1994). The following rock-suite constitute the Singhbhum craton (Fig. 2.6):

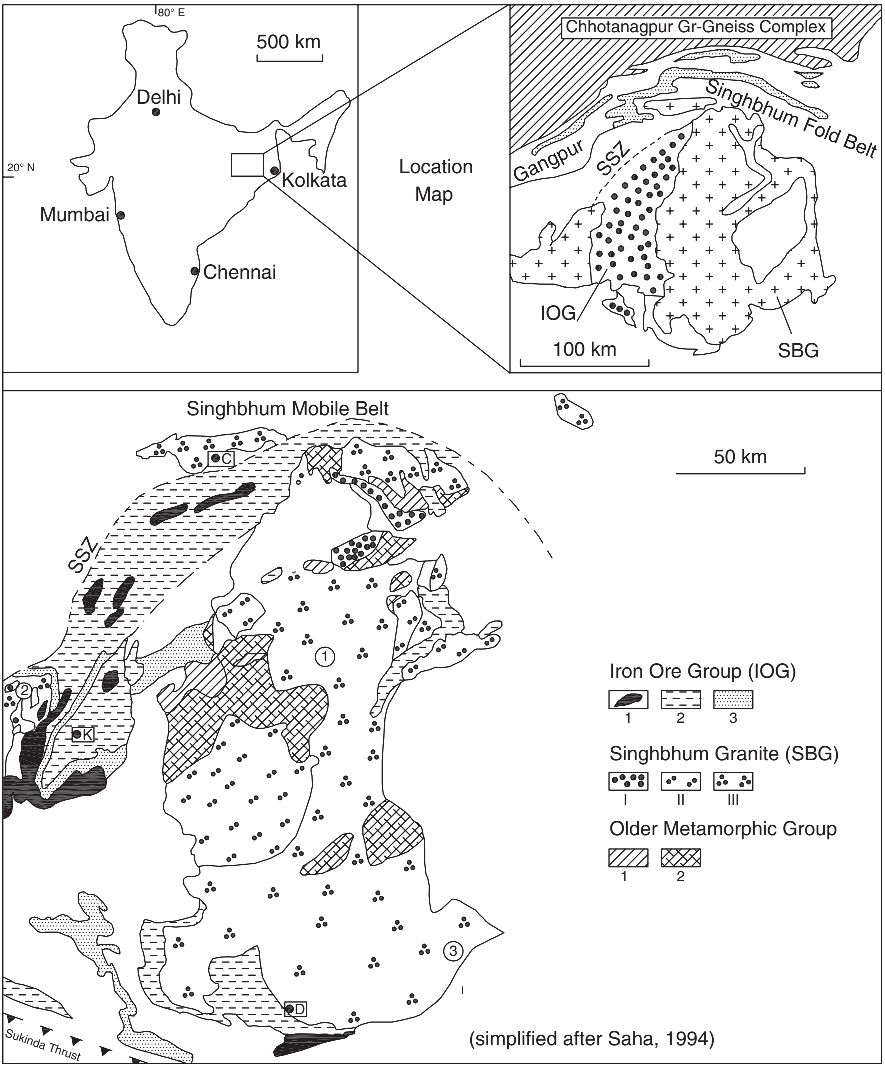


Fig. 2.6 Location and Geological map of Singhbhum (-Orissa) craton comprising Archaean rocks of Older Metamorphic Group (1) and Older Metamorphic Tonalite Gneiss (2), Singhbhum Granite Group (SBG) with three phases (I, II, & III) of emplacement, and Iron-Ore Group (IOG) made up of: 1 – lavas and ultramafics, 2 – shale-tuff and phyllite, 3 – BHJ, BHQ, sandstone and conglomerate. Abbreviations: C = Chakradharpur, D = Daiteri, K = Koira, SSZ = Singhbhum shear zone. (1) = Singhbhum Granite, (2) = Bonai Granite, 3 = Mayurbhanj Granite

1. Singhbhum Granite (I, II, III phases) with enclaves of (i) Older Metamorphic Group (OMG), and (ii) Older Metamorphic Tonalite Gneiss (OMTG).
2. Iron Ore Group (IOG,) dominantly Banded Iron formation (BIF) at the margin of the Singhbhum Granite
3. Volcanics or greenstone belts (Simlipal, Dhanjori, Dalma etc.)

The Older Metamorphic Group (OMG) (Sarkar and Saha, 1977, 1983) is a supracrustal suite of rocks composed of amphibolite facies pelitic schists, garnetiferous quartzite, calc-magnesian metasediments and metabasic rocks. Komatiitic lavas are missing from the OMG, unlike other Archaean terrains of the world. Radiometric dating of rocks of the OMG does reveal ages older than 3300 Ma. The OMG rock-suite is perhaps the oldest supracrustals of the eastern Indian shield, and perhaps equivalent to older Dharwar Schist Belt (Sargur). The OMG rocks are synkinematically intruded by tonalite gneiss grading into trondhjemite and designated as the Older Metamorphic Tonalite Gneiss (OMTG). The OMTG (whole rock) has been dated both by Sm—Nd and Rb—Sr systematics. The Sm—Nd age of 3800 Ma for the OMTG is considered as the crystallization age of the magma, although it might also represent the time of generation of mafic melt in the mantle with crystallization of the melt at the base of the crust (Basu et al., 1981). The Rb—Sr isochron age of $\sim$3.2 Ga for the OMTG (Sarkar et al., 1979) is interpreted as the age of melting associated with metamorphism of the OMG. The OMTG is considered as an anatectic product of the OMG into which the OMTG intruded at depth during metamorphism. The OMG is estimated to have been metamorphosed at 5.5 kbar and 660–630°C, indicating substantial crustal thickening during Archaean. The OMTG is characterized by gently sloping REE patterns without Eu anomaly (Saha and Ray, 1984b), that are comparable to the pattern in the Archaean Gneissic Complex and the tonalitic diapirs of Barberton. The geochemistry and REE patterns suggest derivation of the OMTG by partial melting of OMG amphibolites (Sharma et al., 1994) and even by partial melting of low-K basalt or mantle peridotite. Bose (2000), on the other hand, considers that the OMTG and the amphibolites of the OMG may represent Archaean bimodal magmatism (Saha et al., 1984).

The Older Metamorphic Group (OMG) as a supracrustal must have been initially deposited as sediments and volcanics on an earlier basement, now unrecognizable in the region. This is perhaps due to their transformation and remobilization generating granitic rocks, now seen as OMTG, and possibly also as several later generation granites that are now grouped in the Singhbhum Granite Complex (SGC). This basement to the OMG appears to be granitic, in view of the presence of muscovite and quartz-rich bands as well as the occurrence of zircon in the OMG. At Rairangpur locality a group of dark-coloured tonalite rafts are reported "floating" in the Singhbhum Granite. These rafts are believed to have been basement for deposition of the volcano-sedimentary sequence of the OMG (Dey, 1991). Both OMG and OMTG document two phases of deformation and exhibit a structural accordance, suggesting that the Archaean deformation occurred after the emplacement of the OMTG. The general strike of the OMTG is NE-SW (Saha, 1994), but folding has changed this to NW-SE. According to Saha (1994) the OMG intruded by the OMTG are the oldest formations in the Singhbhum region (Sarkar and Saha, 1983). They have been folded first about steep NE plunging axes and later about the SE plunging axes, with variable dips, seen in the northern region of the Archaean craton. The Older Metamorphic Group in the type area has the axial planes of the first generation strike NW, with axes plunging NE. These have been affected by folds plunging towards SE (Sarkar and Saha, 1983).

The formation of OMG and OMTG was successively followed by the emplacement of the Singhbhum Granite (SBG) that intruded in two phases (SBG I and SBG II), deposition and folding of the Iron Ore Group (IOG) supracrustals and emplacement of Singhbhum Granite phase III (SBG III) (Saha, 1994). The OMG banded amphibolite and OMTG are commonly seen as rafts and inclusions in the vast expanse of the Singhbhum Granite Complex, indicating that the OMG supracrustals and OMTG originally covered a wide area now occupied by the Singhbhum Granite batholith. The structural elements in the OMG area oriented oblique to those occurring in the adjacent supracrustal envelope forming the Iron Ore Group (see below).

The oval-shaped Singhbhum Granite Complex (SBG), together with other smaller plutons of more than one generation, constitutes major part of the Archaean craton. This granite complex is part of the earliest continental segment to cratonise and together with the Archaean supracrustals have been designated the Archaean Cratonic Core Region (ACCR) by Mahadevan (2002). In the granite complex, the supposedly primary foliation shows swirling patterns which led Saha (1972) to identify 12 separate magmatic bodies, domical or sheet-like in shape, which appear to have been emplaced in three successive but closely related phases. Each phase of the magma is believed to have been derived independently from the same source region in the crust, because of distinctive trace element distribution patterns (Saha, 1979). The phase I is K-poor granodiorite to trondhjemite, occurring only as small patches at the northern and eastern parts of the craton. The phase II is dominantly granodiorite, mainly confined to the southern contact of the OMTG. The phase III is mainly granite. The phase III covers the largest part covering an area of $\sim$1800 km^2. However, samples of phase I and II with gently sloping REE patterns and weak or no Eu anomaly are similar to the patterns shown by OMTG. The samples of phase III show similar patterns (LREE enrichment, flat HREE and negative Eu anomaly). Comparable to the Singhbhum Granite are other granites, namely the Chakradharpur granite gneiss in the NW and the Bonai Granite body in the west, occurring at the perpheral region of the granite nucleus (ACCR of Mahadevan, 2002). Granitic rocks of proven diverse ages within the Singhbhum Granite massif (e.g. Mayurbhanj Granite), however, suggest remobilization of the basement during later orogenesis (Naha and Mukhopadhyay, 1990).

Rb-Sr isochrons (Sarkar et al., 1979) for the Singhbhum Granite are less precisely dated than those for the OMTG, indicating a great heterogeneity in the samples. Poorly constrained ages preclude use of existing geochronology for correlation of magmatic/metamorphic events. However, careful geochronological data (Moorbath et al., 1986; Sharma et al., 1994; Sengupta et al., 1996) suggest two crust-forming events in the region during the Archaean, with their ages at 3.4 and 3.2 Ga. The isochron age of 3200 Ma for the tonalite gneiss is considered to represent melting associated with metamorphism of the OMG (Sarkar et al. 1979). The 3800 Ma Sm/Nd age of the OMTG, determined by Basu et al. (1981), is considered the crystallization age of the magma, although it might also represent the time of generation of a mafic melt in the mantle with crystallization of the melt at the base of the crust (Basu et al., 1981). The metasedimentary enclaves in the 3.2 Ga old Singhbhum Granite from southern Singhbum are dated at about 3.5 Ga (see Saha, 1994). The Granite phase III (ca. 3.1 Ga) is believed to be intrusive into the IOG. The emplacement dates of the three phases of Singhbhum Granite (Saha, 1994), underwent a major revision when Sharma et al. (1994) gave the time span of $\sim$3.3–3.1 Ga for the Granite phases I, II and III (Saha and Ray, 1984a and b).

Recent geochronological data reveal (see Misra, 2006) that the equivalent granite bodies of the Singhbhum Granite are the Bonai Granite, Nilgiri Granite and Chakradharpur Granite Gneiss, occurring respectively at the western, southeastern and northern margins of the Singhbhum Granite (Fig. 2.6). The Bonai Granite is dominantly porphyritic granite, intimately associated with less abundant equigranular variety. The pophyritic granite ranges in composition from granite to granodiorite and rarely tonalite, whereas the equigranular variety is a two-mica trondhjemite. The porphyritic granite intrudes the IOG and contains large xenolithic blocks of these metalavas. Therefore, the Bonai Granite is younger than the IOG supracrustals and stratigraphically equivalent to SBG-III. The Bonai granite is separated from the main Singhbhum Granite batholith by a belt of IOG supracrustals (Jamda-Koira horse-shoe synclinorium) (Sengupta et al., 1991; Saha, 1994).

The Nilgiri Granite (Saha, 1994) forms the southeastern part of the Singhbhum (-Orissa) craton, and is separated from the main Singhbhum Granite by a narrow strip, 3–8 km wide of IOG phyllite and greenschist (see Fig. 2.6). The Nilgiri Granite varies in composition from TTG to granite. The Nilgiri pluton is seen intruded by the Mayurbhanj Granite (anatectic product of SBG-III) along its margin.

The Chakradharpur Granite gneiss (Bandyopadhyay and Sengupta, 1984; Sengupta et al., 1983, 1991) is an isolated body of the Singhbhum Granite and occurs amidst the supracrustal rocks of the Singhbhum Group (see Fig. 2.6). This granite gneiss forms the basement to the overlying Singhbhum Group, while its pegmatoid phase intrude both the older gneiss and the enveloping supracrustals. Geochemically, the older tonalite gneiss of the Chakradharpur Granite Gneiss is considered equivalent to the SBG-I or SBG-II, whereas the pegmatoid phase is considered equivalent to younger granite bodies (e.g. Arkasani Granite, Mayurbhanj) that intrude the Singhbhum Group (Saha, 1994).

The Iron Ore Group (IOG), consisting of banded iron formation (BIF) and metasedimentary and metavolcanic rocks, occurs in the western, eastern, and southern flanks of the Singhbum Granite massif. The BIF's are interbanded with lavas and pyroclastics, and even basic volcanics interbedded with rhyodacite and trachytic volcaniclastics (Banerjee, 1982). Along the eastern border zone of the Singhbhum Granite the BIF is intruded by a group of unmetamorphosed gabbro, norite, and anorthosite. The IOG rocks in the Singhbhum craton occur either as linear narrow intra-cratonic belts or as more extensive peripheral bodies. The IOG (formerly

Iron Ore Series; Krishnan, 1935) is believed to have deposited on the OMG. Three major basins of IOG are recognized along the fringes of the ACCR. These are: (1) Gorumhasani-Badampahar basin in the eastern part, (2) the Tomka-Daiteri (D) basin along the southern part, and (3) the West Singhbhum-Keonjhar basin or the Jamda-Koira (K) basin in the western flank of the ACCR. The basin (3) contains the most spectacular occurrence of the BIF in the Jamda-Koira valley to the west, where its outcrop defines a major horse-shoe shaped syncline. This syncline shows transverse folding and variations of plunge. Both features, according to Sarkar and Saha (1983), are considered synchronous with the main folding event. However, Chakraborty and Mazumdar (1986) have recognized three sets of folds within BIF near Malangtoli south of Jamda, and the fold interference is found to have resulted in type 1 and type 2 patterns of Ramsay (1967). The Gorumahisani basin (1) has volcanics and BIF whose strike of the axial planes of the dominant folds is nearly N-S, almost parallel to the elongation of the belt. The Gorumahisani belt represents either a pinched-in synclinal cusp within the basement or a faulted graben (Mukhopadhyay, 1976; Banerjee, 1982). Interestingly, this belt is parallel to one set of regional fractures within the Singhbhum Granite. In the Tomla-Daiteri basin (2) to the south, the regional folds show E-W striking axial planes. Thus, the axial traces of the regional folds within the different basins of the IOG curve round the Singhbhum Granite, suggesting that the fold in these supracrustals envelope were moulded around the rigid basement block.

Sarkar and Saha (1983) place these three Archaean basins in one stratigraphic group, termed the IOG, as interconnected basin, while Iyengar and Murthy (1982) believe that the Gorumahisani basin belongs to much older orogenic cycle during which the IOG (3) welded to the Archaean craton. A.K. Banerji (1974) also suggests that the Noamandi basin of IOG (3) is stratigraphically distinct. He recognized two cycles of iron formations, an older Gorumahisani Group and a younger Iron-ore Group, separated by the Jagannathpur volcanic flows. Dating of the intrusive granite phase-III (3.17 ± 0.1 Ga; Saha, 1994) of the Singhbhum Granite into the IOG suggests that the IOG are older than 3.1 Ga. The supracrustal of the stated IOG is surrounded on its east and north by a younger Dhanjori eugeosyncline in which about 10 km sediments and lava flows were deposited.

The *Dhanjori Group* of volcano-sedimentary formations rest unconformably on the Singhbhum craton and, in turn, are overlain unconformably by the Chaibasa Group representing the lower unit of the Singhbhum Group. The relationship between the Dhanjori volcanics and the argillaceous Chaibasa Formation is a debated topic. According to Dunn and Dey (1942), the Dhanjori is thrust over by the Chaibasa Formation and hence older than the latter. Sarkar and Saha (1962, 1977) regard the Dhanjori to be younger than the Chaibasa. However, on the basis of northward younging of the successive members of the Dhanjori formations and of the juxtaposed Chaibasa formation, Mukhopadhayay et al. (1975) concluded that the Dhanjori is older and is succeeded by the Chaibasa formation. In support of this view, Sinha et al. (1997) reported that there is a conglomerate at the base of the Chaibasa Formation exposed in the Jaduguda mines, separated from the underlying conglomerate of the Dhanjori sequence, rendering the Chaibasa Fm younger than the Dhanjori. The 2.2 Ga old (Pb—Pb age; Sarkar et al., 1985) Soda Granite that syntectonically intruded the Chaibasa Fm fixes the upper age limit of the Singhbhum Group. The age of the Dhanjori volcanics is poorly constrained, but Sm—Nd isotopic studies on Dhanjori basalt from Kula Mara and Kakdha area (S of Rakha Mines) gave an errochron of 2072 ± 106 Ma (Roy et al., 2002b). Recently, Misra and Johnson (2003 in Acharyya, 2003) report whole-rock Pb—Pb ages of 2787 ± 270 Ma while Sm—Nd whole-rock yielded 2819 ± 250 Ma for the Dhanjori basalts. From this we may conclude that IOG and the Dhanjori Group represent the Late Archaean (3000–2500 Ma) supracrustals, and hence should be included in the cratonic region of the Singhbhum region. It is for their older age that the Dhanjori volcanics differ from Dalma volcanic in their trace element and REE pattern (Bose, 1990). Dhanjori basalt has a fractionated REE whereas Dalma basalt (and their intrusive gabbro-pyroxenite) is depleted in LREE and show almost flat HREE (see Saha, 1994).

In the southwestern region of the ACCR the IOG is intruded by 3.16 Ga old Bonai Granite (see Fig. 2.6) and is unconformably overlain by a meta-psammitic cover sequence with conglomerate horizon at base and metavolcanics and tuffites in middle part. This overlying sequence is named *Darjin Group* (Mahalik, 1987). The Darjin Group is intruded by Tamperkola Granite (Mazumder, 1996; Naik, 2001) that has yielded in-situ Pb—Pb zircon age of 2809 ± 12 Ma (Bandyopadhyay et al., 2001). Interestingly, the Darjin rocks and its intrusive Granite are devoid of deformation and metamorphism, despite of their being late Archaean in age, as stated already. The deformed and recrystallized Singhbhum Group exposed further east is intuded by 2.2 Ga old Soda Granite (cf. Acharyya, 2003). The Darjin Group is overlain by a sequence of thick metavolcanics, tuffs, and metasediments (Bhaliadihi Formation of Naik, 2001) with a basal unit of BHJ and BHQ-bearing breccia and conglomerate. The metavolcanic dominated Bhaliadihi Formation resembles the Dalma and/or Chandil volcanics (Proterozoic).

The northern and northwestern boundary of the Archaean nucleus is not well defined, although the northern and eastern side of the cratonic nucleus is demarcated by a broad shear zone, called the Singhbhum Shear Zone (SSZ) (Mukhopadhyay et al., 1975). This zone of variable width consists of extremely deformed clastics with down dip lineation, BIF, wedges of granite gneiss from the Archaean nucleus, lithicwackes of the cover as well as mylonites and phyllonites. The stratigraphic sequence within this zone cannot be worked out (Sengupta and Mukhopadhyay, 2000). Discontinuous sheets of smaller and linear bodies of granites (syntectonic 2.2 Ga old Soda Granite, Arkasani granophyres and Mayurbhanj granite), some of which also occur as basement wedges, often in variable states of deformation and are exposed in the vicinity of the shear zone. According to Dunn (1929) and Mukhopadhyay (1984) the SSZ with its narrow belt of mylonites die out westward. Extension of the SSZ is also reported along the NW margin of the Singhbhum Granite and the southern margin of the Chakrdharpur Granite to appear as the largest tectonic wedge of the basement granitoid in the north (Sarkar and Saha, 1962; Gupta and Basu, 2000). This occurrence led these authors to infer that the SSZ separates the domain of Singhbhum mobile belt and the Archaean craton hosting the Ongerbira

Volcanics. However, some workers recorded a lithological similarity of rocks across this supposed extension of the SSZ (cf. Mukhopadhyay et al., 1975). A continuity of structure and absence of mylonite belt was also noted across the supposed extension of the SSZ (cf. Mukhopadhyay et al., 1990). This controversial situation could be the result of discontinuity of the shear zone between Singhbhum mobile belt in the north and the cratonic region overlain by Ongerbira volcanics in the south.

2.4.1 Geodynamic Evolution

The earliest crust in the Singhbhum craton is found to be the Older Metamorphic-Group (OMG) which yielded the same age as the Old Metamorphic Tonalite Gneiss (OMTG). Zircon ages in politic rocks of OMG suggest that sialic crust had existed at about 3.6 Ga ago, prior to the formation of OMG. It has been suggested that this early continental crust was formed by recycling (through mantle convection) of mafic-ultramafic crust into the mantle whereby TTG gneisses generated, possibly in two-stage melting process. The early melting stage was at about 3.3–3.4 Ga which is the oldest component component, Singhbhum Granite-I in which xenoliths of OMTG are found. The Mesoarchaean continental crust of Singhbhum Granite I with its enclaves OMG and OMTG, rifted and formed greenstone belt of Badampahar Group which is characterized by sphinifex textured komatiites, pillowed tholeiites, BIF and fuchsite quartzite—a common association of Archaean greenstone belts. The closing of the greenstone basins was followed by granite intrusion (Singhbhum Granite phase II and III). The next cycle is marked by the volcanics and sediment association of 2.8 Ga (Roy et al., 2002a). Based on the new radiometric ages on the different rocks of the Singhbhum (-Orissa) craton, the evolutionary history of the craton (after Misra, 2006) is given in Table 2.1.

2.5 Chhotanagpur Granite-Gneiss Complex

The Complex is considered here as a cratonic region whose convergence with the Singhbhum craton to the south gave rise to the Singhbhum mobile belt. It covers an area of about 100,000 km^2 and extends in the E-W across the states of Chattisgarh, Jharkhand, Orissa and West Bengal. The Chhotanagpur Granite-Gneiss Complex (CGGC) is bordered on the north by Gangetic alluvium, on the south by Singhbhum mobile belt and on the northeast by the Rajmahal basalt (Fig. 2.7). Early regional studies on the CGGC are by Ghose (1983), Mazumder (1979, 1988), Banerji (1991) and Singh (1998), but no regional map of the entire cratonic region was available until Mahadevan compiled a geological map (Mahadevan, 2002).

The CGGC comprises mainly granitic gneisses, usually migmatized, and porphyritic granite, besides numerous metasedimentary enclaves. Gneisses from central and granites from the western CGGC gave nearly similar ages of 1.7 Ga (see in Chatterjee et al., 2008). The migmatites and granulites and granitic gneisses from northeastern CGGC (Dumka area) gave Rb-Sr ages of 1.5–1.6 Ga (see in Chatterjee et al., 2008). These dates correspond to the ages obtained by Pb-isotope on galena

Table 2.1 New radiometric ages on the rocks of the Singhbhum (-Orissa) craton, after Misra (2006)

S. No.	Geological events	Rock types	Age (Ga)
8.	Stabilization of Singhbhum (-Orissa) craton		~3.09[5]
	Thermal metamorphism of OMG due to emplacement of SBG-III and Bonai Granite		3.16–3.10[1]
7.	Emplacement of SBG-III and possible upper age limit of formation of SSZ	SBG-III, Granodiorite to granite	3.12[2]
	Emplacement of Bonai Granite pluton	Bonai granite-granite to granodiorite and rarely two-mica trondhjemite	3.16[3]
	Metamorphism of OMG, OMTG and IOG		3.24–3.2[4,5]
6.	Formation of IOG and its folding-Meta morphism	Mafic lava, tuff, felsic volcanics Tuffaceous shale, BHJ-BHQ with iron ore, local dolomite, quartzitic sandstone and minor conglomerate	Between 3.33 and 3.16[5]
Unconformity			
	Thermal metamorphism of OMG and OMTG due to emplacement of SBG-II and Nilgiri Granite		3.30[6,7]
5.	Emplacement of Nilgiri Granite Pluton	Nilgiri pluton, Tonalite to granite	3.29[8]
	Emplacement of SBG-II	SBG-II, granodiorite	3.33–3.3[4]
		Emplacement of tonalitic rocks occurring as enclaves within Bonai Granite Pluton	3.38[3]

Table 2.1 (continued)

S. No.	Geological events	Rock types	Age (Ga)
4.	Emplacement of SBG-I	SBG-I, tonalite to granite	3.44[2]
3.	Folding of OMG supracrustals and syn-kinematic tonalite intrusion of OMTG	OMTG-a bio-hb tonalite gneiss grading to granodiorite	3.44–3.42[4,10]
		Oldest xenocrystic zircon recovered from tonalite xenoliths within Bonai granite	3.44[8]
2.	Deposition of OMG sediments upon unknown basement, with intermittent extensive volcanism and plutonism	Pelitic schists, Qz-Mt-Cumm-schist, banded calc-gneiss, para- and ortho-amphibolites	3.55–3.44[5]
1.	Formation of unstable sialic crust not preserved in the present geological record	Represented by sialic nature of overlying sediments and presence of xenocrystic zircon in them	~3.55–3.6[10]

[1] Sarkar et al. (1969).
[2] Ghosh et al. (1996).
[3] Sengupta et al. (1991).
[4] Misra et al. (1999).
[5] Misra (2006).
[6] Moorbath et al. (1986).
[7] Sharma et al. (1994).
[8] Saha (1994).
[9] Sengupta et al. (1996).
[10] Goswami et al. (1995).

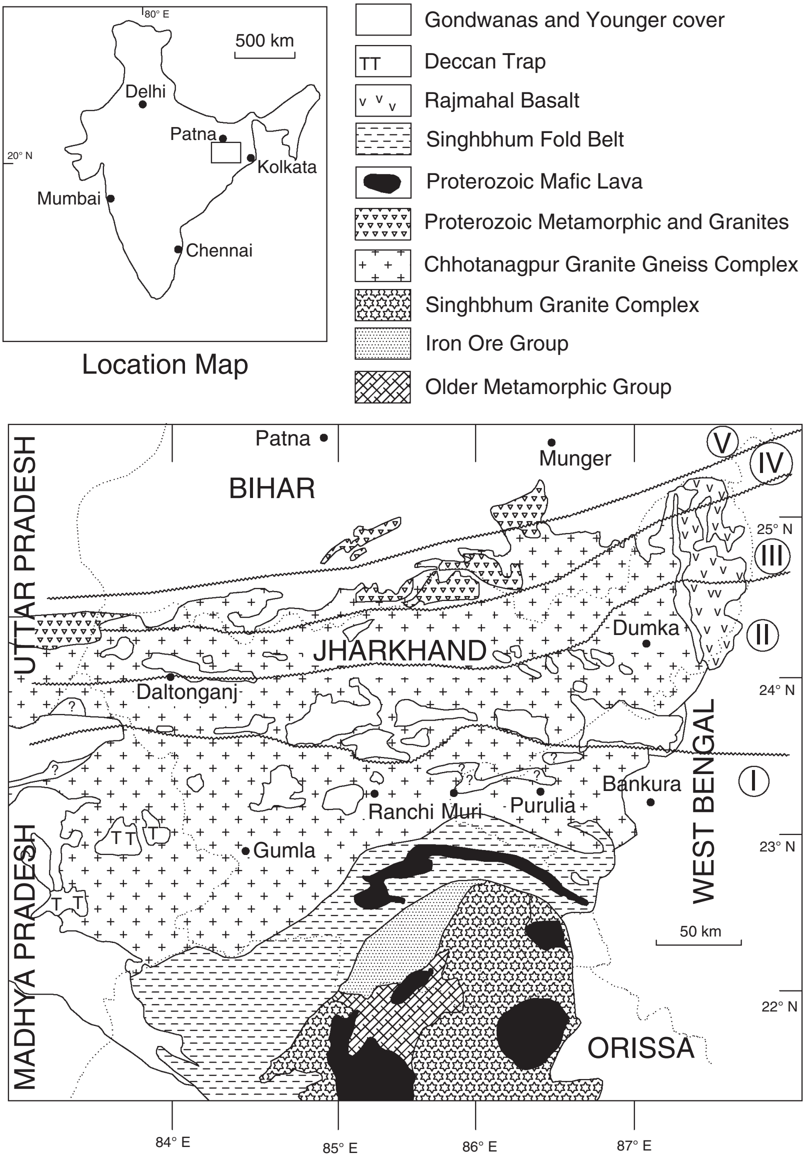


Fig. 2.7 Location and distribution of Chhotanagpur Granite Gneiss Complex (CGGC). The five geological belts (I–V) outlined by zigzag line in the CGGC terrain are drawn after Mahadevan (2002). *Dotted lines* are boundaries of the States

from metasediments in this part of the CGGC (cf. Singh et al., 2001). The metasedimentary rocks, occurring inside and outside the granitic gneisses, show varying degree of metamorphism, ranging from greenschist (mostly in SE part of the CGGC terrain) to granulite facies (central and eastern part of the terrain). The occurrence of metasedimentary and other rocks inside the gneisses of the CGGC suggests that the gneisses were the basement and that both these rock-units were subjected to metamorphism accompanied by profuse granite activities. It is for this reason that the CGGC acquired polymetamorphic character (Sarkar, 1968), like the Archaean gneissic complexes of most cratonic areas. The oldest age of ≥ 2.3 Ga of the gneisses of the CGGC from Dudhi area, west of Daltanganj (Mazumder, 1988) suggests that some of the metasedimentary enclaves within the gneisses were formed in Archaean. The enclaves of pelitic granulites, quartzites etc. within the basement gneisses of the CGGC indicate that the CGGC rocks have undergone partial melting in the Precambrian time, generating granitic rocks as intrusives and granulites as melanosome or restite.

The granulite assemblage in the CGGC is commonly represented by khondalite (garnet-sillimanite ± graphite), calc-silicate granulite (scapolite-wollastonite-calcite-garnet ± quartz), charnockite (hypersthene-granite), two-pyroxene granulite with or without garnet, hornblende granulite—all occurring as dismembered bands within migmatitic granitic gneisses (Roy, 1977; Sarangi and Mohanty, 1998). Apart from these, there are also enclaves of ultramafic bodies (hypersthene-spinel-hornblende ± olivine), lenticular or elliptical massif of anorthosite and syenite bodies (Mahadevan, 2002). The gneissic layering in granulite enclaves is similarly folded with the surrounding gneisses (Mahadevan, 2002; Mazumder, 1988). It is not clear whether the entire terrain shows a progressive regional metamorphism from greenschist through amphibolite to granulite facies or whether the gneisses are retrograded granulites. Anorthosites and alkaline rocks are also locally abundant in the granulites (reviewed in Mahadevan, 2002). The anorthosite in the eastern part of the CGGC was emplaced during or after the second phase of deformation, since these intrusives lack F1 deformation, and possibly F2 (Bhattacharya and Mukherjee, 1984). The granulites in general record at least three main deformation events of which F1 and F2 are intense and coaxial and their axial planes trend E-W to NE-SW. The F3 is a cross fold and is represented by broad warps along N-S trending axes. Although gneisses, migmatites and high-grade pelitic schists are present in the CGGC, attention has been given mainly on the granulites in the CGGC terrain.

The granulites and high-grade gneisses are reported from metamorphic belts located on the north and south of the median Gondwana outcrops that were deposited in intracratonic rifts of the CGGC during Upper Palaeozoic time. The southern belt is named South Palamau-Gumla-Ranchi-Purlia belt and the northern belt is designated Daltonganj-Hazaribagh-Dhanbad-Dumka belt by Mahadevan (2002) who divided the CGGC rocks into five major divisions (Fig. 2.7), based on a broad lithological ensemble (see last section). Three broad centres of the granulite pods are (i) the Palamau district in west (Ghose, 1965); (ii) the Purulia-Bankura region in the SE (Sen, 1967); and (iii) the Dumka-Mayurakhsi Valley in the NE (Bhattacharya, 1976; Ray Barman et al., 1994). Of these, only the granulites from Purulia-Bankura are located in the southern belt of Mahadevan. Other minor occurrences of granulitic rocks in the CGGC are to the east of Ranchi (Sarkar and Jha, 1985), between Parasnath and Madhupur.

According to Acharyya (2003), the More Valley granulite terrain to the west of Dumka is of igneous parentage with very minor supracrustals showing metamorphic imprints. Euhedral zircon from the high-grade gneiss yielded U—Pb upper intercept age of 1624 ± 5 Ma while from massive charnockites in the vicinity the upper intercept age is 1515 ± 5 Ma. In both cases the lower intercept yielded ca. 1000 Ma age, suggesting a thermal overprinting on both gneiss and charnockite. The Upper intercept age signifies the time of crystallization of hypersthene gneiss at high temperature and medium pressure or midcrustal depth (Acharyya, 2003). Ray Barman et al. (1994, cited in Acharyya, 2003) believe that these rocks cooled isobarically in a P-T regime of around 750°C at or above the pressure of 4–7 kbar. Rounded zircons separated from basic granulites that occur as sills and dykes within the hypersthene gneiss yielded 1515 Ma age (Acharyya, 2003, p. 16), suggesting that the hypersthene gneiss and intrusive basic granulites were metamorphosed together at 1.5 Ga and the whole sequence then cooled isobarically. The granitic intrusions of ca. 1000 Ma age indicate Grenville thermal event documented by the lower intercept of the discordia. To the east, the granulites from Dumka also show an isobaric cooling. The age of 1457 Ma obtained by Rb—Sr systematics of syenite in the Dumka sector is taken to indicate the time of anatexis of paragneisses (Ray Barman et al., 1994). Well foliated granitoid from the Ranchi Shear zone containing granulite facies supracrustals yielded Rb—Sr whole-rock isochron ages of 1.7–1.5 Ga (Sarkar et al., 1988).

The granulites from the Purulia-Raghunathpur area in the southern domain of the CGGC are reported to have evolved through ITD (isothermal decompression) path at ca. 1000 Ma. This was probably synchronous with the amphibolite grade migmatization. The granite plutonism, which is widespread during 1.0 Ga, is believed to have affected both granulite facies domains of the CGGC (cf. Ray Barman et al., 1994). The age difference of ca. 100 Ma in the granulites from the north and south of Ranchi shear zone perhaps indicate cooling at different crustal levels rather than to show different evolutionary history (see also Ray Barman et al., 1994).

In Saltora area, Bankura district, Manna and Sen (1974) documented a near-isobaric cooling in a suite of mafic granulites from 950 to 750°C at 8 kbar. Bhattacharya and Mukherjee (1984), on the other hand, proposed a prograde history involving breakdown of hornblende followed by cooling and retrogression to amphibolite facies conditions at 600°C/6.25 kbar. Again, Sen and Bhattacharya (1993) retrieved highest T (820–840°C at 7.5 kbar) for medium scapolite-calcite-plagioclase equilibria in wollastonite-calcite-plagioclase-garnet-quartz assemblage in calc-granulites from the same locality. They also obtained lower temperatures (600–680°C) at 6–7 kbar, estimated from Fe—Mg exchange thermometer, which is attributed to retrograde cooling that led to the formation of garnet corona at the interface of hypersthene-plagioclase (Sen and Bhattacharya, 1986). According to these authors, further cooling resulted in the stabilization of mantling pyroxene in mafic granulites. Using different petrological constraints, Sen and Bhattacharya (1993) computed the peak isobaric cooling up to 680°C and 6.8 kbar. Subsequently, infiltration of mixed H_2O–CO_2 at 500°C/5 kbar developed muscovite, zoisite, and calcite in different proportions in rocks of the area. Sen and his coworkers (Sen and Bhattacharya, 1986) also reported anorthosites that were emplaced during second phase of deformation along the core of doubly plunging folds.

In granulites around Dumka, a near isobaric cooling path was deduced by Ray Barman et al. (1994), based on coronal garnet at the hypersthene-plagioclase interface, similar to that described by Sen and his coworkers from Bankura area in the SE. Ray Barman et al. (1994) also documented a short decompress phase wherein garnet had developed symplectites of hypersthene + plagioclase. These authors also noted the occurrence of hypersthene-sillimanite in the enclaves of granulites from south of Ranchi and Daltonganj area in North belt, which is interpreted by them to be a product of ultra high temperature (UHT) metamorphism. Thus, the granulites from both belts, on either side of the Gondwana Formations, show similar tectonothermal history. However, relationship of the granulite facies assemblages and migmatization in the rocks of the N-belt are poorly known. Ray Barman et al. (1994) consider the isothermal decompressive path at 1.0 Ga for Purulia granulites whereas an isobaric cooling path at 1.5 Ga for Dumka granulites.

The CGGC is also characterized by more than one generation of mafic intrusives, mostly dolerite and gabbros to norites in which corona structure is often noticed at several places, especially in Daltonganj, Dumka and Purulia districts. These metaigneous rocks are generally concordant with the foliation of the host gneisses. Age-wise these metaigneous bodies may be older than 1600 Ma. Geochemically, these metabasics are different, tholeiitic in granulitic rocks while ORB (ocean ridge basalt) in non-granulitic rocks. According to Murthy (1958), the presence of these large-scale coronets in the CGGC implies a major thermal episode in the evolution of the CGGC terrain. These coronites are believed to have been emplaced at mid-crustal levels during a distensional stage (Mahadevan, 2002, p. 273). There are also ultramafic enclaves in the granulitic rocks, especially at Ardra (Purulia district) and Dumka, and a possible linkage is suggested with the noritic rocks generated in the subcrustal layers (Mahadevan, ibid.).

In complexly deformed and metamorphosed rocks of the CGGC, one cannot ascertain geological relationship amongst different lithounits, especially when the complex was overprinted by more than one tectono-thermal event (i.e. orogeny). Geochronological data on the rocks of the CGGC are meager and the three age clusters of K—Ar dates have been taken to indicate three cycles of orogenies. A “Simultala orogeny” was proposed to cover ages in the range of 1246–1416 Ma, obtained in the NE part of the CGGC; the time band of 850–1086 Ma from Ranchi-Gaya areas was assigned to the Satpura orogeny; and ages of 358–420 Ma obtained in the extreme NE part of the CGGC were assigned to Monghyr orogeny (cf. Mahadevan, 2002). Newer dates by Rb-Sr systematics on granitic rocks form Bihar Mica belt and charnockitic rocks from Dumka (belt III of Mahadevan, 2002) gave ages in the range 1000–1600 Ma, pointing to the impact of Satpura orogeny. However, age data based on Rb—Sr methods are susceptible to resetting at lower grades and by post-magmatic alteration, hence they tend to record younger ages. Also, a weak Pan-African thermal event (ca. 590–595 Ma) is recorded in the fission-track dating of mica from the Bihar Mica belt (Nand Lal et al., 1976). The U—Pb data on zircons from massive charnockite yielded 1625 and 1515 Ma (Mesoproterozoic) while its recrystallization ages are at 1071–1178 Ma, indicating Grenville orogeny. Acharyya (2003) and Ray Barman et al. (1994) tentatively correlated the near isobaric cooling event at ca. 1500 Ma and the near-isothermal decompression at ca. 1000 Ma. This time span is recorded in the granitic rocks that are characterized by high initial Sr ratios (Ray Barman et al., 1994). Considering the results of careful field studies, it can be concluded that the charnockites are intrusive into the basement rocks, namely the khondalite, basic granulite, calc-granulite etc. (Mahadevan, 2002). The intrusive granulites with igneous texture have acquired foliation due to deformation imposed on them subsequent to their emplacement. Alternatively, it is also possible that the scattered charnockites occurring amidst high-grade gneisses and migmatites owe their origin to in-situ charnockitization brought about by dehydration melting or by influx of carbon dioxide in the pre-existing gneisses and metasediments. This means that the granulite facies rocks could be as old as the associated gneisses of the CGGC and hence Mesoproterozoic or perhaps older (Late Archaean). However, no information is available about the precursor material either of the Mesoproterozoic charnockite or of granite that intruded the basement. Ghose (1983) and Banerjee (1991) suggested that the charnockite-khondalite-granulite and associated tonalitic gneisses represent the basement complex of Archaean age. Supracrustals to this basement complex are pelitic schists, paragneisses, calc-silicates and marbles—all grouped by the stated authors under *Older metasediments* (equivalent to Singhbhum Group of 2600 Ma age). According to these authors, both basement and cover were metamorphosed up to granulite facies with emplacement of plutonic rocks, such as anorthosites, gabbros, and granitoids and also pegmatites, most probably during Grenville orogeny. Later, igneous activities included intrusion of basic and granitic rocks and extrusion of Rajmahal basalts.

Considering the paucity of reliable geochroniolgical data, Mahadevan (2002) divided the CGGC into five major divisions or belts, based on broad lithological ensemble. These east-west trending metamorphic belts from S to N are:

1. South Palamau-Gumla-Ranchi-Purulia Belt.
2. Daltonganj-(North Palamau)-Hazaribagh Belt
3. North Garhwa-Chatra-Girdih-Deogarh-Dumka Belt.
4. The Bihar Mica Belt
5. Rajgir-Kharagpur Belt.

The rocks of Belt-1 show a progressive change from greenschist facies in the south, through amphibolite facies to granulite facies near Ardra and beyond. The complete Barrovian sequence ending up with charnockitic rocks is seen only in the Purulia district of West Bengal. Charnockites and anorthosites are not found westwards.

The Belt II exposes high-grade rocks, particularly granulites that occur interbanded with granites and gneisses and form concordant bands with metasediments. On the NE extension this belt merges with the E-W- striking Bihar Mica Belt (BMB). Here the most dominant rock is migmatite gneiss amidst biotite-sillimanite gneiss with or without garnet and muscovite, suggesting temperatures in excess of muscovite-quartz stability. The muscovite-free bands are mostly garnet-sillimanite gneiss (khondalite).

The Belt III contains isolated pockets of granulite facies rocks, occurring within felsic gneisses. It is not clear whether or not the whole or some parts of the felsic gneisses ever reached granulite facies conditions.

From the preceding account, one can suspect that rocks older than 1.7 Ga may have been present in the CGGC, but no systematic dating techniques have been applied to the rocks of the CGGC. Surely, U—Pb dating of individual zircons is a powerful tool in geochronology, but the high U content affects the accuracy of $^{206}Pb/^{238}U$, and not the $^{207}Pb/^{206}Pb$ ages (Williams and Hergt, 2000). Again, age data based on Rb/Sr method are susceptible to resetting by post-magmatic alteration or shearing and hence they tend to record younger ages. If the Paleoproterozoic Singhbhum mobile belt is the result of convergence of the Singhbhum craton in the south and CGGC in the north, we should expect Archaean ages in some domains of the CGGC, which could be cratonic nucleus of the complex, similar to the Archaean nucleus of the Singhbhum craton (cf. Ghose, 1992).

The Belt IV, namely the Bihar Mica Belt (BMB), is a sequence of arenaceous and pelitic rocks, interbanded with hornblende schists or amphibolites. These rocks have been intruded by large granitic bodies followed by younger basic dykes. This writer thinks that these granitic rocks with high initial Sr ratio (Pandey et al., 1986) could be the result of crustal melting of the overriding block (CGGC, including BMB) at depth, as a result of northward subduction of the Singhbhum block (cf. Saha et al., 1987). Mica schists, minor amphibolites, micaceous quartzites, and minor calc-granulites characterize the Bihar Mica Belt (BMB). Large phacolithic granitic bodies with a rim of migmatites or injection gneisses that show lit-par-lit injection of granitic material intrude the schistose rocks. The main schistose formations that host the mica-pegmatites are feldspathized and veined by more than one generation of pegmatites (Mallik, 1993). According to Mahadevan (2002) there is a conglomeratic horizon between the CGG and the overlying BMB. If this so-called unconformity happens to be tectonic breccia, a most likely possibility, the BMB belongs to the CGGC and not a separate stratigraphic unit. The BMB rocks show mineral assemblages of upper amphibolite facies appearing as a progressive grade from the underlying granulite facies rocks of the CGGC. This together with the documentation of similarity of three fold phases in the BMB and the underlying CGGC, support the contention that the BMB is a part of the CGGC. Pb—U and Pb isochron ages of several minerals from BMB give consistent ages of ca. 900–1000 Ma (Holmes 1950; Sarkar 1968; Ghose et al., 1973). Again, the granite intrusions in BMB as well as CGGC granulite facies rocks are post-F1 and perhaps also F2 as at some places they escaped F2 overprinting. Lastly, the proposition of Kumar et al. (1985) that the Tamar-Porapahar-Khatra fault (TPKF), referred to by them as Northern shear and also as the South Purulia shear zone defining the southern boundary of the CGGC, is not tenable. This is because a metamorphic belt of CGGC also occurs to the south of this fault, which is designated as South-Palamau-Gumla-Ranchi-Purulia belt (Mahadevan, 2002, pp. 258–259). This fault appears only to delimit the Gondwana outcrops within the CGGC.

Metamorphism in the vast terrain of CGGC reached middle to upper amphibolite facies. The P-T conditions have been deduced to be above 680°C (Bhattacharya, 1988). Under these high-grade conditions the pelitic rocks may have undergone partial melting to give rise to migmatites and anatectic granites. The sporadic occurrence of andalusite and cordierite may be the outcome of low-pressure metamorphism associated with granite intrusions in some areas of the CGGC. Bhattacharya (1988) indicated that the granites of the BMB originated at depth and were emplaced as structurally controlled plutons during F2 folding.

In contrast to the high-grade rocks, there is lower grade schist- phyllite-quartzite association at Rajgir and Munger (Sarkar and Basu Mallik, 1982). In Manbazar, Purulia district there is a report of dendrite rocks interlayered with BIF, mica schists and phyllite (cf. Bhattacharya, 1988).

2.5.1 Archaean Status of CGGC Questioned

From what has been discussed already, the CGGC appears to be an old Precambrian unit and perhaps as old as, or somewhat younger than, the Singhbhum-Orissa craton. However, paucity of geochronological data and problem of resetting of ages, the CGGC does not have proven Archaean-age rocks (Sarkar, 1982, 1988). This has provoked some geologists to question the Precambrian stratigraphic status of the CGGC. On the basis of structural similarity between CGGC and Singhbhum fold belt (Bhattacharya et al., 1990; Bhattacharya and Ghosal, 1992), some workers considered the two metamorphic domains, namely the CGGC and the Singhbhum fold belt (SFB) as equivalent in age. In short, the CGGC is considered as an eastern estension of the Satputra fold belt or Central Indian Tectonic Zone. Dasgupta (2004) states that the CGGC terrain contains comparable geological milieu and tectonothermal events as in the Satpura fold belt.

Following the above view, some authors (Bhattacharya et al., 1990; Dasgupta, 2004; see also Misra, 2006) think that the boundary between the two rock-units is neither any sharp lithological boundary nor a stratigraphic break, but a continuation of deformation and metamorphism. Again, based on geochronological data, Misra (2006) proposed that crustal growth in the eastern Indian region (Singhbum-Orissa) advanced from south to north and that the CGGC is younger than the Singhbhum fold belt. According to him (Misra, loc. cit) the sedimentary precursors of the CGGC are considered to have deposited in shelf region, after the deposition of the Singhbhum Group rocks in the rifted basin north of the Singhbhum (-Orissa) craton. These considerations received further support from the available radiometric ages which show that magmatic-metamorphic events in the CGGC occurred at ∼2.3 Ga, 1.6–1.5 Ga, and 0.9 Ga (see Misra, 2006). Again, in view of the dominant calc-alkaline gneisses amidst the CGGC rock complex and their interleaving with the high-grade pelites and calc-magnesian metasediments, some workers proposed that the CGGC was a magmatic arc (cf. Bose, 2000).

The proposal of CGGC to be younger than or as old as the fold belt is untenable on several grounds. The CGGC is a polymetamorphic complex whereas the rocks of the Singhbhum fold belt are only once metamorphosed (monometamorphic).

This finds support from the work of Singh (1998, 2001) who showed that the CGGC records two cycles of metamorphism-deformation. The first cycle ended at 1.6 Ga during which enclaves of granulites and mafic/ultramaficl rocks are formed with granite intrusions (cf. Ghose et al., 1973). The second cycle is considered to begin with Kodarma Group (conglomerate, quartzite, metapelites, amphibolites and BIF), followed by intrusion of S-type granite which have Rb-Sr ages in the range of 1.2–1.0 Ga (Mallik, 1998; Misra and Dey, 2002). These observations do not support the proposition of time equivalency of the CGGC and SFB. Since the Singhbhum orogenic belt and its early mesoscopic folds have E-W trend, it is implied that N-S compressive forces must have been generated by N-S collision of the Singhbhum (-Orissa) craton against a crustal block to the north, which seems to be none other than the Precambrian massif of CGGC lying just north of the Archaean craton of Singhbhum. Northward subduction of the Singhbhum (-Orissa) craton under the northern block requires collision with the CGGC in all evolutionary models of Singhbhum fold belt, discussed in Chap. 6. In this process the subduction and collision resulted into thickening of the crust that must have generated granitic melt (by partial melting), emplaced as granite intrusions in the overriding plate. This overriding plate was most likely the CGGC, which shows several granitic intrusions and high-grade rocks, all showing resetting of isotopic ages. Although unproven geochronologically, the CGGC should have been a Precambrian crustal block that needed to collide with the Singhbhum (-Orissa) craton in the south to develop the Singhbhum fold belt during Proterozoic.

The proposition that the CGGC is a fold belt and not a craton raises two serious geological implications. First, it needs to explain as to how the two folds could be generated in a small time interval and how were they brought as adjacent terrains of Mesoproterozoic age. The contact between the North Singhbhum fold Belt (SFB) and CGGC is a brittle to ductile shear zone called South Purlia shear zone or Tamar Porapahar shear zone. Second, if the CGGC were also a Proterozoic fold belt like the NSFB, one need to explain the absence of a crustal block that had collided against the Singhbhum craton more than once, first to generate NSFB and then the CGGC. The author recalls that the CGGC has gneisses and granites of variable chemistry and ages, besides granulites that occur as discontinuous bands. In addition, the CGGC also contains tracts of medium-grade enclaves of metasediments and basic rocks. These characteristics are not of a fold belt, and therefore distinguish the CGGC as a typical granite-gneiss massif or a craton that collided against the Singhbhum craton to evolve the Singhbhum fold belt (NSFB) (see Chap. 6). Therefore the hypothesis of some authors that the CGGC is an eastward strike extension of the Satpura fold belt of central India, is unacceptable in view of the cratonic nature of the CGGC vis-à-vis the mobile belt of the Satpura. It would be interesting if SHRIMP U–Pb zircon geochronology could be performed on the rocks of the CGGC in a more systematic way so that a crustal evolutionary model could be attempted, as done in the Dharwar, Singhbhum and other cratonic areas of the Indian shield. With the available geological database any attempt on geodynamic evolution of CGGC will be futile.

2.6 Rajasthan Craton

The Rajasthan craton (RC) is a collage of two cratonic blocks: (1) The Banded Gneissic Complex-Berach granite (BBC), and (2) the Bundelkhand Granite massif (BKC). Therefore RC is in fact a large Rajasthan-Bundelkhand craton These two cratonic blocks are separated by a vast tract of cover rocks, besides the occurrence of the Great Boundary Fault at the eastern limit of the BBC block, making the correlation between the two cratonic areas difficult (see inset Fig. 2.8). However, the two

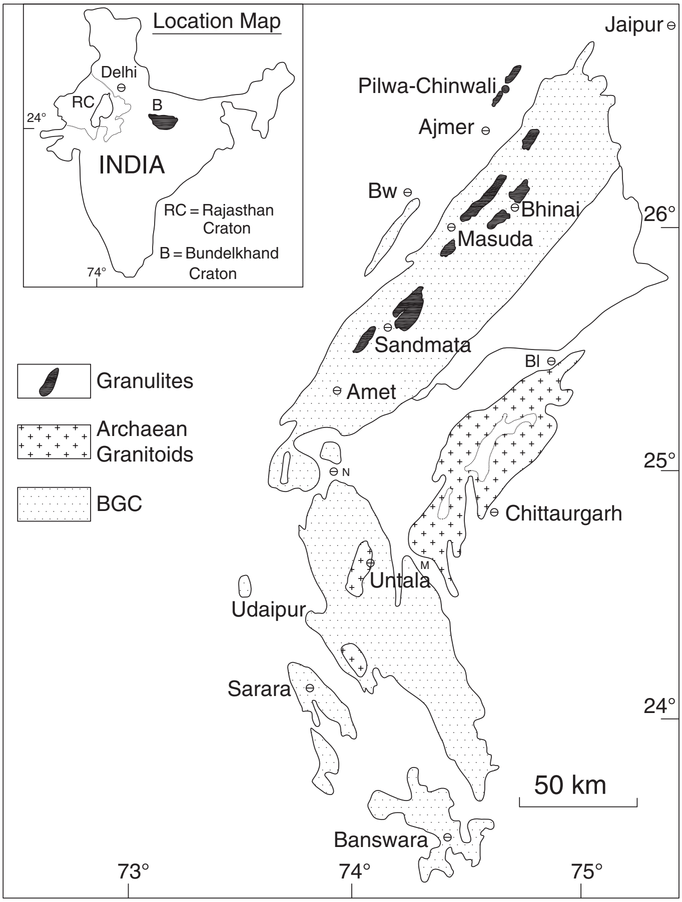


Fig. 2.8 Simplified geological map of Rajasthan craton (after Heron, 1953 and GSI, 1969), made up of Banded Gneissic Complex (BGC), Berach Granite and other Archaean granitoids. Granulite outcrops are in the BGC terrain and in the metasediments of the Delhi Supergroup (see text for details). Blank area occupied by Proterozoic fold belts and sand cover. Abbreviations: BL = Bhilwara, BW = Beawar, N = Nathdwara, M = Mangalwar. Inset shows the location of BBC (Banded gneissic complex-Berach Granite) and BKC (Bundelkhand) cratonic blocks that together constitute what is here termed the Rajasthan (-Bundelkhand) Craton, abbreviated RC

blocks have a common lithology that includes gneisses, migmatites, metavolcanic and metasedimentary rocks and a number of granitic intrusions. Both the BBC (i.e. Banded Gneissic Complex-Bearch Granite) and the BKC (i.e. Bundelkhand Granite Complex) blocks (unitedly designated Rajasthan craton, RC) have been affected by similar deformational events (Naqvi and Rogers, 1987). The two blocks also share same geodynamic settings in Proterozoic as revealed by geochemistry of their mafic magmatic rocks (Mondal and Ahmad, 2001) and same geochronological ages (Mondal, 2003), to be discussed later.

Early geological traverses and their reports were by Hacket, Oldham, La Touche, Middlemiss, Coulson and Crookshank (reviewed in Heron, 1953). The foundation of geology of Rajasthan (formerly Rajputana) is due to B.C. Gupta (1934) and Heron (1953) who gave the following broad divisions of the Precambrian rocks of Rajasthan, with ages given from recent publications (see text).

Malani Rhyolites (730–750 Ma)
Erinpura Granite (850–900 Ma)
Delhi {Ajabgarh Series
System {Alwar Series
-------------unconformity------------
Raialo Series
------- -----unconformity------------
Aravalli System
------------unconformity-------------
Banded Gneissic Complex (3.4 Ga)

2.6.1 Banded Gneissic Complex and Berach Granite

Amongst the early field geologists, Heron (1953) was the first to erect the basic framework of the Precambrian geology of Rajasthan. He recognized a gneiss-granitoid ensemble as the Archaean basement over which Proterozoic cover sequences were deposited with a profound erosional unconformity. To this basement stratigraphic unit he gave the name Banded Gneissic Complex (BGC), which also included the Bundelkhand gneiss. Pascoe (1950) renamed the Bundelkhand gneiss as the Berach granite. The geological synonymity between the crescent-shaped Berach Granite near Chittaurgarh and the Bundelkhand Granite, about 210 km away in the east (Fig. 2.8) is supported by Rb/Sr isotope data (Crawford, 1970; Sivaraman and Odom, 1982) and petrological studies (see Mondal, 2003). The BGC is predominantly a polymetamorphosed, multideformed rock-suite of tonalite-trondhjemite (TT) gneiss, migmatite, granitoids (grey granodiorite to pink granite) and subordinate amphibolite. The latter occurs as bands and enclaves/rafts of various dimensions within the gneisses, producing banded gneiss and migmatites. Besides the complex TT-amphibolite association, the BGC of Rajasthan also shows minor metasediments, mainly quartzite, frequently fuchsite bearing, low-Mg marble, mica schists and metabasic rocks (as amphibolite or greenschist) and minor ultrabasic rocks (as hornblende schists/hornblendite)—all indicating a possible greenstone remnant in the BGC terrain (cf. Upadhyaya et al., 1992). During the Archaean tectono-thermal event when the metasediments and the TT-amphibolite protoliths were recrystallized, granites (generated by partial melting of crustal rocks) were emplaced at different crustal levels, leading to stabilization of the craton around 2.5 Ga ago.

2.6.2 BGC: Antiquity Challenged and Nomenclature Changed

Gupta (1934) proposed a two-fold classification of the Banded Gneissic Complex (BGC). According to him, the BGC in the southern and central parts of Mewar is an undoubted Archaean basement underlying the Proterozoic Aravalli rocks and is designated by him as BGC-I. The migmatitic-gneissic rocks from north of Mewar have debatable basement cover relationship and were called by him as BGC-II. The basement status of the BGC-I is generally accepted on the basis of geological setting and geochronological data (see below), but the basement status of the BGC-II is controversial (cf. Bose, 1992). A brief period of confusion prevailed regarding the antiquity of the BGC-II of Gupta (1934). This was due to recognition of a structural accordance between the BGC basement and Proterozoic cover (Aravalli Supergroup) and interpretation of conglomeratic horizon (a pronounced erosion unconformity of Heron, 1953) at Morchana in Rajsamand district appearing as "tectonic inclusions". These led some geologists to refute the separate stratigraphic status of the BGC of Heron, which was conceived by them as a migmatized Aravalli (Naha and Majumdar, 1971; Naha and Halyburton, 1974). However, in view of the ambiguous erosional unconformity between the BGC and the Aravalli cover at several places and ruling out the possibility of migmatization of the Aravalli rocks due to their low-grade assemblages in contrast to the polymetamorphic character of the infracrystalline BGC (Sharma, 1988), the basement character of the BGC-II was re-established. This is further supported by the occurrence of two types of greenstone sequences in the BGC-II. The older sequence (Sequence 1), called Sawadri, is reported to have komatiite, ultramafic, chert, basic tuff and carbonates (Sinha-Roy, et al., 1998), while the younger sequence (Sequence 2), called Tanwan Group, contains greywacke, amphibolite and carbonates (Mohanty and Guha, 1995).

Another uncertainty occurred in regard to the stratigraphic status of the BGC. The metasediments in the eastern region around Bhilwara, recognized by Heron as the Aravalli system (Proterozoic), were classed as Pre-Aravalli (known as Hindoli Group by the GSI, 1993, 1998; Gupta et al., 1997, 1980; Sinha-Roy, 1985) merely on the assumption that the granitic rocks (e.g. Jahazpur granite) correlatable with the Berach granite (2.5 Ga) were intrusive into them (Raja Rao, 1971). This led Raja Rao et al. (1971) to introduce a new lithostratigraphic term, the Bhilwara Group as the basement for the younger supracrustals of the Aravalli Supergroup. Subsequently, the Bhilwara Group was elevated to the status of the *Bhilwara Supergroup* (see Gupta et al., 1980) which comprises the 2.5 Ga old Berach Granite, the

Aravalli metasediments of Heron, presently classified by the GSI as the Hindoli Group (Gupta et al., 1980), and also the large outcrop of the BGC occurring to the east of Udaipur as well as the granulite complex of Sandmata. The idea behind this grouping was the assumption by Raja Rao et al. (1970) that these metasediments were older than those occurring around Udaipur and Nathdwara. However, the structural as well as physical continuity of the Aravalli supracrustals of the type area around Udaipur into the metasedimentary belt of the Bhilwara region (Roy et al., 1981) and non-intrusive nature of the 2.5 Ga-old Berach granite, the new nomenclature of the Hindoli basement is not preferred over the BGC of Heron.

One more controversy arose when Gupta et al. (1980) of GSI classified the BGC rocks (of Heron) occurring east of the Aravalli axis into Mangalwar Complex and Sandmata Complex, and when both the complexes and the rocks of the Aravalli Sysem of Heron (1953) exposed around Bhilwara (re-named as Hindoli Group by the GSI, Gupta et al., 1980) were grouped under the Bhilwara Supergroup. *The Mangalwar Complex* is essentially a migmatitic complex while the *Sandmata Complex* is a granulite facies rock-suite, and the *Hindoli Group* as low to medium grade supracrustals. One reason that led the GSI workers to group the Sandmata Complex, Mangalwar Complex and the Hindoli Group under one Supergroup (the Bhilwara Supergroup) is the observation that the grade of metamorphism increases from Hindoli (low grade) in the east through Managalwar complex (medium grade) to high-grade of Sandmata granulites. But the present geochronological data indicate that all these rock units have not recrystallized in the same orogeny. The two complexes (Sandmata and Mangalwar) are separated by a tectonic lineament, the Delaware lineament. In a partial modification of this classification, Guha and Bhattacharya (1995) and Sinha-Roy et al. (1992) have restricted the nomenclature of the Sandmata Complex to the shear-bound high-grade granulite facies rocks within the amphibolite facies rocks that are included into the Mangalwar Complex. To combine the Sandmata complex, Mangalwar Complex and Hindoli Group under the Bhilwara Supergroup rests on the uncritical observation of increasing metamorphic grade westwards. The erection of these new Groups, Supergroups and Formation names suggested by GSI geologists is unsound and unjustified particularly when the included rock units are of different ages and show different deformational and metamorphic history. The Hindoli Group is in contact with the 2.5 Ga old Berach Granite which is regarded by GSI as intrusive into Hindoli. Other workers find field evidence for the Granite to be a basement for the Hindoli (Sharma, 1988; Roy and Jakhar, 2002). Rhyodacite of Hindoli Group gave zircon Concordia age of 1854 ± 7 Ma, indicating that it is homotaxial with a part of the Aravalli sequence (see Ramakrishnan and Vaidyanadhan, 2008, p. 275). The divisions of the basement given by GSI (Gupta et al., 1980) are therefore not based on sound Geodata.

Still another confusion in the nomenclature of the basement rock-suite occurred when Sm/Nd isotopes indicated that the biotite gneiss of the BGC east of Udaipur was coeval with amphibolites that occur as conformable bodies within the former (Macdougall et al., 1983), and that their initial isotopic ratio $€_{\mathrm{juv}}$ (T) = 3.5 for these rocks is suggestive of their derivation from a depleted mantle source. This prompted Roy (1988, p. 16) to designate these pre-Aravalli BGC rocks as *Mewar*

Gneiss, which is conceived as a heterogeneous assemblages of biotite and hornblende gneisses, amphibolites, granitic rocks, aluminous paragneisses, quartzites, marbles and pegmatites. This change of nomenclature is unwarranted and unnecessary as the rock assemblage under Mewar Gneiss is the same as those described under the BGC. Moreover, this change in name of a well-established term defies the code of stratigraphic nomenclature and respect of priority of nomenclature. The tonalitic grey gneiss, included within $\sim$2.5 Ga old granite of the BGC terrain, later yielded younger age of 3.3 Ga (Gopalan et al., 1990). This age, supported by the 3.28 Ga single zircon age ascertained by ion probe (Wiedenbeck and Goswami, 1994) again confirms the basement nature of the BGC. Somewhat younger ages of 3.23–2.89 Ga have been obtained from single zircon grains by evaporation method (^{207}Pb/^{206}Pb) for these gneisses (Roy and Kroener, 1996). Revelation of Archaean ages is definitely an undeniable evidence for the nucleus of the BGC in Rajasthan craton, but it does not warrant a new name, replacing a well-established stratigraphic term of the Banded Gneissic Complex given by Heron (1953), after a dedicated fieldwork of over thirty years. The basement complex cannot obviously be wholly Archaean because later magmatic activity affecting the cover rocks had to traverse through the infracrystalline of BGC. Heron (1953) was well aware of this and similar geological phenomenon on the basis of which he stated that the BGC represented a petrological ensemble of gneisses, granites and metasediments of various ages. The 3.3 Ga old gneisses of the BGC simply represent a nucleus of the Rajasthan craton. However, some BGC rocks as at Sarara, are not Archaean in age and their disturbed dates gave scattered ages (Proterozoic) but these BGC rocks are definitely overlain by the Palaeoproterozoic Aravalli supergroup, with an erosional unconformity between them (cf. Poddar, 1965). From this and similar occurrences of BGC inliers, we cannot consider only the isotopic ages but also the geological setting of the rocks (Naha and Mohanty, 1990).

From the above discussion this writer feels that the controversies on status and nomenclature of BGC are unnecessary and unwarranted as it only caused an avoidable confusion. As a mark of respect for priority of nomenclature and conforming to the code of stratigraphic nomenclature this author retains the term Banded Gneissic Complex as given by Heron (1953), even if it is taken as a backward step (see also Roy and Jakhar, 2002). In accordance with this “follow me” tendency the Archaean geology is also shown in the regional maps incorporated in this book (see also GSI, 1993).

2.6.3 Geological Setting

The BGC including the Berach Granite occupies a large tract in the Mewar plains (Udaipur region) of south and east Rajasthan. It is skirted on the west and southwest by Proterozoic fold belts of Aravalli and Delhi Supergroups. The eastern boundary of this cratonic region is demarcated by the Vindhyan platform sediments and southern boundary is covered by Deccan Trap (Fig. 2.8). The BGC cratonic region is dominantly gneissic to migmatitic with amphibolites and metasediments of amphibolite facies, intruded by Late Archaean granites (Untala, Gingla, Berach etc.) and rare ultramafics. Amongst the gneissic rocks, grey coloured biotite gneisses are dominant with leucocratic bands as a result of which the name Banded Gneissic Complex is appropriately given by Gupta (1934) and Heron (1953). One can observe a gradational contact between the biotite gneiss (quartz-feldspar-biotite ± hornblende ± garnet) to leucogranite (quartz-feldspar) with gradual obliteration of gneissic foliation. At certain places, faint relics of gneissic foliation are seen within dominantly massive granitoid. All these features resemble those described from Finland by Sederholm (1923), and are the outcome of partial melting of the crustal rocks when they were at great depths. Intrusion of trondhjemitic veins and pegmatites are not uncommon in the banded gneisses. Retrogression of dark minerals, biotite and hornblende, into chlorite and of K-feldspar into muscovite, and of plagioclase into zoisite/epidote are common. Geochemically, the 3.3 Ga old biotite-gneiss component of the BGC from Jhamakotra, east of Udaipur, is characterized by highly enriched LREE with a relatively weak Eu anomaly (Gopalan et al., 1990). Higher silica content and LREE enrichment of these gneisses suggest evolution of the gneisses through melting of a basic (amphibolite) precursor or, through melting of earlier tonalitic/trondhjemitic felsic rock-series. The latter proposition finds support from (1) the occurrence of Al—Mg rich metasedimentary enclaves in the tonalitic gneisses (Sharma and MacRae, 1981), and (2) an earlier report of 3.5 ± 0.2 Ga Pb—Pb age of detritial zircon in Proterozoic Aravalli schists (Vinagradov et al., 1964). These Archaean gneisses are orthogneisses and the Sm/Nd as well as evaporation ages may be taken to indicate as the minimum age for crystallization of the igneous protolith of the gneisses.

According to Heron, the BGC rocks also occur as inlier within the Delhi Supergroup (Mesoproterozoic) south of Aimer in central Rajasthan. The Ana Sagar granite gneiss near Ajmer is a possible extension of the inlier, since the former rocks are dated at 2.58 Ga (Tobisch et al., 1994).

The gneiss-amphibolite association of the BGC from most part of Rajasthan, particularly from central region, shows ample evidence of partial melting that gave rise to pods and bands or layers of quartzo-feldspathic material (leucosome) within the gneisses and hornblende-biotite schist/gneiss and amphibolites. Not infrequently the amphibolites occur as enclaves within the granite-gneiss milieu. The amphibolites (greenstones) of central Rajasthan have been divided into two litho-types, namely (i) the older Sawadri Group in which the amphibolites are associated with high-grade metasediments and granulites as at Sandmata, and (ii) the Tanwan Group in which the amphibolites lack ultra basics but are associated with fuchsite-quartzite and metasediments (cf. Mohanty and Guha, 1995). However, such a division of these amphibolites from the BGC terrain is undesired because intensity of deformation and metamorphism and degree of exposures could be responsible for this association.

Amphibolites in the BGC range in size from small enclaves of irregular shape to large linear bodies showing complex fold pattern due to superposed folding. These amphibolites are older component of the BGC. Chemically, these amphibolites show similarity with basaltic andesite and are characterized by slight LREE enrichment and virtually flat HREE, to suggest their derivation from shallower mantle rock (plagioclase peridotite or spinel peridotite). Metasediments in the BGC craton are greenish quartzites (fuchsite bearing), marble, calc-silicates and ironstones, and pelitic schists. A large body of quartzite at Wahiawa (west of Mavli) is complexly folded and intruded by ca. 2828 Ma old metabasalt (amphibolite).

The BGC to the north of Nathdwara in central Rajasthan also contains granulite facies rocks comprising garnet-sillimanite gneiss, with or without cordierite, calc-silicate gneiss, enderbite-charnockite, leptynite and two-pyroxene-garnet granulite (basic granulite). This granulite-gneiss association is referred to by the name Sandmata Complex by Gupta et al. (1980). The granulites occur as isolated exposures from north of Amet in the south to Bhinai and Bandnwara in the north. Besides these rocks, granite, norite, pegmatite and quartz veins are also found as later intrusives.

It is a matter of enquiry whether these granulites are Archaean or Proterozoic in age, although B.C. Gupta (1934), a coworker of Heron, mapped these rocks under the BGC. Surely, the parent of the pelitic granulites is pelitic and the two-pyroxene granulite is obviously derived from basaltic parentage. Both these granulite types are undated, but the enderbite-charnockite occurring as intrusion in the Sandmata complex yielded 1723 Ma age by U–Pb zircon geochronology (Sarkar et al., 1989), suggesting that the granulite facies event is Mesoproterozoic (Sharma, 1995, 2003). As is described later, the metapelites and other rock units of the BGC were subjected to high temperature recrystallization (granulite facies metamorphism) as a result of underplating by basaltic magma at depth. The two-pyroxene basic granulites occurring within the Sandmata granulite complex and elsewhere in central Rajasthan, and perhaps also the norite dykes, are possible representative of this underplated/intraplated magma.

There are no age data to constrain the Archaean event of deformation and recrystallization during which the igneous tonalite rock developed the gneissic fabric and the associated sediments and basaltic supracrustals were transformed to paragneiss and amphibolite, respectively. This metamorphic event would be expressed in the development of distinctive regional metamorphic minerals, such as garnet, and also in the generation of melt phase at depth, resulting into the intrusion of granitic plutons that are recognized as Gingla granite, Untala granite etc in the BGC terrain. A two-point garnet-whole rock Sm/Nd age gave 2.45 Ga age for this mineral from a 3.3 Ga old biotite gneiss (Gopalan et al., 1990). It seems that the 2.45 Ga age of garnet is not a meaningful age, since this date is not obtained from any other mineral or rocks from the BGC. The leucocratic granite gneiss from Jagat area, showing retrograde features, yielded a zircon evaporation age of 2887 ± 5 Ma (Roy and Kroener, 1996), and an amphibolite from Mavli showing cofolding with the granite gneiss gave Sm/Nd whole-rock isochron age of 2828 ± 46 Ma (Gopalan et al., 1990). These ages may be taken to indicate the age of crystallization/emplacement of anatectic melt generated at depth during Archaean orogenesis. The main Archaean metamorphic event (pre-Aravalli) affecting the TTG-amhibolite protoliths could therefore be earlier than 2.85 Ga. This tectonothermal event was probably also responsible for the disturbance of Sm/Nd systematics in the tonalitic-trondhjemitic gneisses of the BGC (see Tobisch et al., 1994).

A second thermal event at about 2.6 Ga is also recorded in the BGC terrain as is evident from U/Pb isotopic ages for Untala and Gingla granitoids. The Untala granite is pink, medium-grained mostly massive K-feldspar bearing granite which grades on the margin into gneissic variety of granodioritic to trondhjemitic composition. The pink Untala granite is considered as the youngest phase of granite intrusion in the BGC. The Gingla granite shows variation from granodiorite to trondhjemite and even quartz-diorite. It contains a number of inclusions of amphibolite and biotite gneiss. Roy and Kroener (1996) give single zircon evaporation ages for these granites: Trondhjemite gneiss from Untala = 2666 ± 6 Ma; Low Al_2O_3 granite from Jagat = 2658 ± 2 Ma; and Leucogranitoid of Gingla = 2620 ± 5 Ma.

Outside the main BGC outcrop, there are two large bodies of granitic inlier. These are the Berach Granite near Chittaurgarh and the Ahar River Granite near Udaipur. A characteristic feature of these granites is their coarse-grained porphyritic texture, without any conspicuous foliation. The Berach granite covers an extensive area to the west of Chittaurgarh in eastern Rajasthan (Fig. 2.8). Based on identical mineral composition and physical character, Gupta (1934) correlated this granite with the Bundelkhand gneiss of central India, and claimed that the Berach Granite served as a basement rock upon which the Aravalli rocks were deposited. As discussed later, this proposition also finds support from Rb/Sr isotopic age of 2555 ± 55 Ma for the Bundelkhand gneiss and for the Berach Granite (Sivaraman and Odom, 1982; Choudhary et al., 1984; Wiedenbeck et al., 1996a, 1996b), although the two granite blocks are separated over 400 km by the Vindyhan sediments. Recent zircon evaporation ages (Roy and Kroener, 1996) also confirm the Archaean age for the granite inliers. These granitoids were interpreted by Sharma (1999) to have derived by partial melting of already existing rocks of the BGC (orthogneisses and metasediments). With the emplacement of these granitoids within and outside the BGC terrain, the Rajasthan craton was stabilized. There are a few more Late Archaean granites, for example, the Gingla Granite close to Jaisamand Lake (Dhebar lake), giving 2.8–2.6 Ga age; Bagdunda dome which is an elongate gneissic dome found within Jharol Group rocks of the Aravalli Supergroup. As a basement, the dome is rimmed by quartzite-metabasalt association of the basal Aravalli sequence.

Metamorphic studies of the BGC rocks show that they are generally recrystallized in upper amphibolite facies in most places, but polymetamorphic character of the rocks, mostly of pelitic compositions, does not allow delineation of metamorphic isograds. Sharma (1988) clearly showed that the BGC rocks suffered two metamorphic events: M1 ($\sim$3.0 Ga) reached staurolite-kyanite zone in most parts including the Mewar region, which also shows lower grade (epidote-amphibolite facies) while M2 ($\sim$1.6 ± 0.2) attained varying degree of metamorphism from upper amphibolite to granulite facies. However, a following shearing event retrograded these amphibolite facies rocks to lower grade mineralogy in which chlorite is the most common mineral after biotite, garnet and hornblende in different rock compositions.

Deformation in the BGC rocks is heterogenous, making correlations between different domains difficult. Structural features and deformation patterns of the BGC often resemble those in the Proterozoic cover. However, an early folding episode and related planar and linear structures distinguish the BGC terrain from the Proterozoic cover. In the northern part the deformation of BGC shows interesting features in the Khetri region where the Delhi Supergroup (Proterozoic) rests unconformably on the BGC schist-gneiss. In these gneissic rocks two prominent foliations belonging to two different episodes superimposed on the relicts of an earlier (Pre-Delhi) gneissosity/schistosity. The first deformation resulted in transposition of an already existing foliation (s-surface). Subsequent deformation of the BGC is of brittle to brittle-ductile nature, resulting in the development of regional NE-SW trending foliation as well as NW-SE striking cross faults and folds.

Moving towards south of the Khetri belt, the BGC shows large-scale folds (F3) that are coaxial with the F2 folds (developing Type 3 interference pattern of Ramsay, 1967) and control the map pattern of the BGC. Associated with the F3 are the ductile shear zones that mostly occur in conjugate sets. Later shears of brittle nature overprinted the early shears and also caused dislocation.

In central Rajasthan three fold phases (F1, F2, F3) have been identified in the BGC whose map pattern is controlled by large-scale F2 folds. The F1 and F2 folds are isoclinal, often with reclined geometry and having dominantly E-W axial plane foliation. Both F1 and F2 isoclinal folds are affected by NE-SW trending upright open folds (F3). The superposition of these later folds on coaxially folded isoclinal folds has resulted in dome and basin structures. Broad transverse warps represent the last phase (F4) of folding (see Naha et al., 1967).

Progressive deformation in the high grade BGC has been studied by Srivastava et al. (1995), particularly in Masuda-Begaliyawas, and Bandanwara area, lying to the SSW of Ajmer and NNE of Sandmata. Based on the overprinting relationship these authors recognized two groups of folds: F1 group folds comprising three sets of successively developed folds F_{1A}, F_{1B} and F_{1C}, and F2 group folds. In F_{1A} folds, the fold closure is cut across by gneissic foliation. The F_{1B} folds refolded F_{1A} folds, producing Type-3 interference pattern of Ramsay (1967). In some Type-3 interference, the early folds do not have an axial plane foliation, and they are attributed to refolding of F_{1B} by another phase of coaxial F_{1C} folds. The F2 group folds have refolded F1 axial planes and deformed the early lineation around F2 axis. Two more sets of folds have been identified by Srivastava et al. (1995). F3 folds are characterized by recumbent geometry and F4 group folds have steep axial planes and occur as transverse structures with axial planes perpendicular to the regional NE-SW or NNE-SSW striking foliation. Along the axial planes of F1 and F2 there are also shear zones in the BGC rocks. These shear zones are oblique slip type with large strike-slip component and show both dextral and sinistral sense of movement. However, slip lineation on the shear surfaces is reportedly absent (Srivastava et al., 1995).

In Sandmata area, three deformation phases have been recognized (Gupta and Rai Choudhuri, 2002) which produced three sets of closely related planar structures. Strain partitioning has been noted in the development of planar structures with varied intensity in different parts of the area. These authors also noticed that granulite facies rocks were overlying the amphibolite facies rocks without structural discontinuity, and this superposition is interpreted by them due to overfolding (see Gupta and Rai Choudhuri, 2002), indicated by the interrelationship between S1 and S2 foliation planes. Conjugate shear zones associated with F3 are recognized by these authors and by Joshi et al. (1993). From geothermometry and geobarometry, Joshi et al. (1993) gave temperatures in the range 850–600°C and pressures from about 11 to 4.5 kbar. Somewhat lower P but comparable temperatures are also obtained by Dasgupta et al. (1997) for these granulites. From these P-T data and microstrucutral criteria, Joshi et al. (1993.) deduced counter-clockwise P-T path for the Sandmata granulites. Gupta and Rai Choudhuri (2002) noticed that the shear zones showed variations in the intensity of development of s-c fabrics that have steep or vertical dips, but the shear sense indicators suggest oblique slip with dominant strike-slip component. The ductile shearing is considered responsible for the variation in the plunges of fold axis and for excavating these granulites from deeper levels to shallower depths (Sharma, 1993).

2.6.4 Evolution of the Banded Gneissic Complex

The evolution of both units of Rajasthan craton are separately described, taking first the Banded Gneissic Complex (BGC) and then Bundelkhand Granite massif. The evolution of the BGC is described below and summarized in Table 2.1 (modified after Sharma, 1999).

From the occurrence of folded enclaves of amphibolites within the 3.3 Ga old biotite gneisses it is inferred that the earliest deformation in the BGC was definitely ductile, some time during Mid to Late Archaean. These early amphibolites are comparable to type 1 amphibolite from Jagat area, described by Upadhyaya et al. (1992). These, together with the associated talc-antigorite schist as metamorphosed ultramafics along with some metasediments like the paragneisses and marble, represent an early greenstone association. Although the oldest rock so far dated in Rajasthan is the 3.3 Ga old banded gneiss (biotite gneiss-amphibolite) from Jhamakotra area (Gopalan et al., 1990), supported by the ca. 3230 and 3281 Ma single zircon ages obtained respectively by evaporation method (Roy and Kroener, 1996) and ion microprobe (Wiedenbeck and Goswami, 1994), still older crust in Rajasthan is indicated by the report of 3.5 Ga age for the detrital zircon from the cover of the Aravalli metasediments (Vinagradov et al., 1964). Another mafic activity is indicated by the 2.83 Ga old metabasalt/amphibolite (Gopalan et al., 1990) that intrudes the quartzites and biotite gneisses at Rakhiawal (Roy et al., 2000). This lithological association indicates local rifting of the BGC rocks of the Rajasthan craton during Late Archaean. The rifted basin with its rock deposits was subsequently deformed and metamorphosed during which the 2.9 and 2.6 Ga old granitoid phases of Untala and Gingla were intruded within the BGC. With the emplacement of typical Potassic granites of 2.5 Ga age, notably the Berach Granite and Ahar River Granite, the Rajasthan craton was finally stabilized (see Table 2.2).

In the Archaean craton of Rajasthan, two magmatic activities of Proterozoic age are also recorded. First is the carbonatite intrusion in the 2.5 Ga Untala granite at Newania and second is the intrusion of 1550 Ma old granites (Bose, 1992) that occur in a series of outcrops at Tekan, Kanor and several other localities within the

Table 2.2 Evolution of Rajasthan craton with summary of events, modified after Sharma (1999)

Age (Ga)	Geological events	Remarks
>3.5	1. Basaltic and tonalitic liquid extruded and intruded to form bimodal suite, making up the early crust in Rajasthan	3.5 Ga old detrital zircon from early Proterozoic Aravalli schist (Vinagradov et al., 1964)
	2. Deformation of the bimodal suite, folding and gneissic foliation of the mafic and felsic components	Evidenced by folded enclaves of old amphibolites (greenstone 1) within 3.3 Ga old biotite gneisses (Roy and Jakhar, 2002, p. 60)
3.3	Synkinematic melt generation to form second stage TT rocks from 3.5 Ga old orthogneisses and amphibolites (greenstone 1) at deeper levels of thickened crust	Occurrence of 3.3 Ga old biotite gneisses/banded gneisses as at Jagat (Gopalan et al., 1990; Upadhyaya et al., 1992)
2.9	Rifting and basin sediments subsequently deformed and metamorphosed with decompression melting of upper mantle	Folded quartzite-biotite gneiss at Rakhiawal intruded by metabasic (amphibolite 2) and dismembering of older greenstones as at Jagat (Upadhyaya et al., 1992)
	Archaean gneissic complex originated	
2.83	Crustal dialation	Emplacement of mafic dykes e.g. at Mavli (Gopalan et al., 1990)
2.65–2.5	Decompression melting of orthogneisses and paragneisses and also amphibolites at depth to produce felsic melts to intrude upwards	Granite intrusion of Gingla, Untala, Berach, and Ahar River (Roy and Kroener, 1996; Wiedenbeck et al., 1996b; Choudhary et al., 1984)
	Archaean crust of Rajasthan (stabilized)	

BGC. This Proterozoic granite is a leucogranite and perhaps related to the Delhi orogeny (see Chap. 4). The carbonatite forms a low ridge (2 × 0.5 km area) with NW-SE trend within the milieu of Untala granite. According to Chattopadhyay et al. (1992), the Newania carbonatite is a funnel-shaped body with a low E-W plunging axis. This alkaline body has a notable zone of fenitization. The sequence of carbonatite emplacement is dolomite followed by ankeritic and finally calcitic carbonatite (Pandit and Golani, 2000). Schleicher et al. (1997) gave Pb—Pb isochron age of 2273 ± 3 Ma (MSWD = 18.1%) for the dolomitic carbonatite and 1551 ± 16 Ma (MSWD = 22%) for the ankeritic carbonatite. These two ages can be seen to coincide with the opening of the Paleoproterozoic Aravalli basin and the intrusion of Mesoproterozoic Tekan granites, respectively. Earlier, Deans and Powell (1968) determined 959 ± 24 Ma age for the Newania carbonatite on the basis of Strontium isotope data. This age could represent a thermal imprint during later phase of the Delhi orogeny. Because of the Proterozoic tectono-thermal events the BGC rocks also show re-working as at Sarara, southeast of Udaipur and at other places like Anasagar, near Ajmer, where the gneissic rock is an inlier (Tobisch et al., 1994).

Besides the above-mentioned magmatic bodies of Proterozoic age, the BGC also contains ~1725 Ma old granulites, mainly at Sandmata (Gupta et al., 1980). These granulites are mainly three types: the pelitic granulites with polymetamorphic assemblage, the garnet leptynite, and the garnet-bearing two pyroxene basic granulite with coronitic texture (Sharma, 1988; see also Dasgupta et al., 1997). The basic granulite is obviously mantle derived and most probably from the melt that had underplated the Archaean crust in this part of the Indian shield. As a result, the BGC rocks overlying the mafic magma recrystallized at high T and P of the granulite facies (Sharma, 1988) in a magma-underplated crust, documented by their anticlockwise P-T path (cf. Sharma 1999, 2003). As shown in Chap. 4, the granulite rocks at depth were also intruded by 1723 Ma old charnockite-enderbite (Sarkar et al., 1989). It is for this reason that the banded gneisses (BGC) are seen as enclaves within the unfoliated granulite, charnockitic as well as basic granulite (see Srivastava, 2001). Subsequently, the granulite complex as a whole was excavated from depth to shallower level along a shear zone, which abounds the Sandmata complex (cf. Joshi et al., 1993). The enderbite-charnockites with mafic granulites are the major lithology in the Bhinai-Bandanwara area. Recently, Roy et al. (2005) dated their zircons by evaporation technique that yielded ages in the range of 1620–1675 Ma. The geochronological data as well as the nature of the occurrence of the granulite rocks at Sandmata, Bhinai, Bandanwara and other places of the BGC suggest that the granulite facies metamorphism is Mesoproterozoic, connected with the Delhi orogeny and not with the Paleoproterozoic (2100–1900 Ma) Aravalli orogeny. This is because the Aravalli orogeny predates the 1900 Ma old syntectonic Derwal granite (Choudhary et al., 1984) that intruded the Aravalli metasediments during their first phase of folding (Naha et al., 1967). Considering the age of 1723 Ma for the charnockite-enderbite intrusion (Sarkar et al., 1989) and the fragmental occurrence of the granulites in the Delhi metasediments, it is emphasized that the 1723 Ma old granulite are not reworked BGC as conceived by Roy and Jakhar (2002). They are recrystallized lower crustal rocks with minor upper mantle material in form of basic granulites and perhaps norite dykes. During Delhi orogeny these lower crustal rocks were exhumed along ductile shear zone and are now seen as fragmented or torn “pieces” in the Delhi metasediments (Fareeduddin, 1995) (see Chap. 4, for discussion).

2.6.5 Bundelkhand Granite Massif (BKC)

As discussed above, the Bundelkhand Granite massif is also a part of the Rajasthan craton in the northern Indian shield. The Bundelkhand Granite massif or the Bundelkhand Granitoid Complex (abbreviated BKC) is a semi-circular outcrop, occupying nearly 26,000 km^2 (Basu, 1986) in parts of Central Indian shield (Fig. 2.9). It contains polyphase TTG gneisses (ca. 3.5–2.7 Ga), metamorphosed volcano-sedimentary rocks, and syn- to post-tectonic granitoids (ca. 2.5–2.4 Ga). The rock-suite is intruded by numerous quartz reefs followed by dolerite dyke swarms of ca. 1700 Ma age. The dolerite dykes are possibly related to the development of

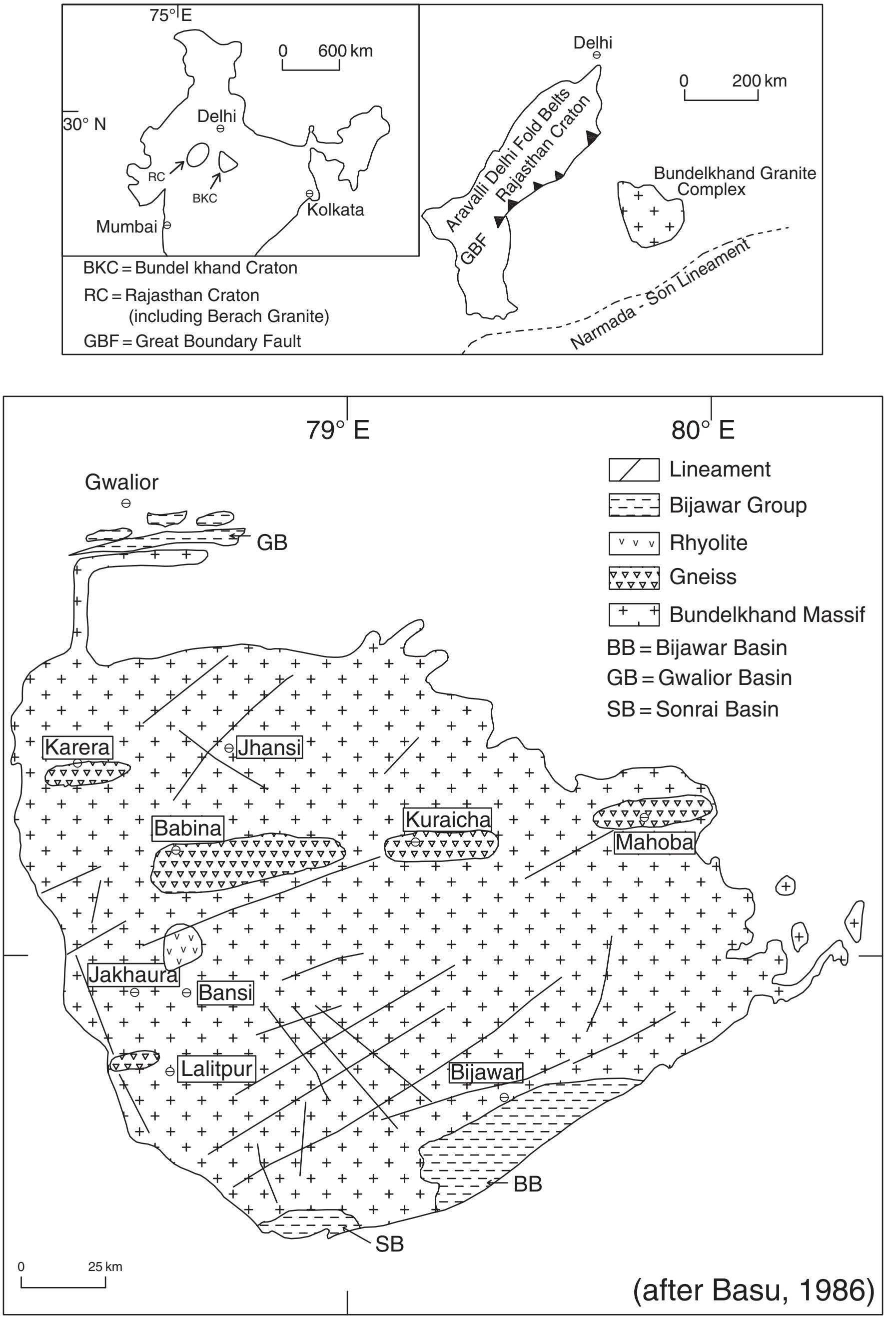


Fig. 2.9 Location and geological map of the Bundelkhand craton/massif (after Basu, 1986). BB = Bijawar basin, GB = Gwalior basin, SB = Sonrai basin

rift basins of Bijawar (or Mahakoshal Group) and Gwalior Formations. The overall tectonic trend of the BKC is E-W to ENE-WSW. The BKC is flanked along its southern and northwestern margins by the Pre-Vindhyan siliciclastic shelf sequence—the Bijawar Formation. The west, south and east margins of the BKC are covered by the Vindhyan rocks (1400 Ma and younger), while the northern border is covered under alluvium. The Bundelkhand craton is correlatable with the 2.5 Ga old Berach Granite of Rajasthan on its west but the continuity between the two granite complexes is concealed under the younger cover (including Vindhyan rift sediments), making the geological correlation only tentative.

The bulk of the Bundelkhand massif is made up of 2500–2600 Ma old granites that are coarse-grained equigranular and sometimes porphyritic to fine-grained (Sarkar et al., 1995). The granitic rocks contain numerous enclaves of schists, gneisses, banded magnetite, calc-silicates and ultramafics (Basu, 1986). Inclusions of older tonalitic gneiss are seen in the early phase of K-rich granite in the northern part. This grey to pink medium-grained gneiss is assumed as a partial melt of garnet-amphibolite parent at depth (Sharma, 1998; Sharma and Rahman, 1996). The granitoids and their gneissic varieties are calc-alkaline in nature and are characterized by highly fractionated REE patterns and depleted in HREE. They resemble the Archaean TTG suites and may thus represent relics of early crustal components in BKC. The gneisses are composed of quartz and plagioclase with accessory magnetite, apatite and zircon. They are highly deformed. The ^{207}Pb/^{206}Pb systematics in zircon of 19 samples of granitic gneisses, enclaves and granitoids and rhyolite from BKC massif gave Archaean ages (Mondal, 2003). These geochronological data indicate the presence of two-age components: one indicates higher age value of 3270 ± 3 Ma, which is interpreted as the "minimum" age for crystallization of the protolith of the gneiss. The other age with lower value of 2522–2563 Ma is due to Pb loss and indicates a thermal event, documented in overgrowth of old zircons in the gneisses.

Besides the gneisses, granitoids have also been studied in the BKC. The dark-coloured hornblende granitoid is calc-alkaline in nature similar to the biotite-granitoid which is a pink-coloured, coarse to medium-grained rock, occasionally with some hornblende. The leucogranitoid has very little (<10 vol.%) ferromagnesian minerals. This rock is reported with equal proportions of plagioclase quartz and K-feldspar (mostly perthite), suggesting equilibrium crystallization under the load pressure of over 12 km (cf. Tuttle and Bowen, 1958).

The age of 3.25 Ga for zircons from deformed gneissic enclave within Mahoba granitoid indicates that this rock represents the earliest phase of TTG magma and hence an early Archaean crustal component in the Bundelkhand massif. Besides, the ages of 2.8–2.9 Ga and even 2.7 Ga in gneisses indicate the presence of multiple protolith age components within the massif. It is interesting to note that the 3.3 Ga old gneisses are cofolded with amphibolites and metasedimentary rocks from Mahoba and Kuraicha. This probably indicates granite magmatism and deformation in the BKC at about 3.3 Ga ago.

The younger gneisses are restricted to E-W shears. The zircon ages of 3 suites of granitoids (Mondal, 2003) suggest that their emplacement occurred in a quick succession at $\sim$2.5 Ga, within a few tens of million years (Panigrahi et al., 2002).

The 2517 Ma old rhyolite from Bansi indicates felsic volcanism (anorogenic) in Proterozoic period, unrelated to an arc magmatism (cf. Mondal, 2003). The age of 2492 ± 10 Ma for the Lalitpur leucogranitoid (Mondal, 2003) is taken to indicate the time of stabilization of the Bundelkhand massif, like that of the BGC of Rajasthan. The BKC has a general trend in E-W to ENE-WSW direction, similar to the Rajasthan craton, hence indicating its correlation with the BGC and Berach granitoid on the west.

Following the granite intrusions, there occurred intrusion of giant quartz reefs in the BKC. The southern part of the massif contains striking NE-trending quartz ridges up to 200 m high with Cu mineralization (Crawford, 1970). Mondal et al. (2002) describe these giant quartz reefs to have been from residual silica left over from large-scale granite magmatism and assigned 2.3–1.9 Ga ages for them. Sharma (1998) links the development of the quartz reefs occurring along brittle-ductile shear zones to K-rich granite magmatism during the Paleoproterozoic, connecting this period to late-stage cratonization in the Bundelkhand area. The geochronological data on various felsic intrusives tightly constrain their emplacement age between 2.5 and 2.2 Ga (Crawford, 1970; Sarkar et al.,1990; Mondal, 2003). The extensive development of holocratic intrusive quartz-reefs along the brittle-ductile shear zones is a unique feature of the BKC. According to Roday et al. (1995) the quartz reefs are recrystallized or sheared quartzites. But they could also be a product of metamorphic differentiation (secretion) following the opening of cracks (shear zones) that acted as low- pressure domains within the BKC granitoids. Mineral ages of muscovite obtained from pyrophyllite of giant quartz veins suggest that hydrothermal activity was between 1480 ± 35 and 2010 ± 80 Ma (Pati et al., 1997).

A number of basic dykes of tholeiitic affinity occurs at several places in the BKC. These dykes generally truncate the early-formed quartz reefs. It is believed that the mafic magmatism occurred in two phases, in the NW-SE and NE-SW, suggesting that dyke activity in the region was episodic, which may be slightly older than the initiation of volcanism in the peripheral Gwalior and Bijawar basins. The mean ages of 2150 and 2000 Ma of the mafic dykes in the region (see Rao et al., 2005) clearly demonstrate that the dykes are younger than the granitic rocks (2500–2600 Ma) of the Bundelkhand massif and older than the volcano-sediment deposited in the rift-related basin (Gwalior traps 1830 ± 200 Ma; Crawford and Compston, 1970). The age data on mafic dykes by Mallickarjun Rao et al. (2005) constrain the timing of mafic magmatism within the Bundelkhand granite massif.

The dyke activity in the Bundelkhand massif is similar to the activity in the Rajasthan craton in the northern Indian peninsular shield. Again, both BKC and the BGC-Berach Blocks of Rajasthan craton have stabilized at 2.5 Ga ago. It must be pointed out here that the Singhbhum region in eastern India stabilized much earlier, at 3.1 Ga (Mishra et al., 1998). Zircon ages for the various lithounits of the Bundelkhand massif and BGC-Berach Granite of Rajasthan craton are summarized in Table 2.3.

The oldest granitic crustal component in the two terrains/blocks of Rajasthan and Bundelkhand has similar ages: 3300 Ma for Kuraicha gneiss of the BKC, and 3281± and 3307 ± 33 Ma (Pb—Pb and Sm/Nd ages respectively) for Mewar gneiss

Table 2.3 Geochemical and geochronological comparisons between BGC-Berach Granite and Bundelkhand massif (after Mondal, 2003)

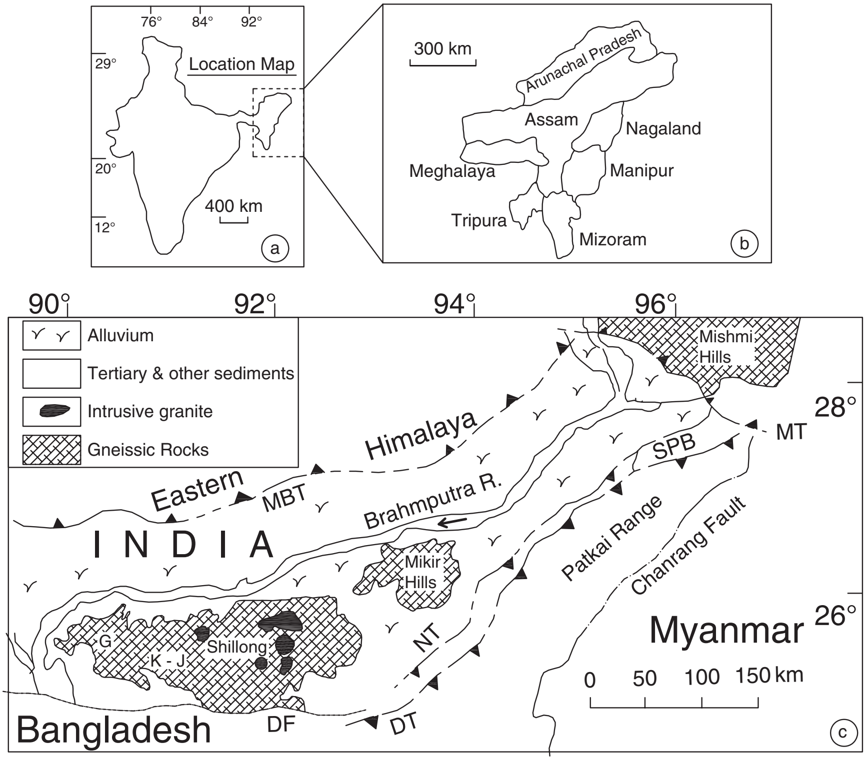
Features	Bundelkhand massif (BKC)	BGC-Berach Granite of RC
Composition of gneiss	Tonalite, Trondhjemite, highly fractionated REE patterns with depletion of HREE, small negative Eu anomaly	Tonalite, Trondhjemite, highly fractionated REE patterns without depletion of HREE, small negative Eu anomaly
Composition of granitoid	Calc-alkaline, moderately fractionated REE pattern without HREE depletion, large Eu anomaly	Calc-alkaline, moderately fractionated REE pattern without HREE depletion, large Eu anomaly
Regional metamorphism and deformation	3.29 Ga (oldest gneissic component at Kuraicha); 2.5 Ga (youngest gneissic component at Panchwara)	3.28–3.3 Ga (oldest gneissic component S of Udaipur); 2.5 Ga (youngest gneissic component in Vali River, Udaipur district)
Emplacement of granitoid	∼2.5 Ga	∼ 2.5 Ga
Age of stabilization	∼2.5 Ga; no widespread evidence for much younger activity	∼2.5 Ga; evidence for the presence of Mid-Precambrian and younger activity
Mafic rocks	Mafic dyke swarms	Mafic volcanism

of Rajasthan craton (Gopalan et al., 1990; Wiedenbeck and Goswami, 1994). Furthermore, the age of 2506 ± 4 Ma for the youngest gneissic event (Vali River gneiss) in the Rajasthan craton (Wiedenbeck and Goswami, 1994) is very close to the age of the youngest gneissic event in the Bundelkhand massif (Panchwarz gneiss and Karera gneiss) (Mondal, 2003). Also, the gneisses from both these terrains share common compositional characteristics (Gopalan et al., 1990; Mondal, 2003). The Mid-Archaean gneissic components as well as the Late Archaean granitoids intruding the gneiss in both cratonic regions are also geochemically similar (Ahmad and Tarney, 1994; Sharma and Rahman, 1995).

The above discussion leads one to conclude that the two cratonic areas, namely the BGC-Berach Granite and the Bundelkhand massif, evolved as a single large protocontinent, named here as Rajasthan craton, RC, that stabilized at ∼2.5 Ga ago (see Mondal, 2003, p. 10; see also Yedekar et al., 1990).

2.7 Meghalaya Craton

The Precambrian rocks in the eastern India occur in the Shillong Plateau of the Meghalaya State and in the Mikir Hills (also called Kabri Hills) Plateau located in the State of Assam (see inset of Fig. 2.10). The Shillong-Mikir Hills Massif is here called the Meghalaya craton. It is roughly a rectangular plateau, about 50 km wide and 200 km long made up of crystalline rocks with nearly E-W, rather ENE-WSW, trend. It is bordered on the north by Brahmaputra River. The river flows nearly E-W between the Shillong and Mikir Hills Plateaus and the Main Boundary Thrust of



(after Das Gupta, 1977)

Fig. 2.10 Location of Meghalaya in the northeastern states of India (**a** and **b**) and Geological map (**c**) of the Shillong-Mikir Hills Plateau, herein called the Meghalaya craton, with location of Garo Hills (G), Khasi-Jantia Hills (K-J), Mikir Hills (renamed as Kabri Hills by some authors). Other abbreviations: DF = Dauki Fault, DT = Disang thrust, MBT = Main Boundary thrust, MT = Mizu thrust, NT = Naga thrust, SPB = Schuppen Belt (Zone of imbrication)

the Eastern Himalaya in the north. The southern boundary is demarcated by Dauki Fault, which also defines the northern limit of the Sylhet Trap (110–133 Ma).

Oldham (1856), Medlicott (1869), Desikachar (1974) and more recently Nandy (2001) and Dasgupta and Biswas (2000) gave a general geological account of the Shillong-Mikir Hills Plateaus, although the fringes of these plateaus are covered by Cretaceous to Eocene sediments. The oldest unit in the Meghalaya craton is the Archaean Gneissic Complex or Older Metamorphic Group (Mazumder, 1976). It consists of granite gneiss, augen gneiss and upper amphibolite to granulite facies metamorphic rocks. The latter rocks are cordierite-sillimanite gneiss, quartz-feldspar gneiss (orthogneiss) and biotite schists with or without hornblende (Rahman, 1999). In the central part of the Shillong Plateau, particularly in the Khasi Hills the biotite-quartz-sillimanite-cordierite and quartz-sillimanite rocks associated with sillimanite-corundum occur as lenses within granite- gneiss. These occupy a belt one kilometer wide with E-W strike of foliation. To the east, these rocks are cut by granite in which lenses of sillimanite rocks may be found. Recently, Bidyananda and Deomurari (2007) dated zircons from quartzo-feldspathic gneisses of the Meghalaya craton. The ^{207}Pb/^{206}Pb isotope gave 2637 ± 55 Ma for core and 2230 ± 13 Ma for rim of the mineral, indicating that the cratonic gneisses are Archaean, not unlike other cratonic regions of the Indian shield, and that the thermal overprinting on these basement rocks occurred during Proterozoic event(s). The overgrowth on detrital zircons from the cover trocks of the Shillong Group gave 1.5–1.7 Ga which is considered to be the age of metamorphism related to the Mesoproterozoic orogeny that affected both basement and cover rocks of the Indian shield (cf. Ghosh et al., 1994).

Recently, Chatterjee et al. (2007) dated monazite from high-grade metapelites of the craton. Their study provide well-constrained age of 1596 ± 15 Ma for the Garo-Golapar Hills, which is considered to date the counter-clockwise P-T path with near peak conditions of 7–8 kb/850°C. The EPMA monazite age in the Sonapahar high grade area are about 500 ± 14 Ma which nearly coincides with 408 Ma Rb-Sr dates of the porphyritic granite that intruded the Meghalaya gneiss complex. These dates correspond to Pan-African event which is widely documented in the southern granulite terrain (SGT) and in the Himalaya, besides at other places of the Indian shield.

The Gneissic Complex is unconformably overlain by the Proterozoic Shillong Group, which is mainly siliciclastic sedimentary association, now observed as phyllites and quartzites. According to Mitra (2005), the metasedimentary units (mica schists, quartzites, phyllites, slates etc.) belonging to the Shillong Group have been involved in four phases of folding. The earliest structures are very tight to isoclinal folds (F1) on bedding plane (So). These folds have high amplitude to wavelength ratio, with a penetrative axial plane cleavage (S1). These structural elements have been coaxially deformed into open to tight upright F2 folds with axial plane striking NNE, with the development of crenulation cleavage (S2). Both F1 and F2 folds appear to be buckle folds. In the more schistose rocks, NE-trending recumbent folds (F3) developed on F1 and F2 axial plane foliations. The last structures are upright conjugate folds and kink bends (F4) with axial plane striking NE, EW, and cheveron folds with NW striking axial planes. The structures of F4 thus provide evidence of longitudinal shortening of the Shillong Group of rocks (Mitra, 2005, p. 117).

The maximum time limit of the Shillong Group is given by Rb—Sr whole rock isochron age of 1150 ± 26 Ma old granite gneiss that occurs at the base of the Shillong Group (see Ghosh et al., 1991). The Millie granite (607 Ma; Chimote et al., 1988; see also Crawford, 1969) occurring as intrusive into the Shillong Group appears to suggest an event of thermal reactivation, because there is evidence that both the basement and the cover rocks of the Shillong Group are intruded by such anorogenic granites whose Rb—Sr whole-rock ages are in the range of 885–480 Ma (Ghosh et al., 1994). Both rock groups (the Gneissic complex and the cover of Shillong Group) are also intruded by basic and ultrabasic rocks, some of which belong to Late Cretaceous period (Mazumder, 1986). There is also a report of a carbonatite intrusion (Late Jurassic) from the Sung Valley of Meghalaya. Fission track ages of zircons from the adjoining Kyrdem Granite gives 1043 ± 101 Ma (Nandy, 2001). The granitic plutons occurring amidst the gneisses also extend in the direction of the regional foliation. The general alignment of these granitic bodies in the Meghalaya craton is E-W to ENE-WSW, conformable with the tectonic axis or the major lineaments of the Shillong Plateau (GSI, 1973). Rahman (1999) reports a narrow thermal aureole, about 400 m, suggesting shallow depth of the granite intrusion. The granite varies in texture from porphyritic to fine grained, consisting of quartz-microcline-micropethite and oligoclase with some biotite.

In 1964, Evans conceived that the Sylhet Trap (ca. 110 Ma old) located on the southern part of the Shillong plateau represents a part of the Rajmahal Trap (105–117 Ma; Bakshi, 1995) that is situated on the NE part of the Chhotanagpur Granite Gneiss Complex (CGGC). This led him (Evans, 1964) to believe that the Shillong Plateau has dextrally moved along the Dauki Fault for about 250 km towards east. The Dauki Fault, according to Evans (1964) is a tear fault (transcurrent or strike slip fault) that trends transverse to the strike of the deformed rocks of the Shillong-Mikir Hills Plateaus. But Murthy et al. (1969) contradicted this proposition of Evans and argued with evidence that the Duke fault has a vertical uplift to the north, causing the Shillong-Mikir Hills Plateaus as an uplifted region with northward tilting. Another view for the elevated Shillong-Mikir Hills Plateaus is proposed, according to which the upliftment occurred as a consequence of nearly N-S collision of the Indian plate with the Eurasian plate. Dasgupta and Biswas (2000) believe that the Mishmi Hills added another compressional force from the NE in aiding upliftment of the Meghalaya craton (i.e. Shillong-Mikir Hills Plateaus).

According to Dasgupta and Biswas (2000), the Dauki Fault splits towards the east, with southern part linking up with the Disang Thrust that merges further east in the "Schuppen Belt" or belt of imbricated thrusts (namely Naga, Disang and Patkai Thrusts) (Fig. 2.10). More recent study involving remote sensing and ground checks by Srinivasan (2005) revealed that the Dauki Fault is a single gravity (Normal) fault dipping towards south. However, a limited dextral slip is indicated by bending towards NE to ENE of the axial surfaces in folded Miocene sediments (Surma Series) (cf. Srinivasan, 2005). Dasgupta and Biswas (2000) pointed out that there are a number of E-W faults. Besides these, there are also N-S trending faults that are considered to have developed during the Late Jurassic-Early Cretaceous during which ultramafic-alkaline-carbonatite complexes (ca. 107 Ma old) have been emplaced (Srivastava and Sinha, 2004; Chattopadhyay and Hashimi, 1984).

The Mishmi Hills, lying mostly outside the Indian Territory, is mainly a granodioritic complex with high-grade schists and migmatites. Its geographic position has prevented any detailed study, but the predominance of granite gneisses reported from the Indian part suggests that the Mishmi Hills is similar to that of the Shillong Plateau. The Indo-Burma fold belt is thrust upon the Mishmi Hills, while the Roing Fault marks the SE end of the Mishmi Hills complex. The fault terminates the Himalayan MBT and the Siwalik belt. Whether the Mishmi Hills is a part of the Indian crust (Shillong and Mikir Hills Plateaus), or it is more closely related to any part of the two neighbouring colliding plates of Burma and South Tibet, needs to be resolved by collaborative studies.

The basement complex was block-faulted or rifted in Permian to Early Cretaceous during which Gondwana sediments were deposited. Subsequently, the composite crustal mass of Shillong and Mikir Hills Plateaus is criss-crossed by a large number of nearly rectilinear lines along which rivers and streams have cut straight valleys. The above account of the Precambrian cratonic rocks of the eastern India is general and demands intensive geological studies on modern lines, similar to that attempted on other cratonic regions and Proterozoic fold belts.

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