Chapter 6
Singhbhum Fold Belt

6.1 Introduction: Geological Setting

The Singhbhum fold belt (SFB) or Singhbhum Mobile belt, also called North Singhbhum belt (Saha, 1994) in eastern India is sandwiched between the Singhbhum craton in the south and Chhotanagpur Granite-Gneiss terrain (CGGC) in the north (Fig. 6.1). Although slightly curvilinear, the fold belt has nearly E-W strike like that of the Satpura fold belt (Chap. 5) and is believed to have evolved in the Proterozoic Satpura orogeny (Sarkar and Saha, 1962). The Singhbhum fold belt is made up of metasedimentary and metavolcanic rocks categorized in three domains. Gupta and Basu (2000) of Geological Survey of India gave the following lithostratigraphy of the Singhbhum fold belt.

Dalma Group

Singhbhum Group {Dhalbhum Formation
{Chaibasa Formation

Dhanjori Group

- - - - - - - - - - - - -unconformity- - - - - - - - - - - -

Singhbhum Granite basement

The *Singhbhum Group* which consists of pelitic and semipelitic schists, quartzites, amphibolites, felsic and intermediate tuffs recognized near the craton as *sericite schists and phyllite in upper part* (Dhalbhum Formation, DH) *and mica schists, quartzites, amphibolites in lower part* (Chaibasa Formation, CB), occurring north of the Dhalbhum Formation (Fig. 6.1). The Singhbhum Group unconformably overlies the Singhbhum Granite phase III (~3.12 Ga old) and its equivalent Bonai Granite and Chakraddharpur Granite Gneiss (CH) (Bandyopadhyay and Sengupta, 1984; Saha, 1994; Sengupta et al., 1991). Second is the *Dalma Group or Dalma volcanics* comprising ultramafic lavas and high Mg-basalts overlain by low-K pillowed tholeiites in the middle part. Third group is a low-grade metamorphosed volcano-sedimentary assemblage further north, contacting the CGGC along a shear zone, called the Northern Shear zone. Another shear zone occurs in the southern boundary

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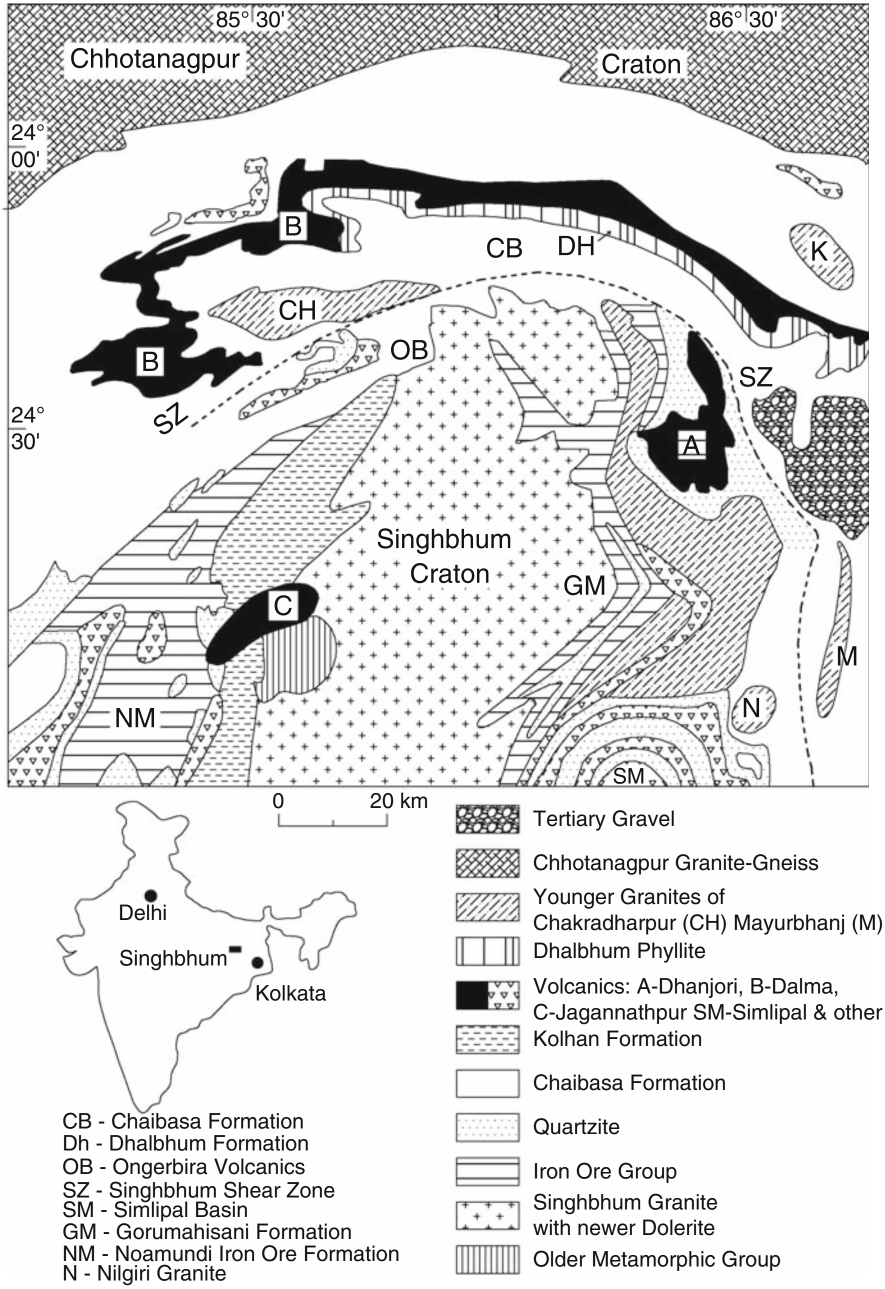

Fig. 6.1 Location of Singhbhum fold belt between Singhbhum craton and Chhotanagpur Granite Gneiss Complex (Chhotanagpur craton) (after A.K. Saha, 1994). (A) = Dhanjori volcanics, (B) = Dalma volcanics, (C) = Jaganathpur volcanics, CB = Chaibasa formation, CH = Chakradharpur granite, DH = Dalma formation, GM = Gorumahisani formation, K = Kuilapal Granite, N = Nilgiri Granite, NM = Noamandi Iron-Ore formation, M = Mayurbhanj Granite, OB = Ongerbira volcanics, SM = Simlipal basin, SZ = Singhbhum shear zone

of the Singhbhum fold belt against its contact with the Singhbum Granite of the Singhbhum craton in the south and is familiarly known as the Singhbhum shear zone, SZ (see Fig. 6.1). The fold belt, like the Singhbhum craton, is most intensely studied region of the Precambrian terrains of India (Saha, 1994).

The Chaibasa Fm of domain (1) is reported to occur in a geoanticline (Dunn, 1929; Dunn and Dey, 1942), later termed Singhbhum anticlinorium by Sarkar and Saha (1962). This anticlinorium is bound on the north by Dalma syncline of domain (2) and by another anticlinorium further north, corresponding to domain (3) (Fig. 6.1). The Chaibasa Formation of domain (1), encompassing the high-grade metamorphic rocks, has a confusing history in regard to its geologic position. Dunn and Dey (1942) placed the Chaibasa (stage) in the lower part of the Iron-Ore Series (Chap. 2), while Sarkar and Saha (1962) placed them in the Singhbhum Group. Later, Iyengar and Murthy (1982) re-named the Chaibasa stage as Ghatsila Formation and placed it at the base of the Dhanjori sequence (equivalent to Dalma volcanics). Recently, Srivastava and Pradhan (1995) found a thrust relationship between them due to which the Chaibasa was thrust upon the Dhanjori. It may be noted that the southern limit of the Chaibasa Formation is the Copper Belt Thrust or the Singhbhum shear zone (SZ). The Chaibasa Stage/Formation was also traced by Dunn and Dey (1942) westwards in the Rajkharswan-Chakradharpur area where the Iron Ore Group (IOG), owing to its westward plunge, successively overlies them. Northward, the high-grade rocks of Chaibasa gradually merge into an overlying sequence of low-grade rocks (phyllite, chlorite schist, carbon phyllite and orthoquartzite) that occur in a belt south of the Dalma volcanics. The low-grade rock-suite was grouped into the Iron-Ore Stage by Dunn and Dey (1942) and into Dhalbhum Formation by Sarkar and Saha (1962) who placed this formation in the Singhbhum Group.

The domain (2) is made of the *Dalma volcanics* which have been called Proterozoic greenstone assemblage by Gupta et al. (1982) who recognized them as low-K, high Fe-tholeiites with pillowed structures; and also minor high-Mg volcanics as flows and komatiitic intrusives. Associated with these volcanics are high-Mg volcaniclastics, tuff and carbon phyllites. The Dalma volcano-sediments have been metamorphosed under the greenschist facies.

To the north of the Dalma volcanics the domain (3) is an assemblage of low—grade metamorphic association of volcanics (acid and basic/ultrabasic), volcaniclastics and metasediments, collectively named *Chandil Formation* by Ray et al. (1996). This assemblage, according to Ray et al. (loc. cit), is distinct from the dominantly metasedimentary assemblage exposed to the south of the Dalma volcanic belt (see Acharyya, 2003). The contact between the Chandil Formation with the CGGC on the north is marked by a shear zone and by carbonatite intrusions (Gupta and Basu, 2000). The acid tuff of the Chandil Formation from Ankro yielded Rb–Sr whole-rock isochron age of 1487 $\pm$ 34 Ma (Sengupta and Mukhopadhyay, 2000), indicating a thermal event in the Singhbhum orogeny. The Chandil supracrustals are intruded by a number of oval granite bodies. Amongst them, the Kuilapal Granite (see K in Fig. 6.1) yielded Rb–Sr whole-rock isochron age of 1638$\pm$38 Ma (Sengupta et al., 1994 in Acharyya, 2003) that fixes the upper age limit of the Chandil Formation.

The age of the Dalma volcanics is not satisfactorily constrained. A gabbro-pyroxenite intrusion into the Dalma volcanics from Kuchia, located in the eastern part of the Dalma belt, has yielded 1619 ± 38 Ma age by Rb–Sr whole-rock isochron method (Ray, 1990; Roy et al., 2002b). Trace element, REE and Sr and Nd isotopic studies on these intrusives indicate highly depleted nature of the parent mantle (Acharyya, 2003). Bose (2000) also inferred depleted nature of the mantle beneath the Dalma volcanics. In view of the very similar character of trace elements and REE, both gabbro-pyroxenite intrusive and the Dalma volcanics are inferred to have been derived from the same depleted mantle source (see Acharyya, 2003). Thus, we can conclude that both the Chandil Formation and the Dalma volcanics were metamorphosed together and were intruded by granite and coeval gabbro-pyroxenite at about 1.6 Ga ago. The age of the extrusion is, however, not yet definitely known but may not be much different (cf. Acharyya, 2003).

It may not be out of place to state here that south of the Singhbhum shear zone there are a number of volcano-sedimentary basins, especially the Dhanjori (A), Simlipal (SM), Jagannathpur (C) and Malangtoli basins, which are circum-cratonic (Fig. 6.1). These basins with prominent tholeiitic magmatism are believed to have generated along circum-cratonic peripheral rifts around the Singhbhum craton (or ACCR of Mahadevan, 2002) in the Early Proterozoic or Late Archaean. The Simlipal volcanics are intruded by Simlipal granite of 2.2 Ga old (cf. Mahadevan, 2002). This means that the Simlipal basin and Dhanjori basin (with 2.2 Ga old Mayurbhanj Granite intrusion in the Dhanjori sequence; Gupta et al., 1982) are older than 2.2 Ga while the Dalma basin may be older than 1.6 Ga. According to Sarkar et al. (1992) the Dalma volcanism was the culmination of the mafic volcanism that manifested in Dhanjori, Jagnnathpur, Simlipal basins, resulting due to crustal thinning and mantle upwelling (Iyengar and Anand Alwar 1965).

To the south or southwest of Chakradharpur granite there is another volcanic sequence, called *Ongerbira volcanics* (OB), which resembles the assemblage of the Dalma rocks and the Chandil volcanics. The Ongerbira volcanics is a sequence of ash beds, tuffaceous metasediments and low-grade metapelites resting on mafic/ultramafic rocks. Like the Dalma syncline, the Ongerbira volcanics occur in an E-W trending syncline. Earlier the Ongerbira volcanics were correlated with Newer Dolerite (Neoproterozoic) by Dunn (1929) who later suggested them to be a continuation of the Dalma volcanics. Sarkar and Saha (1962, 1977), on the other hand, considered the Ongerbira volcanics as part of the Iron Ore Group (IOG) and hence within the Singhbhum craton, separated from the mobile belt by the Singhbhum shear zone (see also Gupta et al., 1981; Gupta and Basu, 2000). Subsequently, many other workers, chiefly Sarkar (1982), Sarkar and Chakraborti (1982) and Mukhopadhyay et al. (1990) considered these volcanics as the extension of the disrupted and folded sequence of the Dalma. This appears to be quite plausible if one observes the synclinal nature and similarity of rocks of the Ongerbira with the Dalma syncline. The Ongerbira volcanics could be a detached portion of the refolded Dalma rocks since their continuity with the Ongerbira volcanics is disrupted by the Chakradharpur Granite Gneiss and the shear zone, that affected these rocks in its vicinity. Although the Ongerbira syncline is disrupted from the Dalma volcanics, there is no evidence favouring an extension of the shear zone to separate these two volcanic domains. The Ongerbira magmatic suite with E-W trending folds belong to the Singhbhum mobile belt and appears tectonically juxtaposed against the NNE-striking IOG rocks (Noamandi-gua) belonging to the Singhbhum craton. Perhaps due to the presence of the Singhbhum shear zone (Copper Belt Thrust), Ray (1990) inferred the Ongerbira volcanics to occur as klippe of the overthrusted Dalma volcanics overriding the rocks of southern Singhbhum belt and the IOG in the Singhbhum craton. Recently, the GSI disclosed that both northern and southern boundaries of the Ongerbira volcanics are faulted (see Mazumdar, 1996). That the Ongerbira volcanics are detached portion of the Dalma volcanics is supported by the comparable major and trace element data from Ongerbira volcanics and Dalma basalt (Blackburn and Srivastava, 1994). The chemical data on the Ongerbira basalts are interpreted for continental rift tholeiites with oceanic affinity or back-arc rift setting (Blackburn and Srivastava, 1994), which is not much different from the interpretation of Sarkar (1982) for ensimatic mid-oceanic rift. The geochemical data of the Dalma volcanics also indicate back-arc setting. The Ongerbira volcanics are distinct from the primitive volcanics from the IOG (Sengupta et al., 1997; Bose, 2000). The asymmetric distribution of the Dalma volcanics and the development of acid-dominant Chandil belt exposed to the north of the Dalma belt, and the absence of 1.6–1.5 Ga old charnockites in the southern part of the CGGC belt flanking the Dalma belt, do not support the postulation by A. Roy et al. (2002a) that the Dalma volcanics are generated by Mid-Proterozoic plume-related thermal event.

6.2 Deformation

The rocks of the Singhbhum fold belt show three major fold phases each characterized by their linear and planar structures. There is a progressive change in the geometry and morphology of these structural elements across the fold belt, from the fold belt to the thrust or shear zone. This means that that the deformation changed in style in different domains of the fold belt. The first generation planar structure is the metamorphic banding formed by F1 folding in the recrystallized rocks of the Singhbhum Group. In the lower formation (Chaibasa Formation) of the Singhbhum Group, the F1 folds are few and small which are characterized by reclined geometry, found at places as rootless hinges with mineral lineation L1 due to intersection of S_0/S_1 (see Acharyya, 2003). The second fold phase (F2), generally coaxial with F1, gave rise to E-W regional folds with a strong axial plane foliation (S2) that is recognized as regional foliation in the terrain. In the eastern sector (e.g. in Ghatsila) of the SFB, the F2 folds are represented by the antiforms and synforms in pelitic schists (Mukhopadhyay, 1988; Gupta and Basu, 2000). These structures were earlier identified as F1 folds by Sarkar and Saha (1962) and also by Naha (1965). According to Mukhopadhyay et al. (1990) a secondary foliation has developed at low angles to the bedding, defining the blunt-hinged synformal closure (as at Ghatsila) and puckered nature of the S_0. The large-scale folds in the bedding schistosity are considered the outcome of F2 in the Galudih area near Ghatsila (Mukhopadhyay et al., 1990). These authors also described steeply plunging U-shaped F2 folds with closures facing in opposite directions to form steeply plunging sheath folds with acute hairpin curvature of fold axis.

The F2 folds in the northern belt are asymmetric and indicate that rocks in the N have moved upwards relative to the rocks on the south (Sengupta and Chattopadhyay, 2004). In the southern part the F2 folds are upright in nature with regional foliation maintaining a vertical attitude. A little to the south, the folds maintain the same sense of asymmetry but the axial plane dips in a northerly direction. According to Sengupta and Chattopadhyay (2004), the variation in the plunge of these F2 folds in the southern sector is pronounced in contrast to the consistent gentle plunge of folds in the north. Interestingly, Dunn and Dey (1942) recognized the Singhbhum anticlinorium as a refolded fold whose asymmetric digitations shown by the outcrops of the Dalma volcanics at its closure region are the second-generation folds (F2). The F2 folds are upright, asymmetric, and in the middle part of the Singhbhum fold belt they show northerly-dipping axial planes (S2). The F2 folds become progressively overturned to the south as the Singhbhum shear zone is approached. Here the schistosity is more intensely developed, its dips moderate towards N and the fold axes are conspicuously parallel to the down-dip stretching lineation. All shear sense indicators in the zone suggest upward transport of the northern block relative to that occurring towards south.

Thus it can be inferred, following Sengupta and Chattopadhyay (2004), that the second deformation (F2) across both fold belt and the shear zone has been contemporaneous and non-co-axial. Consequently, the folds changed from being upright in the north to overturn in the south. Plunges of the fold also show change from subhorizontal to steep in the same direction, seen from N to S. Sengupta and Chattopadhyay (2004) interpret this variation in the fold geometry to be the result of progressive non-axial deformation in the ductile shear zone.

Third generation folds (F3) occur mostly within the Singhbhum shear zone. They are superposed on F1 and F2 fold structures (Bhattacharya and Sanyal, 1988). The F3 axes have variable plunges towards NNE and the F3 folds gradually die out northward and southward.

The F4 folds appear as macroscopic folds in the SE part of the Singhbhum fold belt, e.g. near Hathimara. These folds are open and upright, developed on S3 and earlier S-planes. Axial planes are often marked by a fracture cleavage (S4) that has NNE strike and subvertical dips towards E or W. The fold axes plunge at low angles towards NNE. F4 folds diminish toward N and W into minute crinkles on S4 (Bhattacharya and Sanyal, 1988).

6.3 Metamorphism

Compared to structural studies, metamorphic investigation of the rocks of the Singhbhum belt is limited. The highest grade rocks are the Chaibasa Fm that show amphibolite facies assemblages and are exposed all along the middle part of the anticlinorium. The association of the highest grade with the central part of the anticlinorium is most striking but not correlatable with the granitic intrusions in the region. From this high-grade central part of the anticlinorium the metamorphic grade decreases northward to greenschist facies (see review in Gupta and Basu, 2000). High-grade rocks of amphibolite facies are also found in the Kuilapal migmatite complex of domain (2). Here as well as in Sini area the metamorphism is Barrovian type (Lal et al., 1987). The progressive regional metamorphic sequence from chlorite, biotite, garnet, staurolite, and kyanite zones are clearly seen in eastern Singhbhum (Ghatsila) (Naha, 1965). A similar sequence is also found in central Singhbhum (Gamaria) (Roy, 1966). In all these areas, the higher-grade rocks occur against the direction of axial plunge and the regional metamorphism is found to be syn- to post-kinematic with respect to F1 and pre-kinematic with respect to F3 (Bhattacharya and Sanyal, 1988). Migmatization is slightly later and the associated rocks are found to contain sillimanite in suitable compositions. Although evidence of partial melting of lower continental crust is seen in the occurrence of the Arkasani granophyre and associated Soda granites, the Singhbhum fold belt, like the Singhbhum craton, is devoid of granulitic rocks. The granulites are conspicuously present as boudins in the CGGC craton occurring in the north of the Singhbhum fold belt.

6.4 Geochronolgy

The Singhbhum (-Orissa) craton in the eastern Indian shield is found to attain stability at around 3.1 Ga, which is the age of the Singhbhum Granite phase III. No such dates are, however, recorded in the Chhotanagpur Gneissic Complex (CGGC), although > 2.3 Ga old gneissic rocks of the complex contain metasedimentary enclaves, presumably Archaean in age (Saha et al., 1988). Like other Archaean gneissic complexes, the CGGC is also a polymetamorphic gneissic complex, but without record of Archaean history, perhaps due to resetting of ages in the constituent rocks. It, therefore, seems that the CGGC was once united with the Singhbhum (-Orissa) craton and this united cratonic block (here called SC-CGGC) subsequently rifted (Sarkar and Saha, 1977, 1983; Bose, 1990) to give rise to a basin for the deposition of the volcano-sedimentary rocks of the Singhbhum fold belt. No definite date is available for the time of rifting and the lower age of these supracrustal rocks cannot be constrained. As stated earlier, the supracrustal volcano-sedimentary succession, collectively called the Singhbhum Group (Saha, 1994; Gupta and Basu, 2000) unconformably overlies the 3.12 Ga old Singhbhum Granite phase III and its equivalent Bonai Granite and Chakradharpur Granite gneiss (see Saha, 1994). This means the rifting could be Mesoarchaean or much later after the cratonization.

The supracrustal sequences of the Singhbhum Group are seen intruded by granites. Amongst these is the undeformed Mayurbhanj Granite (Sarkar and Saha, 1977), having U–Pb zircon age of 3.09 Ga (Misra, 2006). Since this Pb–Pb zircon age of the Mayurbahnj Granite (see locality M in Fig. 6.1) is very close to the age of the Singhbhum Granite Phase III, it is highly probable that the analyzed zircons in the sample (BG-64; Misra, 2006, p. 367) have ^{206}Pb proportion comparable to that of the Singhbhum Granite. This becomes significant because the Mayurbhanj granite is considered as an anatectic product of the SBG-III (Misra, 2006, p. 367). Furthermore, this granite is found to have three phases of intrusions (Naha, 1965; Sarkar et al., 1979), out of which only the third phase postdated the Singhbhum Shear Zone (SSZ). It is in this context that the whole-rock Rb–Sr age between 2.37 and 2.08 Ga for the MBG (Vohra et al., 1991; Iyengar et al., 1981) is relevant to constrain the upper age limit of the Singhbhum Group rocks.

The Singhbhum Group was followed by a major mafic volcanism known as the Dalma Volcanics (Bose, 1994; Gupta and Basu, 2000; Saha, 1994). Field study reveals that the sequence starts with shale-phyllite, carbon phyllite-tuff with interlayered volcanics followed upward by ultramafic volcaniclastics and komatiitic intrusives. The ultramafic horizon in the lower part is followed by tholeiitic lava flows, separated from each other by pyroclastic rocks. The Dalma volcanics which overlie the Singhbhum Group yielded whole-rock Rb–Sr age of $\sim$ 2.5–2.4 Ga (Misra and Johnson, 2005). This means that the temporal equivalency of the Dalma Volcanics with the 2.8 Ga old Dhanjori volcanics should be seen in terms of tectonothermal history of the Singhbhum fold belt. Dalma volcanics are deformed and weakly metamorphosed.

Deformational study shows that both supracrustal sequences of Singhbhum Group and Dalma Volcanics were subjected to superposed folding attended with regional metamorphism (syn- to post F1). The Singhbhum fold belt records tectonomagmatic activity at 2.2, 1.6, and 1.0 Ga. The 2.2 Ga event within the fold belt is documented by the emplacement of 2.2 Ga old Soda granite while 1.6 Ga old event is recorded by: (i) intrusion of 1.6 Ga old Kuilapal Granite within the fold belt (Sengupta et al., 1994, whole-rock Rb–Sr age), and (ii) copper mineralization at 1.65–1.7 Ga (Johnson et al., 1993, whole-rock Pb–Pb age). Furthermore, an isolated gabbro-pyroxenite body intruding the Singhbhum Group rocks just north of the Dalma Volcanics yielded whole-rock Rb–Sr age of 1.6 Ga (Roy et al., 2002b).

These afore-said geochronological data lead us to conclude that the Singhbhum orogeny began with rifting somewhat earlier in Mesoproterozoic, perhaps in Palaeoproterozoic, and the sedimentation-volcanism in the rifted basin terminated at about 2.2 Ga. The main orogenic event involving deformation, metamorphism attended by granite intrusion evidently occurred in the time span of 2.2–1.6 Ga, as documented by granite intrusions (Soda Granite, Kuilapal Granite) and 1.54 Ga K–Ar ages for hornblende from amphibolite dykes (Sarkar et al., 1979). The K–Ar ages between 1.18 and 0.84 Ga for muscovites and biotites from schists perhaps denote end stage of regional metamorphism, with or without shearing. The age of 1.0 Ga is also recorded by the shearing of Arkasani Granite along Singhbhum shear zone (Sengupta et al., 1994, whole-rock Rb–Sr age).

When the Singhbhum fold belt experienced Proterozoic deformation and metamorphism, the Singhbhum craton recorded mafic magmatism by way of emplacement of Newer Dolerites, which have yielded K–Ar dates at 2.0, 1.6, and 1.12–1.0 Ga (Mallik and Sarkar, 1994; Sarkar et al., 1979).

6.5 Agreed Observations and Facts

Before we discuss these evolutionary models we take an inventory of the relevant facts and agreed observations about the constituent rocks of the Singhbhum fold belt. They are stated as follows:

1. The Singhbhum fold belt with E-W trend is made up of metasedimentary and metavolcanic rocks.
2. The constituent rocks are dominantly arenaceous-argillaceous (Singhbhum Group) in the south, the Dalma volcanics in the middle and a suite of volcano-sedimentary rocks in the north.
3. The Singhbhum fold belt is located between the Singhbhum craton (SC) in the south and the Chhotanagpur Granite Gneiss Complex (CGGC) in the north.
4. The evolution of the SMB started with rifting of the once united SC-CGGC Archaean block before the 1.7 Ga, the age of the sulphide mineralization. The rocks suffered the last thermal overprinting or cooling at about 900 Ma ago which is the closing time of the Satpura orogeny (Bhattacharya and Sanyal, 1988).
5. The volcano-sedimentary rocks of the rift basin have been deformed with earliest episode, producing E-W trending folds which have been superposed by folds with NE-SW to NNE-SSW striking axial planes.
6. The age of metamorphism coeval with F2 is dated at 1700 Ma (Sarkar et al., 1979); metamorphic isograds generally show an accordant relation with structural trends and stratigraphic boundaries.
7. Post-dating these folds is a 200 km long and up to 25 km wide arcuate Singhbhum Shear Zone (SSZ) or Copper Belt Thrust, between the Singhbhum belt in the north and the Singhbhum-Iron Ore cratonic Province in the south. The SSZ also shows localized folding.
8. The uranium ores in SSZ are dated at about 1600 Ma (Rao et al., 1979; Pb–Pb uraninite age).
9. The Singhbhum shear zone is developed near the southern boundary of the North Singhbhum fold belt.
10. The Dalma volcanics "spine" subdivides the Singhbhum fold belt into two segments.
11. The granite rocks in the fold belt have been dated between 2080 Ma (age of Mayurbhanj Granite) and 1700 Ma (age of Soda Granite) (Iyengar et al., 1981; Sarkar et al., 1985).

With these relevant informations we can now discuss the different evolutionary models for the Singhbhum fold belt (SMB).

6.6 Evolution of the Singhbhum Fold Belt (SMB)

Several tectonic models have been proposed for the evolution of the Singhbhum mobile belt. But preference of one over the other seems difficult because sedimentation, volcanism, or tectonism in the fold belt are not well constrained, geochronologically. However, nearly all models believe that the Singhbhum fold belt formed in a rift basin generated during Palaeoproterozoic time. In this basin we have a thick sequence of arenaceous and argillaceous rocks, now seen as deformed and recrystallized metasediments at the periphery of the Singhbhum craton (or the Archaean Core Craton Region, ACCR, of Mahadevan, 2002) at the southern contact. The dominant arenaceous rocks (Chaibasa Formation) often alternate with argillaceous components. The Chaibasa Formation is described as tidal flat, shallow marine deposits (Bose et al., 1997). The oldest member of the formation is a lithicwacke with lenses of matrix-supported conglomerate, which occurs extensively as a basal unit immediately overlying the Archaean basement to the south. The remaining younger units in the Chaibasa Formation are pelites and psammi-pelites, now seen as quartz-mica schist, garnetiferous mica schist, quartz-kyanite schist, and quartzites with well-preserved sedimentary structures. The presence of sedimentary structures, coarse grain size, and detrital plagioclase suggest that these rocks were deposited in a near-shore basin, proximal to the Singhbhum craton (Bhattacharya, 1991). The Chaibasa Formation is overlain in the north by the Dhalbhum Formation (younger unit of the Singhbhum Group), which is dominantly argillaceous (now metapelitic schists) with subordinate quartzite. The quartzites are fine-grained, resembling metachert. Besides this, Dunn and Dey (1942) reported tuffaceous rock, implying that the Dhalbhum Formation possibly contains volcanogenic material. These features indicate that the Dhalbhum Formation in the north represent a deep-water facies rock association (eugeosynclinal deposits). The clastic arenaceous facies is taken over by the dominantly argillaceous facies up to the linear belt of the Dalma volcanics. Beyond Dalma volcanics in the north there is a broad belt of volcano-sedimentary rocks, similar in lithology to the rocks in the south of the Dalma belt, that include tuff, acid and basic volcanics, all continuing up to the high-grade CGGC in the north. It seems that the Singhbhum Group and the Dalma volcanics overlap in time; the former developed in the rift basins that initiated the latter due to thinning of the continental lithosphere (cf. Mahadevan, 2002).

All the different lithologies occur as linear units with E-W orientation parallel to the trend of the fold belt. This regional trend is the consequence of compression of the volcano-sedimentary belt by the N-S collision of the Singhbhum craton in the south against the Chhotanagpur Granite Gneiss Complex in the north. During the collision of the crustal blocks both volcano-sedimentary rocks and Dalma volcanics were metamorphosed and intruded by granite and coeval gabbro-pyroxenite at about 1.6 Ga ago (Ray, 1990; Roy et al., 2002a, b). The Proterozoic granites of Kharswan, Arkasani, Mosabani etc., occurring as linear bodies parallel to the extent of the mobile belt, are possibly the expression of partial melting of the underlying crust of the fold belt. The Chandil supracrustal in the volcano-sedimentary belt north of the Dalma volcanics is also intruded by granites, amongst them the

Kuilipal Granite is dated by Rb—Sr whole-rock isochron at 1638±38 Ma (Sengupta et al., 1994). Thus, the collision of the Precambrian blocks is expressed in the E-W trending folds, regional foliation and E-W running metamorphic isograds (see previous section). Regional metamorphism of the Singhbhum Group rocks was during 1.6 Ga is also supported by the Rb—Sr whole-rock isochron age of the Soda granites (Sarkar et al., 1985), syntectonically intruding the Chaibasa Formation. Following Sengupta and Chattopadhyay (2004), this writer also thinks that the Singhbhum fold belt developed without closure of any large ocean. The presence of marked asymmetry of the fold belt and the reactivated basement fully accord with the origin of the fold belt by continental collision. The nature of the sediments and deformation style in the Singhbhum fold belt suggest them to be similar to a fold-and-thrust belt developed due to collision tectonics. It has involved shallow-water sediments and their continental basement and is therefore of intra-continental nature (cf. Sengupta and Chattopadhyay, 2004).

The southerly vergence of the structures in the fold belt suggests that the domain of collision should lie beyond the Dalma volcanic "spine", but certainly not to include the E-W trending Chhotanagpur Granite Gneiss Complex (CGGC) as postulated by Acharyya (2003). He (Acharyya, loc. cit.) regarded the CGGC and the Singhbhum fold belt (SFB) as the southern fold belt of the Central Indian Tectonic Zone in its eastern sector and recognized that they (CGGC and the SFB) are formed by collision of the Bundelkhand craton in the north and the Singhbhum craton in the south (Acharyya, 2003, p. 11). This proposition is not supported by the progressive underthrusting of the Singhbhum craton deep under the Northern region as a result of which several bodies of ultramafic rocks and mafic schists (Gupta and Basu, 2000) occur all along the shear zone (Banerji, 1975; Saha, 1994).

The southern boundary of the Singhbhum fold belt (SFB) against the eastern and northern margins of the Singhbhum craton is demarcated by a shear zone, called the Singhbhum Shear Zone (SSZ) (Mukhopadhyay et al., 1975). Discontinuous sheets of smaller bodies of granites, namely Soda Granite (2.2 Ga), Arkasani Granophyre (1052 Ma), Mayurbhanj Granite (some of which may even represent wedges of basement granitoids, see Fig. 6.1 for location), occur close to the shear zone and in variable state of deformation. The SSZ with its narrow belt of mylonites, according to Dunn, 1929) and Mukhopadhyay (1984), tapers out westward. However, some workers (Sarkar and Saha, 1962; Gupta et al., 1981; Gupta and Basu, 2000) think that the SSZ also extends along the NW margin of the Singhbhum Granite and along the southern margin of the Chakradharpur Granite (CH), which represents the largest tectonic wedge of the basement granitoid exposed to the north. These workers also infer that the SSZ separates the domain hosting the Ongerbira volcanics and the craton. This proposition, however, is not accepted by Sarkar and Chakraborti (1982) who recorded lithological similarity of rocks across the supposed western extension of the SSZ. A continuity of structures and absence of mylonite belt were also established across the supposed extension of the SSZ by Mukhopadhyay et al. (1990). Recent mapping by the GSI shows the absence of any major dislocation along the southern margin (Mazumdar, 1996). Beyond Porhat (location not given in Fig. 6.1), the SSZ possibly grades into a high-angle gravity fault and extends SW along the western boundary of the low-grade Iron-Ore Group (IOG) and then along the western margin of the Bonai Granite (Saha, 1994, p. 177).

The SSZ is an arcuate belt of high strain and is characterized by ductile shearing, soda-granite magmatism and polymetallic mineralizations. The major movement along the shear zone is mainly vertical, as evidenced by steeply plunging a-lineation. Perhaps impressed by the curvilinear nature of the shear zone, presence of crushed rocks and mylonites and retrogression of the different rocks along the SSZ, Dunn and Dey (1942) regarded the SSZ as a late orogenic feature of the deformation affecting the SFB. Other workers (e.g. Mukhopadhyay et al., 1975; Mukhopadhyay, 1984; Gupta and Basu, 1985) consider the SSZ as an early feature, the earliest recognizable phase of deformation. The early features are believed to have been obliterated by phases of deformation and protracted ductile shearing (cf. Gangopadhyay and Samantha, 1998). Recently, Pradhan and Srivastava (1996), on the basis of their study in Chakradharpur area, showed that the ductile shearing occurred between F1A and F2 group of folds. This was followed by brittle deformation, claim the authors (Pradhan and Srivastava, 1996). The authors also recognized four phases of ductile folding separated by two phases of brittle deformation in the shear zone. Since the SSZ traverses rocks of different ages and separates contrasted metamorphic facies on its either side, it is highly likely that the SSZ is coeval with or post-dates regional metamorphism of the Singhbhum Group rocks and hence younger than 1.6 Ga.

The evolution of the Singhbhum shear zone is considered multiepisodic (Misra, 2006) at 2200, 1800, 1600, and 1000 Ma. The soda granite is emplaced at 2.2 Ga; Copper mineralization occurred at 1.8 Ga; Kuilapal Granite and Uranium mineralization occurred at 1.6 Ga and Arkasani Granite intrusion at 1.05 Ga. The granitic rocks have been sheared and occur as detached bodies. It is also possible that the Singhbhum shear zone was the last event to have deformed all the granitoids emplaced prior to shearing, and the mobilization during shearing is responsible for the U and Cu mineralization.

6.7 Evolutionary Models and Discussion

Keeping in view the above discussion, we now critically evaluate below the different evolutionary models for the Singhbhum fold belt.

Model 1: Intraplate Subduction Model (Sarkar and Saha, 1977, 1983)

On the assumption that the Singhbhum Shear Zone (SSZ) is a deep suture between the Proterozoic Singhbhum fold belt and the Archaean Singhbhum craton, Sarkar and Saha (1977, 1983) proposed that the rocks north of the SSZ were developed in a geosynclinal basin and were later involved in the Satpura orogeny (1600–900 Ma). The evolutionary model can be summarized in the following stages:

- Long after cratonization (~3.1 Ga) a geosyncline (ocean) developed around 2.2 Ga in which Proterozoic sediments of the North Singhbhum Mobile belt were deposited.

- The geosynclinal sediments of the Singhbhum Group were subsequently deformed and metamorphosed due to northward subduction of the Singhbhum craton (along the SSZ) under the lithospheric plate to the north.
- There occurred a regional tension phase during which tholeiitic lavas of Dhanjori-Dalma were erupted and gabbro-anorthosites were emplaced.
- Subsequently there was a renewed subduction of the Singhbhum plate on the south, whereby partial melts in the upper part of the subducting plate were developed and emplaced as Soda Granite, Arkasani Granite, and the Mayurbhanj and Kuilapal granite suites.
- Renewed compression continued deformation of the Singhbhum Group and the Dalma-Dhanjori volcano-sedimentary formations.
- Final stage is marked by transcurrent faulting and thrusting (North shear zone) as well as the renewed shearing along the Singhbhum Shear zone (SSZ).

The above model was challenged on several accounts. First relates to controversies of constituent rocks in respect of their structural and stratigraphic status as outlined by Sarkar and Saha (1977, 1983). Second is the absence of typical subduction-related assemblages along the SSZ. Third is the uncertain reason for generating a tensional phase between two compressive regimes acting in nearly the same direction. Fourth is lack of explanation for the tholeiitic ocean floor (that characterize the Dalma lavas) on the overriding plate and lack of any large-scale movement across the SSZ (Mukhopadhyay et al., 1990; Sarkar et al., 1992).

Model 2: Microplate Collision Model (Sarkar, 1982)

A.N. Sarkar (1982) proposed a model of converging microplates to interpret the tectonic evolution of the Singhbhum and Chhotanagpur Granite Gneiss Complex (CGGC) regions. In this model the CGGC block represents an overriding plate and the Singhbhum microplate as the subducting plate. The collision of these continental microplates took place around 1600 Ma ago. The model considers convergence and collision of the Singhbhum microplate against a stationary Chhotanagpur microplate (CGGC) in three cycles. The first cycle (2000–1550 Ma) relates with the northward movement of the Singhbhum microplate and its collision with the CGGC microplate. In this event it is believed that Dalma volcanics was emplaced as ophiolite in a flysch environment. In the second cycle (1550–1000 Ma) the Singhbhum plate is assumed to have rotated clockwise towards NE and generated F2 folds, including the NW-SE trending fold of the Dhanjori rocks. The third cycle (1000–850 Ma) relates to the overriding of the Singhbhum plate onto the CGGC plate in a NNW-SSE direction, obduction of the continental lithosphere in the southern part of the Singhbhum fold belt, and also F3 deformation and M3 metamorphism. At the close of the orogenic cycle the Singhbhum fold belt was uplifted and subjected to erosion.

The collision model of A.N. Sarkar implies a very long period of subduction history, spanning over 300 million years. The model is based on poor database and necessitates extremely slow motion or very long distance journey of the Singhbhum plate.

Model 3: Marginal Basin Model (Bose and Chakraborti, 1981; Bose, 1990, 1994)

In this model, it is proposed by Bose and his co-authors (see Bose, 1990, 1994) that secondary spreading (rifting) of the Singhbhum craton occurred due to heating of the craton above a subducting slab. This resulted into separation of a continental mass making the continental arc of the Chhotanagpur Gneissic Complex (CGGC), what Bose (1990) called the "fossil island Arc" lying on a supra-subduction zone. The rifted basin between the Singhbhum craton and the separated continental arc of CGGC became the marginal basin which had a spreading ridge, called Dalma volcanic ridge (Fig. 6.2), located somewhere in the middle. This ridge separated the marginal basin into two sub-basins (see Fig. 6.2) that received supracrustals of the Singhbhum Group and the Dalma volcanics.

Deformation and metamorphism of the Proterozoic supracrustals in the marginal basin is stated to have occurred due to southward subduction of a lithospheric plate. The subduction zone in this model, according to Bose and his coauthor (see Bose, 1994), was to the north of the Chhotanagpur Gneissic Complex in what is today the Ganga Basin (Fig. 6.2). The N-S convergence of the south-directed plate against the Singhbhum craton situated on the south gave rise to the E-W trending Singhbhum fold belt.

Although the marginal basin model satisfactorily explains the high-temperature mineralogy of the CGGC (see Chap. 2), as a continental arc, and also other metamorphic deformation characteristics of the Singhbhum fold belt, it fails to explain some important geodynamic questions. The model envisages subduction zone somewhere to the north of the CGGC but the North shear zone (NSZ), located at the contact of the CGGC-Singhbhum fold belt, cannot be considered as a subduction zone. This is because there are no ultramafics associated with it and the NSZ is too impersistent to be considered as a subduction zone. Again, there is no evidence of arc-type volcanism or plutonism within the CGGC terrain. Finally, it is a matter of debate whether the Indo-Gangetic plain is also a part of the Singhbhum-Orissa microplate because northerly extension of the Singhbhum (-Orissa) carton is questionable. Lastly, the

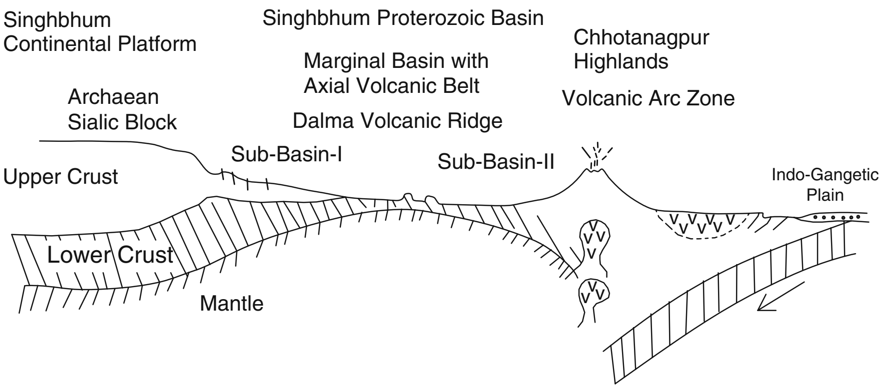

Fig. 6.2 Diagram showing tectonic setting of Singhbhum marginal basin and associated morphostructural unit (redrawn from Bose, 1994)

model starts with the second phase of the Wilson cycle without any reference to the first stage (Gupta and Basu, 2000).

Model 4: Ensialic Orogenesis Model (Gupta et al., 1980; Mukhopadhyay, 1984; Sarkar et al., 1992)

A least controversial model is the ensialic orogenesis model in which the Archaean crust of the region is assumed to have attenuated and rifted in response to mantle heat cell during which the Dalma volcanics erupted while sedimentation was initiated. Later, extension is believed to have been replaced by plate convergence during which the subducting lithospheric plate was delaminated, similar to that proposed for the Aravalli fold belt. This event of A-subduction not only caused deformation but also regional metamorphism of the Proterozoic rift sediments along with the Dalma lavas (Gupta et al., 1980; Mukhopadhyay, 1984). This model of ensialic orogenesis was first applied by Gupta et al. (1980) and later by Mukhopadhyay (1984) and Sarkar et al., (1992) and further refined with additional data and discussed by S.C. Sarkar et al. (1992) and Gupta and Basu (1985). The ensialic orogenesis model for the Singhbhum fold belt is summarized by Gupta and Basu (2000) and is briefly reviewed here.

Mantle plume below the continental lithosphere in this part of the Indian shield rifted a united craton of Singhbhum-Chhotangpur gneiss Complex. This gave rise to a rift basin between the Singhbhum craton in the south and the CGGC in the north. The basin became the site of deposition of the Singhbhum Group supracrustals; shallow deposits near the Singhbhum craton and distal facies sediments with contemporary volcanic-plutonic rocks farther. Dalma volcanics were in the central part of the basin while volcanism near the cratonic margin appeared in Dhanjori and equivalent basins. This volcanism occurred with intermittent effusion of acid/basic tuffs, alkali basalt and co-magmatic mafic-ultramafic intrusions. The carbonatite intrusion occurred along the northern boundary of the North Singhbhum Mobile belt and locally along the Dalma belt. It must be stated here that geochemistry of the volcanics in the mobile belt is mainly MORB type (cf. Bose, 1990) and is therefore indicative of rift environment. At some stage of the volcanic activity the stable continent also developed cracks along which mafic melt intruded as what is now called the Newer Dolerite dykes in the Singhbhum craton. The model envisages Singhbhum as a foreland block for the south-directed stresses generated by plate convergence and overriding of the north plate, the CGGC. Partial melting of the sialic upper crust of the southern plate seems to have generated granites of Arakasani, Mayurbhanj etc.

The ensialic orogenesis model is supported by the geophysical evidence, which indicates continuation of the continental crust below the entire width of the fold belt (Verma et al., 1984). The model explains many of the geological observations, but it assumes that both Singhbhum Group and Dalma volcanics were deposited at the same time. The geochronological data suggest the Dalma Volcanics are younger than the Singhbum Group. The model also fails to explain as to why granulites are absent in the fold-and-thrust terrain of the Singhbhum when so much quantity of mafic magma appeared during rifting and lithospheric delamination.

The metamorphic history in this ensialic orogenesis model by Mukhopadhya and Mukhopadhyay (2008) suggest that the early stage of heating was by asthenospheric upwelling and extension in the Singhbhum craton. This event (M1) formed andalusite-bearing paragenesis. The next stage was a collision related compressional deformation followed by M2 metamorphism (Barrovian) which was followed by cooling and decompression. The last event (M3) is retrogression and post D3.

The formation of andalusite prior to sillimanite and kyanite is not compatible with the stability of the Al-silicate minerals. If magmatic underplating was there, why did not granulites form and why did the temperature remain near 500°C to from andalusite. It is a serious question as to how did the early andalusite remain stable in D2 and D3 deformation and P-T conditions that were beyond the stability of this low-pressure mineral.

Model 5: Slab-Breakoff Model

Slab-Breakoff Model by the present writer takes into account the age considerations of the Dalma Volcanics and the Singhbhum Group rocks and also the presence/absence of the granulites in the colliding plates on the north and south of the Singhbhum fold belt. The proposed model is similar to the Model 4 described above, but it explains the features of fold belt and its constituent rocks more elegantly. The model, shown in Fig. 6.3, envisages that ductile stretching and rifting of the once united craton of Chhotanagpur Granite Gneiss Complex (CGGC) and Singhbhum craton (SC) gave rise to sedimentary basin (s) in the Palaeoproterozoic time, which became the site of sedimentation of the Singhbhum Group rocks (Fig. 6.3a). Further stretching developed large ensialic rift, the deeper parts of which in the north seems to have received minor tuff (Dunn and Dey, 1942) (Fig. 6.3b). This was followed by collision of CGGC and SC at about 1.6 Ga ago, resulting in the folding of the supracrustal and the underlying basement (Fig. 6.3c). This convergence (perhaps oblique in nature) of the N and S crustal blocks with subduction of southern block (Singhbhum block) was followed by a narrow rifting and slab weakening (location by small double arrows, Fig. 6.3d). Because of slab rupture and underplating, extrusion of mafic magma (Dalma Volcanics) occurred amidst sediments of the Singhbhum Group, and more volcano-sedimentary deposits took place with high-level intrusion of mafic (gabbro-pyroxenite) dykes at 1.6 Ga (Fig. 6.3e). As a consequence of slab rupture and underplating there occurred extrusion and intrusion of mafic magmas as well as 1.6 Ga old granites (Kuilapal etc.) and Granophyre (at Arkasani), formed as a result of partial melting within the crust due to heat from underplated magma (Fig. 6.3f). Further slab break off and its downgoing, i.e. sinking of the slab, generated melt of calc-alkaline composition that appeared in various forms as volcanics (Chandil) and acid tuff Ankro area of Chandil (1487±34 Ma; Sengupta and Mukhopadhyay, 2000) (Fig. 6.3 g). Finally, the slab sinks away and melts at depth, producing the last phases of granitoid liquid while dykes (Newer Dolerite; 900–935 Ma; Saha, 1994) were injected from the underplated magma into the overlying crust (Fig. 6.3 h).

In this model proposed by the author it is claimed that the SFB developed without closure of any ocean basin. The basement for the volcano-sedimentary sequence of

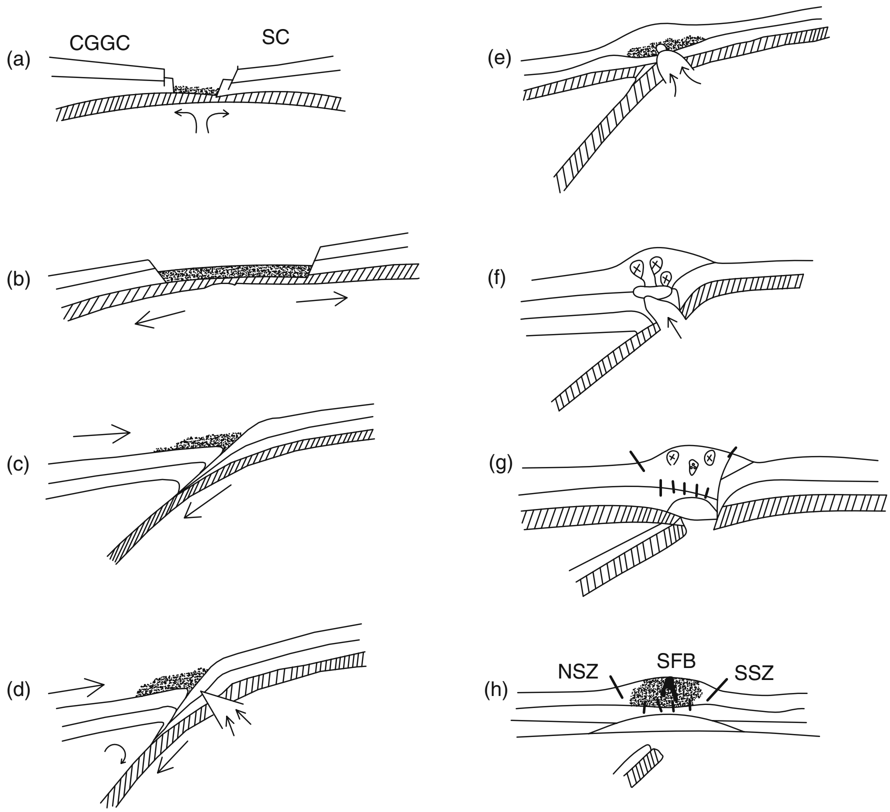

Fig. 6.3 Slab break off evolutionary model for the Singhbhum fold belt, based on available geological-geochronological data. (**a**) Ductile stretching and rifting of Archaean craton (SC+CGGC) in Palaeoproterozoic (ca. 2.1 Ga) and sedimentation of Singhbhum Group. (**b**) Development of ensialic crust and deposition of more sediments with minor tuffs (cf. Dunn and Dey, 1942). (**c**) Start of collision at about 1.6 Ga ago and folding of supracrustal and basement rocks. (**d**) Convergence (perhaps oblique) and subduction of southern block (SC) followed by narrow rifting and slab weakening. (**e**) Slab rupture, underplating and extrusion of mafic magma (Dalma volcanics) amidst sediments of Singhbhum Group. Additional volcano-sediment deposition and high level intrusion of mafic (gabbro-pyroxenite dykes at 1.6 Ga). (**f**) With underplating following slab rupture, mafic magma extruded and intruded. Heat from the underplated magma also induced partial melting within the crust to produce 1.6 Ga old granites (Kuilapal etc.) and granophyre (Arkasani). (**g**) Further slab break off and slab downgoing/sinking generated melt, giving rise to calc-alkaline magma that appeared as volcanics (Chandil) and acid tuff (Ankro area of Chandil) at 1487 ± 34 Ma (Sengupta and Mukhopadhyay, 2000). (**h**) Slab sinks away and melting at depth produced the last phases of granitoid liquid while dykes (Newer Dolerite; Saha, 1994) were injected from the underplate into the overlying crust. Abbreviations: CGGC = Chhotanagpur Granite Gneiss Complex, SC = Singhbhum Craton, SFB = Singhbhum Fold Belt, SSZ = Singhbhum Shear Zone, NSZ = Northern Shear Zone

the Singhbhum belt was evidently continental rock(s) of Archaean age. The Dalma volcanics are the outcome of slab breaking that gave access to the melt produced by decompression. The model rules out the proposition of some authors that the Dalma volcanics represent island arc magma or an ophiolite belt, because the metamorphic rocks are no higher than amphibolite facies in the entire fold belt. The deformed and metamorphosed rocks of the Singhbhum fold belt are bordered on both sides by shear zones against the cratonic blocks, which were rigid mass to squeeze the rocks and elevate them into what we call the Singhbhum fold belt. Several detached granitic bodies, namely the Chakradharpur granite, Arkasani granophyre and soda granite near Kharswan, occur along the shear zone, specially the Singhbhum shear zone. The Soda granite is retrograded into feldspathic schists when it underwent intense deformation.

In the Singhbhum fold belt the metasediments occurring north of Darjin Group and to the west of structural closure of the Dalma rocks are not included, because their metamorphic-deformational history is not yet established. These rocks are known as the *Gangpur Series* or *Gangpur Group* (Mahalik, 1987). The rock-association consists of calcareous, psammopelitic and Mn-metasediments that have been named the Gangpur Series by Krishnan (1937) who, mainly because of easterly plunging antiformal structures, inferred these to be older than the Iron-Ore Series on the south and east. Contrary to this, Banerjee (1968) finds that the eastern plunging folds are inverted towards the core and constitutes a reclined fold, later re-folded in an antiform during Satpura orogeny. Banerji considered the Raghunathpalli conglomerate as the base of the Gangpur Group. The rocks of the Gangpur belt also shows three fold phases (F1–F3), F1 and F2 coaxial while F3 are trending N-S upright folds. The Ekma granite pluton intruding the Gangpur metasediments yielded Rb—Sr whole rock isochron age of 1024 ± 4 Ma (Pandey et al., 1998), setting the upper age limits of the deformation affecting the Gangpur rocks.

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