Earth Sciences
2015; 4(4-1): 1-14
Published online July 27, 2015 (http://www.sciencepublishinggroup.com/j/earth)
doi: 10.11648/j.earth.s.2015040401.11
ISSN: 2328-5974 (Print); ISSN: 2328-5982 (Online)

Archean Metallogeny and Crustal Evolution in the East Indian Shield

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To cite this article:
Tapan Kumar Baidya. Archean Metallogeny and Crustal Evolution in the East Indian Shield. *Earth Sciences*. Special Issue: Archean Metallogeny and Crustal Evolution. Vol. 4, No. 4-1, 2015, pp. 1-14. doi: 10.11648/j.earth.s.2015040401.11

Abstract: *East* Indian Shield bears the evidences of Archean metallogenic and crustal evolution like the other major shield areas of the world. The primordial continental crust in the form of more silicic bodies were floating like metallurgical slags over the hotter and denser ultramafic-mafic lithosphere (UM-ML) before 3800 Ma. Earliest sediments, now represented by the Older Metamorphic Group (OMG) , were deposited in small basins the basement of which was made of UM-ML containing rafts of primitive silicic bodies. Possibly the earliest greenstone rocks (some banded iron formation, associated high-Mg basalts and ultramafics) formed in the OMG with deformation and metamorphism continued upto about 3500 Ma. Partial melting of the lower amphibolitic crust due to underplating and asthenospheric sagging formed the tonalitic magma around 3500 Ma (Older Metamorphic Tonalitic Gneiss or OMTG) and subsequently Singhbhum Granite Type-A (Phase-I and Phase-II) around 3300 Ma both of which intruded the folded and metamorphosed OMG rocks. *The* major event of greenstone belt formation took place during 3500-3200 Ma both in the eastern part and in the western part of the Singhbhum granitic craton. The general trend of these two greenstone belts is NNE-SSW and they were the repositories of the Iron Ore Group (IOG) sediments, volcanics and ultrmafic-mafic rocks. The IOG rocks formed prolific mineralization of Fe,Mn,Cr,Ti,Cu,Ni,Au and platinum group elements(PGE). Multiple phases of tectonism and partial melting of crustal materials ultimately led to the formation of Singhbhun Granite Type-B (Phase-III) around 3100 Ma which later intruded the folded and metamorphosed IOG rocks. *From* 3000 to 2500 Ma cratonization of the East Indian Shield formed the batholitic mass of Singhbhum granitic complex at the central part with the greenstone belts on either side. Around 2500 Ma the Singhbhum craton became tectonically active again with the formation of three mobile belts – Dalma in the north, Dhanjori-Simlipal in the east and Jagannathpur-Malangtoli in the west.The sediments and lavas of these mobile belts are the major resources of Proterozoic Fe, Ti, Au, U, P, Cu, Pb, Mo, W and Ni mineralization.

Keywords: Archean, Metallogeny, Tectonics, East Indian Shield

1. Introduction

The Indian Shield is one of the oldest continental blocks of the earth like those of Australia, South Africa, Canada, Brazil, Greenland, China, Russia and Antarctica. It is further divided into several segments e.g. East Indian Shield, South Indian Shield, Central Indian Shield and West Indian Shield.

The East Indian Shield (EIS) is mainly bounded by 21^0 – 25^0N lat. and 85^0 – 88^0E long. including parts of the states of Bihar,Jharkhand,U.P.,Odisha and West Bengal. Geologically it has three major tectono-metamorphic-cum-lithological domains which are southern greenstone-granite terrain of Singhbhum-Odisha,the northern granulite-gneiss terrain of Chhotanagpur and the Singhbhum orogenic belt or the Dalma mobile belt between these two. Fig.1 shows the geological map of the EIS. It is worthmentioning that only from the southern greenstone-granite terrain undoubted Archean rocks have been reported till date. Over 150 years numerous earth scientists have investigated this greenstone-granite terrain with their different views on petrology,structure,economic geology etc.,but comprehensive idea on Archean metallogeny and crustal evolution is yet to come out.

Ball[1] geologically mapped a large area of Purulia district in West Bengal and Singhbhum district in Jharkhand, and reported some gold,copper and lead deposits. Bose[2] discovered the Gorumahisani iron ore deposits which ultimately led to the establishment of Tata Iron and Steel Company(TISCO) at Jamshedpur in the year 1911. Jones[3] on behalf of the Geological Survey of India mapped the major part of the Singhbhum district of Jharkhand and adjacent Gangpur area of Sundargarh district, Odisha. Dunn[4] and Dunn and Dey[5] geologically mapped almost all the units of the greenstone-granite terrain giving the characters of the economic mineral deposits and have attempted to correlate the lithounits stratigraphically. Correlation of the greenstone rocks with the granitic rocks through different aspects of petrology,structure,geochronology and economic geology was done by Sarkar and Saha[6,7,8], Saha et.al.[9] , Saha[10] , Sarkar et.al.[11,12], Banerji [13,14], Prasada Rao et.al.[15], Iyenger and Alwar[16] ,Mukhopadhyay[17] ,Chakraborty and Majumder[18] and many others. A comprehensive model of Archean metallogeny and crustal evolution of the EIS is presented based on hitherto available data on geochronology,petrology,structure,stratigraphy and economic mineral deposits.

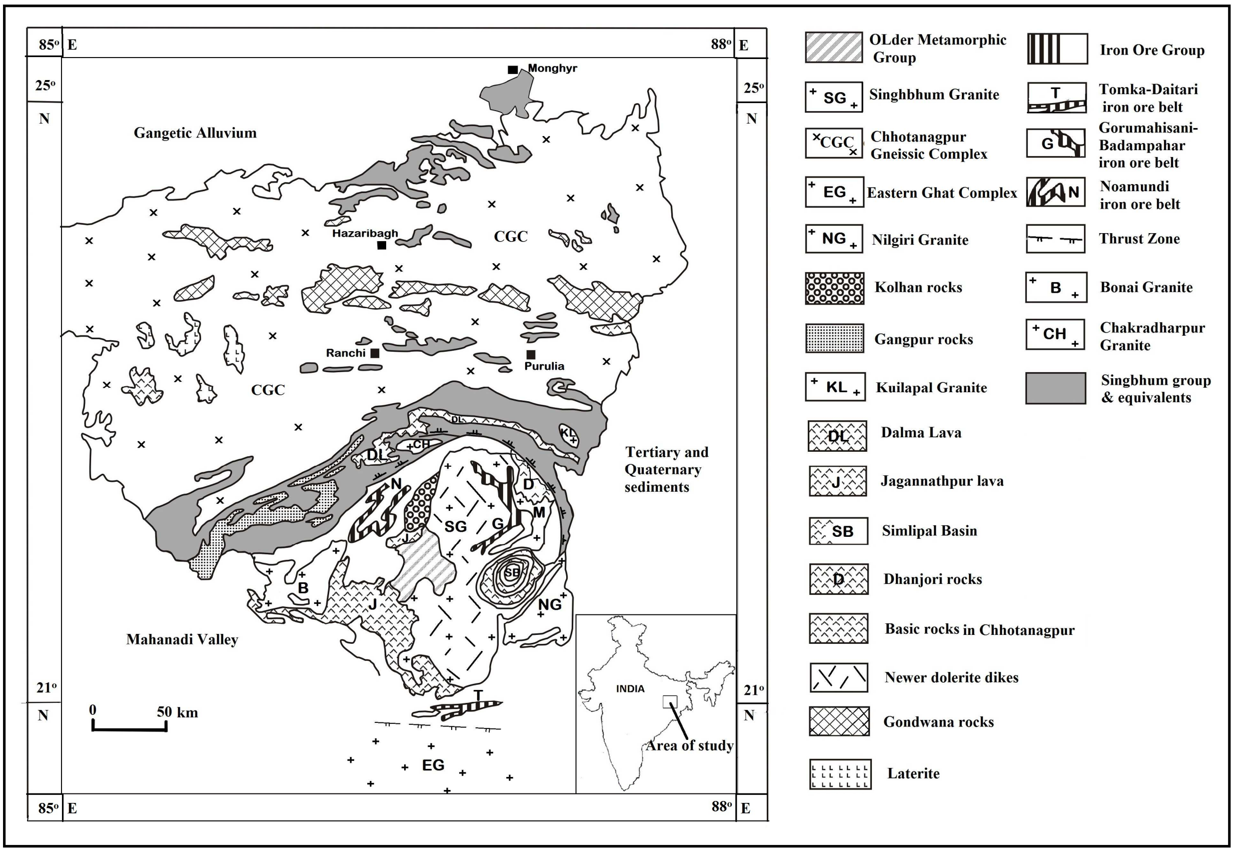

Fig. 1. Geological map of the East Indian Schield.

2. Regional Geology and Stratigraphy

The EIS comprises the following rock types the chronostratigraphic sequence of which may be summarized with important mineral deposits in Table.1.

2.1. Older Metamorphic Group (OMG)

The oldest rocks possibly belong to this group which comprises some metamorphosed pelitic, arenaceous, occasionally calcareous sediments and mafic-ultramafic rocks. The rocks are regionally metamorphosed to amphibolite facies. The meta-sediments are mainly represented by quartz-muscovite-biotite-schist, quartz-sericite-schist, quartzite, quartz-magnetite-gneiss and quartz-magnetite-cummingtonite-schist. The metamorphosed mafic-ultramafic rocks are mainly schistose and banded amphibolites. Saha et.al.[19] based on mineralogy and geochemistry, considered that the schistose amphibolite , hornblende schist and some massive varieties are formed from magmatic rocks (ortho-amphibolite), whereas the banded amphibolites are formed by metamorphism of calc-magnesian sediments (para-amphibolite). The pelitic schists have little higher SiO_2 (65.43%), K_2O (4.62%), K_2O/Na_2O ratio (2.62) and lower TiO_2 (0.46%), CaO (1.17%),

Al_2O_3(15.18%).These metapelitic rocks contain little higher amounts of Cr, Ni, Cu, V and Ga but lower contents of Sr, Li, Y and Zr in comparison with the average metapelitic rock of Shaw [20,21]. The average TiO_2 content in ortho-amphibolite (1.27%) is much higher than that of para-amphibolite (0.16%). The ortho-amphibolites belong to tholeiitic affinity and they have slightly enriched LIL elements like K, Ba and Rb.

2.2. Older Metamorphic Tonalite Gneiss (OMTG)

The OMG rocks are intruded by OMTG compositionally which varies from biotite/hornblende-rich tonalite through trondhjemite to granodiorite and shows structural similarity with the OMG rocks. A prominent gneissic foliation is pervasive in OMTG. Saha et.al.[19] compared OMTG with early Archean tonalities and trondhjemites from different parts of the world and showed that the composition of OMTG in the FeO-MgO-(Na_2O+K_2O) diagram mainly falls in the calc-alkaline field like the field of Amitsoq grey gneiss of Greenland(cf. Barker and Arth[22]). OMTG on average shows abnormally high Mn (0.10%) and Sr (633ppm) but low contents of TiO_2 (0.10%), V (37ppm), Y (13ppm), Zr (203ppm), Ba (225ppm) and Rb (64ppm). It is relatively enriched with LREE with respect to HREE and the La/Yb ratio is 41. Overall REE-geochemistry of OMTG resembles the Archean tonalite diapirs of Barberton, S. Africa (cf. Condie and Hunter,[23]). Saha [10] proposed that OMTG was possibly formed by fractional crystallization of basaltic/ultramafic magma or by partial fusion-cum-contamination of the parent rock like quartz-eclogite/garnet-amphibolite/amphibolite/greywacke. OMTG also contains some small rafts of the possible greenstone rocks including BIF (Misra et.al.,[24]).

Basu et.al.[25] reported Sm/Nd isotopic dating of OMTG as 3775 +/_ 89 Ma, but Moorbath et.al.[26] and Moorbath and Taylor[27] rectified this age to be between 3520 Ma and 3450 Ma.

Table 1. *Chronostaratigraphic sequence of rocks in the East Indian Shield.*

Age	Successions
Tertiary and Quaternary	Laterites with sporadic bauxite, china clay, lateritic type Fe, Mn, Ni – deposits
	Unconformity
Jurrasic Permo-Carboniferous	Rajmahal volcanics and basic intrusives in Chhotanagpur Gondwana sandstones and shales mainly with Permo-Carboniferous coal horizons and fire clay deposits in Chhotanagpur
	Unconformity
2100-800 Ma	Late phase granites and pegmatites of the Chhotanagpur Gneissic Complex with profuse quartz, feldspar, mica mineralization and minor beryl, garnet, topaz, corundum, Li-Nb-Ta-U-Th-REE minerals. Development of Singhbhum Thrust Zone and U-P-Fe-Ti-V-Cu-Ni-Mo-REE-Kyanite-mineralization in the thrust zone involving parts of Singhbhum Group, Dhanjori rocks, Soda granites and Singhbhum Granite. Development of Tamar-Porapahar shear zone and North Purulia shear zone with U-P-Fe-Ti-REE-mineralization in the shear zones and various pegmatitic- hydrothermal beryl, corundum, topaz, lepidolite, quartz, feldspar, muscovite, tourmaline, Nb-Ta-REE-minerals near the contact of the Chhotanagpur Gneissic Complex (CGC) and further north within CGC
2300-900 Ma	Newer Dolerite dykes & sills (in places gabbroic and noritic)
2100 Ma	Kolhan group (sandstones, shales and limestones)
	Unconformity
2500-2100 Ma	Singhbhum orogeny and development of three major mobile belts viz.Dalma, Dhanjori- Simlipal and Jagannathpur-Malangtoli belts. Pelitic and arenaceous metasediments with mafic-ultramafic intrusives and lavas of Singhbhum group, Dhanjori-Simlipal and Jagannathpur groups (major sources of Cu, Ni, Mo, Pb, W, Fe, Ti, V, Au, U, P, REEs and PGEs). Folding and metamorphism in multiple phases.
	Unconformity
3100 Ma	Singhbhum Granite Type-B (SBG-B) Phase-III
3500-3200 Ma	Iron Ore Group (low grade metamorphosed volcanics, tuffs, shale, quartzite, banded iron formation, with iron, manganese ores, ferruginous chert, local dolomite and conglomerate). Typical greenstone belt with volcanism, sedimentation, ultramafic-mafic magmatism. Fe, Mn, Cr, Au, Cu, Ni, PGE-mineralization. Folding, metamorphism and hydrothermal activity in multiple phases.
	Unconformity
	Singhbhum Granite Type-A (SBG-A) Phase- I and Phase-II.
	Folding and metamorphism of OMG and OMTG
	Older Metamorphic Tonalitic Gneiss (OMTG)
4000-3500 Ma	Older Metamorphic Group (OMG) : Pelitic and arenaceous sediments in primitive sedimentary basins and ultramafic-mafic rocks. Now represented as pelitic schists, quartzite, ortho- and para-amphibolites. Possibly earliest greenstone rocks with remnants of banded iron formation (BIF) and metamorphosed mafic-ultramafic rocks.
	basement unknown

2.3. Singhbhum Granite

The Singhbhum Granite batholithic complex is composed of at least 12 separate magmatic bodies which are emplaced in three successive but closely related phases (Saha,[28]) viz. Phase-I and Phase-II i.e. SBG-A and Phase-III as SBG-B. Phase-I rocks vary from K-poor granodiorite to trondhjemite mainly, whereas Phase-II and Phase-III rocks range from granodiorite to adamellite mainly. Saha et.al.[29] observed with increasing differentiation index SBG-A as a whole shows decreasing trends of Ba and Ti , increasing trends of Pb and Pb/K ratio, decreasing Ni/Fe^{2+} ratio, lower values of Ba,Ga, Y, Zr, Mn, Cu, Ni and distinctly higher Cr/Ni ratio, but the Phase-II granite shows increasing trend of Zr and highest values of Cr and Sr of all the three phases. The Phase-III granites characteristically show with increasing differentiation index increasing trend of Ba, decreasing Pb/K ratio, highest values of Ni, Rb, Pb but lowest Co/Ni ratio. The SBG-A granites have gently sloping REE-pattern with slightly depleted HREE and very weakly negative or no Eu-anomaly. Their REE-patterns are similar to those of OMTG (Saha[10]). The SBG-B granites have LREE-enriched fractionated pattern, flat HREE and moderate to strong negative Eu-anomaly.

The SBG-A granites often occur as basement of the IOG rocks, but SBG-B granites distinctly show intrusive relation with the host IOG. Saha [10] from Pb/Pb isotopic ratios found whole rockisochron of 3297+/_41 Ma for SBG Phase-II which shows close similarity of Pb/Pb whole rock isochron age of 3292+/_51 by Moorbath et.al.[26]. The SBG Phase-III, intrusive into IOG, shows Pb/PB whole rock isochron age of 3130+/_28 Ma (Saha[10]) and Rb/Sr isochron age of 3145+/_282 Ma (Paul et.al.,[30]).

2.4. Iron Ore Group (IOG)

The IOG comprises typical greenstone rocks with a thick pile of low grade metamorphosed sediments, volcanics and mafic-ultramafic plutons. The rocks are phyllites, tuffaceous shales/phyllites, manganese ores, BIF (banded hematite jasper/quartzite, banded martite jasper/quartzite, banded magnetite quartzite/jasper) with iron ores, ferruginous quartzite, cherty banded quartzite, local dolomitic rocks and conglomerate, basic to acid volcanics, mafic-ultramafic plutons with titaniferous magnetite and chromite ores, etc. The rocks are localized mainly in the two major NNE-trending greenstone belts and sedimentary basins. The western belt is also called as Jamda-Koira belt (named after two type areas) which comprises the Noamundi basin. At least two phases of isoclinal folding and a later open-type cross fold are discernable in the IOG rocks of this belt. The eastern greenstone belt comprises the IOG rocks of Gorumahisani-Sulaipat-Badampahar and Tomka-Daitari iron ore basins (Fig.1). The trend of the Tomka-Daitari basin (ENE) is little different from that of the Gorumahisani-Sulaipat-Badampahar basin(NNE) due to later deformational effects, but continuity of structures and lithology of these two regions are found in some apparently isolated IOG outcrops in the intervening areas (Banerji[14], Chakraborty and Majumder[31]). Acharya [32] observed at least three major phases of folding in the Tomka-Daitari area , the F_1 and F_3 both having nearly east-west axial planes but F_2 –folds show orthogonal relation to them. The Gorumahisani-Sulaipat-Badampahar part with a general NNE-trend, locally changing to NNW near Gorumahisani, also shows at least two earlier phases of isoclinal folding and a later cross fold . This eastern belt contains rocks like phyllites, tuffaceous shales/phyllites, carbonaceous phyllite, chloritic shale/phyllite, agglomerate, cherty/gritty quartzite, fuchsite-quartzite, grunerite-quartzite, BIF (banded hematite jasper/quartzite, banded magnetite jasper/quartzite) with iron ores, conglomerate, hornblende-schist, amphibolite, talc-tremolite-schist,quartz-chlorite-actinolite-schist, serpentinite various ultramafics and associated chromite ores, gabbro-norite-anorthosite with titaniferous magnetite etc. The basal conglomerate contains pebbles of SBG-A, OMTG and OMG. The present author during recent geological investigation in October,2014, has found that the ore bodies in Gorumahisani mines are co-folded with the associated banded magnetite quartzite/jasper and phyllite having general dip 20^0 -60^0 towards northeast and they are often folded with southeasterly or westerly plunging axes . The ore is mainly composed of magnetite but considerably martitized in places. In Badampahar mines the ore is mainly hematitic(hard, laminated ore) and associated with banded hematite quartzite and phyllite all of which dipping northerly. Mesoscopic folds and puckers have northerly plunging axes. The southeastern wing of the Badampahar range shows a large synclinal structure in the basal quartzite where bands of fuchsite-quartzite and dark grey or nearly black cherty quartzite are also present.Chakraborty and Majumder [31] reported average low values of Al_2O_3 (0.1-1.57%), CaO (0.08-0.38%) and MgO (0.05-0.3%) in the BIFs of the EIS and they suggested absence of extra-basinal clastic materials during deposition. They also found lower values of Cr, Ti and Zr in BIFs but higher values in the associated tuffaceous rocks. The Eu/Sm, La/Yb and La/Ce ratios of the banded magnetite jasper and banded magnetite quartzite have also similarity to the corresponding ratios of the Archean BIF (cf. Fryer[33]). Saha et.al [9] proposed that the IOG rocks should have been formed between the emplacement of SBG-A(3300 Ma) and SBG-B(3100 Ma), but Mukhopadhyay et.al.[34] reported 3506+/_2.3 Ma U-Pb SHRIMP zircon age for dacitic lava of the IOG from Tomka-Daitari area.

2.5. Chhotanagpur Gneissic Complex (CGC)

The CGC in the northern part of the EIS represents granulite-gneiss terrain largely composed of granitic rocks with enclaves of meta-pelites (khondalite, quartz-kyanite-garnet rock,quartz-sillimanite-corundum rock etc.) quartzites, ortho- and para-amphibolites, calc-granulites and recrystallized limestones, gabbro-norite-anorthosite, pyroxene-granulite, charnockite, leptynite, alkali syenite, apatite-magnetite rocks, banded garnetiferous magnetite-ilmenite rocks, numerous pegmatites and pneumatolytic-hydrothermal veins.The ganitic rocks of the CGC were formed in different times and phases with widely varying compositions like tonalite, adamellite, trondhjemite, granodiorite, migmatitic gneiss, biotite-granite gneiss, porphyritic biotite granite, alkali feldspar-rich massive leuco-granite, quartz-diorite, unakite, aplite, pegmatite etc. The CGC was subjected to polyphase tectonism, metamorphism and granitic activity. Ghose [35] considered that in the CGC the early phase granites were sodic varieties like tonalite, quartz-diorite, but the late phase granites were of potassic varieties like porphyritic granites. The late phase basic magmatic activities (dolerite, gabbro, pyroxenite intrusives in the early stage and basaltic volcanics i.e. Rajmahal traps in the much later stage) are also evident in the CGC.

Geochronological work in the CGC is very limited in comparison with the Singhbhum greenstone- granite terrain. Mahadevan [36] from the available data suggested a widespread granitic activity in the CGC in the time span of 1300-1100 Ma and earlier in the 1600-1500 Ma, the charnockites and granulites being older than 1600 Ma. He also suggested that the crystalline basement of the CGC comprising tonalitic gneiss, charnockite, khondalite, granulite and leptynite underwent first phase of metamorphism ca. 2600 Ma. Pandey et.al. [37,38] determined Rb-Sr isotopic ages of some granites intrusive into the high grade metamorphites from Palamau area and Bihar mica belt as 1300-1110 Ma and around 1590 Ma respectively. Dunn [39] and Dunn and Dey [5] based on geological mapping in parts of Chhotanagpur and adjacent Singhbhum areas concluded that the major clastics of the sediments in the north of Dalma volcanic belt were derived from the Chhotanagpur part. This also indicates possibility of Chhotanagpur craton even in the Archean. Baidya and Chakravorty [40] also suggested Archean basement rocks for the high grade meta-sediments of the CGC.

2.6. Other Granite Bodies

The Mayurbhanj granite, Nilgiri granite, Bonai granite, Chakradharpur granite and Kuilapal granite bodies almost surround the Singhbhum Granite batholith and specially petrologically, structurally, geochronologically they are comparable with the Singhbhum granitic complex.

Mayurbhanj granite occurs on the east of the Gorumahisani-Badampahar iron ore belt and is composed of three units (Saha et.al.[41]) : a fine-grained granophyric biotite-hornblende-alkali feldspar granite, a coarse-grained ferrohastingsite-biotite-granite and a biotite-aplogranite. Iyenger et.al.[42] from Rb-Sr isochron , determined the age of Mayurbhanj granophyres as 2084 +/- 70 Ma which also corresponds to the c. 2100 Ma age of Mayurbhanj granite by Saha et.al.[9]. Dunn and Dey [5] considered Mayurbhanj granite to be a part of Singhbhum granite which has also been supported by 3100 Ma Pb-Pb isochron age of Misra et.al. [24].This indicates possibly that the Mayurbhanj granite belongs to part of the Singhbhum granite Phase – III.

Nilgiri granite occurs on the southeast of the Singhbhum granite batholith and it is principally composed of tonalite, granodiorite and granite. The Pb-Pb isochron ages of Nilgiri granite are determined as 3308 Ma, 3292 Ma, 3225 Ma and 3294 Ma, whereas the Sm-Nd isochron ages of the same rocks are 3715 Ma, 3270 Ma, 3290 Ma and 3130 Ma respectively (Saha[10]).Thus petrologically and geochronologically Nilgiri granite is comparable with SBG-A except the first one i.e. 3715 Ma which may be a still older unit.

Bonai granite on the southwest of the Noamundi-Jamda-Koira iron ore belt (Fig.1) comprises mainly porphyritic granite and equigranular granite with numerous tonalitic xenoliths. It occurs mainly at the core of the regional antiform adjacent to the Noamundi synclinorium. Sengupta et.al [43], from Pb-Pb isochron , reported the average age of Bonai granitoids as 3163 +/_ 126 Ma and those of tonalite xenoliths as 3369 +/_ 57 Ma. Saha [10] considers that the younger major part of Bonai granite is comparable with SBG-B, while the older tonalitic and trondhjemitic parts may be synchronous with OMTG or SBG-A. Chakradharpur granite occurs near the northern end of the Noamundi synclinorium and it is mainly composed of two types of granitic rocks- an earlier grey gneiss (trondhjemite) which is more dominant and a later pegmatitic granite (Bandyopadhyay[44,45]). This granitic complex has suffered at least three phases of deformation with two sets of prominent foliation and it encloses numerous blocks and patches of amphibolite, chlorite-schist, talc-schist, rootless bodies of conglomerate and quartzite (Bhaumik and Basu [46]). Saha et.al. [19] proposed that the Chakradharpur granite represents an uplifted Archean basement within the Singhbhum mobile belt.

Kuilapal granite is an elliptically outcropped granitic complex in the eastern part of the Singhbhum mobile belt and north of the Dalma volcanic range (Fig. 1). It is surrounded by the schistose rocks of the Singhbhum Group which shows progressive metamorphic zones with formation of biotite, garnet, staurolite and sillimanite (Ghosh[47]). The gneissic granite range in composition from trondhjemite through granodiorite(dominant), adamellite to granite proper. Sarkar et.al.[11] determined K-Ar age of 1163 Ma from biotite of the Kuilapal granite gneiss which possibly indicates the last metamorphic age. The actual age of emplacement of the granite should be much older.

2.7. Mobile Belts

Towards the end of the Archean three major mobile belts were developed surrounding the Singhbhum granite batholith: Singhbhum Mobile Belt (SMB) or Dalma volcanic belt on the north, Dhanjori-Simlipal Belt (DSB) on the east and Jagannathpur-Malangtoli Belt (JMB) on the west and southwest (Fig.1). Each of these three mobile belts comprises thick pile of volcanics (mainly basaltic lavas) and sediments.

The SMB is the largest one (about 200 km long) and it is characterized by a central volcanic range with Dalma lavas and tuffs which are flanked by Singhbhum Group sediments and some ultramafic-mafic plutons both on the north and on the south. The sediments are generally metamorphosed to greenschist facies forming different types of phyllites, mica-schists and quartzites. The ultramafic-mafic plutons are now transformed to chlorite-schists, chlorite-actinolite-schists, talc-tremolite-schists. Dalma lava varies from komatiitic to tholeiitic types. MgO-content gradually decreases towards the younger flows. SMB occurs between the CGC and the Singhbhum Thrust Zone (STZ). Though the general trend of this mobile belt is east-west but it bears the evidences of at least three phases of tectonic deformation. Cu, Ni, Pb, Au, W, Fe, Ti, V, U, P, REEs are mineralized in different parts of this mobile belt. Some carbonatite and nepheline-syenite bodies have followed the nearly ESE-WNW shear zone near the northern border of this mobile belt.The DSB includes the Dhanjori basin proper in the northern part and the Simlipal basin in the southern part. The general trend of this mobile belt is north-south and both the basins comprise sediments and magmatic rocks. The Dhanjori basin suffered multi-phase tectonic deformation and contains mainly intercalated sediments and basic volcanics. The lower part of Dhanjori lava is komatiitic and the upper part is more tholeiitic. The metavolcanic rocks are chlorite-phyllite, chlorite-biotite-schist, talc-chlorite-schist/-phyllite etc. The sediments are mostly transformed to different quartzites and meta-pelites. The Dhanjori rocks are separated from the Singhbhum Group by the STZ (Fig.1). Dhanjoris are the possible parent rocks for Cu, Ni, Mo, Au, Fe, Ti, V, P, U, REE mineralization in the eastern part of the STZ.

The Simlipal basin attains a lopolithic structure containing intermittent bands of volcanics (mainly spilitic lavas and tuffs) and orthoquartzitic sandstones (Iyenger and Banerjee,[48]). A differentiated tholeiitic sill (Amjori sill) has intruded the Simlipal volcanics and sediments near the centre of the basin. This sill is about 800m thick and contains dunite at the bottom passing upward to peridotite, picrite, gabbro and quartz-diorite. Prospecting for platinum group elements is being carried out in different parts of the Simlipal basin.

The JMB is almost entirely composed of tholeiitic lavas with minor andesitic flows. The lavas are mostly vesicular in character and in places contain pillow structures. Banerjee [49] estimated 25-30 flows. Saha [10] observed that in the east and south JMB overlies the Singhbhum Granite unconformably, but it is faulted against the Noamundi iron ore basin. Near Malangtoli some quartzitic sandstone and conglomerate (Kolhan) overlie the lava sequence with an unconformity.

2.8. Eastern Ghat Rocks

The rocks of the Eastern Ghat do not belong to the East Indian Shield with which the Eastern Ghat blocks shows a thrusted contact (Fig.1). The Eastern Ghat Mobile Belt is extended from Odisha to Andhra Pradesh following a general NE-SW trend. It comprises high grade metamorphic terrain with various rock types like migmatites, granites, leptynite, enderbite, mafic schists and gneisses, granulites, quartzites, calc-silicate gneisses, khondalites, charnokites, gabbro-norite-anorthosite suite, dunite, peridotite, serpentinite with chromite, alkaline rocks, carbonatite etc. This Proterozoic mobile belt suffered polyphase deformation, metamorphism and it was possibly connected with Madagascar, Srilanka and Antarctica (Shaw et. al.[50]).

3. Metallogeny and Crustal Evolution

Mineralisation in association of the Archean greenstones in the East Indian Shield may be classified into the following types:

a. Fe-Mn ores associated with BIFs and phyllites.
b. Chromite ore associated with ultramafics.
c. Titaniferous magnetite ore associated with gabbro-norite-anorthosite.
d. Gold associated with metamorphosed mafic-ultramafics and hydrothermal veins.
e. Platinum group metals, Cu-Ni associated with mafics and ultra-mafics.

The IOG rocks contain the aforesaid five types of ore deposits.

3.1. Fe-Mn Ores

Large resources of sedimentary iron ores in association with BIFs (banded hematite jasper/quartzite, banded magnetite jasper/quartzite) occur in the IOG in the three major iron ore belts on the east, west and south of the Singhbhum granite batholiths (Fig.1). The eastern Gorumahisani-Sulaipat-Badampahar belt and the southern Tomka-Daitari belt possibly belong to the same NNE – trending greenstone belt as continuity of the IOG rocks has been found as intermittent outcrops in the region between these two iron ore belts.

In the western greenstone belt i.e. Noamundi-Jamda-Koira belt rich deposits of iron ore with over 60% Fe occur in Noamundi, Joda, Thakurani hills, Khondband, Kalimati, Barsua, Koira, Kiriburu, Meghataburu, Lutuburu, Pansiraburu, Ghatkui, Bolani, Jamda, Gua and Chiria areas distributed in a regional synclinorium (Noamundi synclinorium) which is isoclinally folded with NNE – plunging axis. The western iron ore belt of this regional syncline is relatively continuous (about 50 km long), but the eastern belt is highly dissected by numerous faults and minor folds. At least two phases of isoclinal folding (F_1 and F_2) and a later open-type cross fold are evident in these iron ore areas. Mineralogically the iron ore is mainly composed of hematite or martite and the silicate band is mainly made of jasper. The following types of iron ores are usually found in the Noamundi-Jamda-Koira belt:

i) Massive ore – Dark brown to steel grey compact hematite with faint trace of bedding. Fe is usually greater than 65%.
ii) Laminated hard ore – Dark brown well bedded or laminated hematitic ore with minimum siliceous band.
iii) Flaky friable ore and relatively soft ore having open spaces in between the laminae and the open spaces usually filled by finely granular dusty hematite with some silica.
iv) Blue dust – This is finely granular or flaky hematite having a metallic blue colour.
v) and almost devoid of silica. It is high grade iron ore.
vi) Lateritic ore composed of hematite and iron hydroxide minerals mainly. It is low grade iron ore (Fe = 50-60%) and usually occurs as thin cover over the higher grade massive or laminated ore.

In all types of iron ores the constituent ore minerals are mainly hematite or martite with variable amounts of goethite and minor amounts of magnetite and siderite. The gangue material is principally composed of cherty silica (in the form of jasper or quartzite), kaolinitic clay and minor amounts of chlorite, quartz, biotite and rutile. Spencer and Percival [51] also found some oolitic grains of hematite in the ores. Jones [3] carried out detailed geological mapping of the iron ore bodies in this western belt, which was later followed by Dunn [52,53] and many other workers from Government and non-Government sectors. Chemical analyses of the ores show negative correlation of Fe with SiO_2, Al_2O_3, TiO_2 and V_2O_5. Positive correlation have been found between TiO_2-V_2O_5, CaO-MgO and K_2O-Na_2O pairs (Saha[10]). P and S contents are in the ranges of trace to 0.5% and 0.002 to 0.018% respectively (Beukes et.al., [54]). TiO_2 varies from 0.005 to 0.61% and V_2O_5 from 0.001 to 0.03%. Al_2O_3 varies from 0.7 to 9.4% and it is highest in the lateritic ores. SiO_2 values ranges from 0.3 to 2%. Contents of Au, W, Ni, Cu, Mo, As, Co and U in the iron ores as determined by ICP-OES are in the ranges of 0.8-1.1 ppm, 1-1.3 ppm, 1.5-3.1 ppm, 1.1-3 ppm, 0.6-3 ppm, 0.5-5.4 ppm, 0.7-1.1 pm and 0.5-0.7 ppm respectively (Beukes et.al [54]).The REE distribution pattern of the partly mineralized , granular iron formation is almost identical to those for Archean and early Paleoproterozoic iron formations as reported by Klein and Beukes [55]. In the Noamundi-Jamda-Koira belt manganese mineralization is a very conspicuous feature in close association with iron ores. Manganese ores occur as massive, thinly laminated or lenticular stratabound bodies hosted by differently coloured (red, pink, yellow, brown, purple, smoky grey etc.) phyllites which are kaolinised in many parts to different degrees. Large deposits of manganese ores are being mined in Bichakundi (near Joda), Khondband, Bamebari, Guruda and Joribar areas in the eastern part of the Noamundi synclinorium. Mineralogically the manganese ores are principally composed of pyrolusute, cryptomelane and manganite i.e. low temperature higher oxides of Mn, but detail ore petrographic study by the present author and coworkers has also revealed presence of earlier high temperature lower oxide minerals like jacobsite, hausmannite, bixbyite, braunite etc. (Ghosh et al. [91]). The major Mn-ore bodies have mainly localized in the axial zones of the F_2 folds. In Khondband and Guruda areas manganese ore bodies are very closely associated with iron ores. The massive Mn-ore bodies show typical colloform structures (often pisolitic and botryoidal). The ore bodies, in places, are co-folded with phyllites forming mesoscopic synforms and antiforms. They are also affected by faults which have caused brecciated ores. Mn-minerals were formed in different phases – syngenetic sedimentary/ exhalative, low-medium grade metamorphic, hydrothermal and lateritic or supergene types. Roy [56] proposed the Mn-ores to be of lateritoid type only and Banerjee [14] concluded that manganese ores formed later than the iron ores. Wad and manganiferous phyllite or chert are also present in many places. Murthy and Ghosh [57] reported pyrolusite-cryptomelane-manganite-rhodochrosite bearing Mn-ores in association with chert and dolomite beds. The MnO content of the ores usually varies between 35 and 45%, but in places high grade Mn-ores containing 50-55% MnO are also present.

The eastern greenstone belt containing Gorumahisani-Badampahar and Tomka-Daitari iron ore deposits is characteristically devoid of significant Mn-mineralization. At least two phases of earlier isoclinal fold and a later cross fold are also evident in the ore bands which are co-folded with the host phyllites and quartzites. Massive, laminated or compositionally banded and brecciated ores are the principal types.The laminated ores often show penecontemporaneous folds and faults. Magnetite, martite, hematite and goethite are the principal ore minerals and the silicate bands are mostly composed of cherty silica (now transformed to finely granular aggregates of quartz). Acharya [32] observed manganiferous shale/phyllite in association with iron ores in Daitari area. Specular hematite (specularite) mainly occur as thin veinlets following the fractures and fissures of the iron ores particularly where they are affected by faults. Majumder et.al., [58] described that the BIFs of the East Indian Sheild contain average (n=10) 47.02% SiO_2, 0.07% Al_2O_3 , 44.16% Fe_2O_3, 8.28% FeO , 0.06% MnO, 0.10% Na_2O, 0.13% K_2O, 0.17% CaO, 0.13% MgO and 0.07% P_2O_5. The sedimentary magnetite contains 5-20 ppm Ba, 4-5 ppm Cr, 10-70 ppm Ti, 20-45 ppm V, 10-20 ppm Cu, 900-1700 ppm Mn, 25-200 ppm Ni and 5-20 ppm Mo. The same magnetite shows total REE content 16.62 with Eu/Sm, La/Yb and La/Ce ratios 1.01, 1.35 and 0.33 respectively (Majumder et.al.,[59]).

3.2. Chromite Ores

Chromite mineralization in association with IOG ultramafics are present in the eastern, southern and western parts of Greenstone-granite terrain. In the eastern part chromite ores occur in Baula, Nuasahi, Bangur areas of Mayurbhanj district, Odisha. In the southern part chromite mineralization is found in Sukinda valley including Kathapal, Kalrangi, Sukrangi, Kaliapani and Saruabil areas of Dhenkanal and Cuttack districts, Odisha. The chromite ores in the above two sectors belong to the eastern greenstone belt. Comparatively the western greenstone belt contains much less amount of chromite ores which are only present in the Jojohatu and Roroburu areas. Banerjee [60] and Singh [61] carried out ore petrographic and geochemical studies of the Jojohatu chromite ores. Mukherjee [62] under the supervision of the present author undertook detail field and laboratory investigations of Jojohatu chromite. The chromite ore bodies are hosted by schistose serpentinite, dunite and websterite which are again closely associated and co-folded with the IOG phyllites and quartzites. The schistosity corresponds to the compositional bands of the chromitite and ultramafics having ENE-strike and 30^o-40^o dip towards southeast. Chromite mineralized zone runs from the Chitang Buru hill on the NNW to Roro hill on the SSE over a length of about 1 km. The host rocks along with the chromite bands also show open type folds plunging low to moderate towards east. Chromite ore bodies are mainly lensoid and banded types. Both cumulate and inter-cumulus chromite are present and they are considerably affected during serpentinization. Sulfide minerals (chalcopyrite, pyrite and chalcocite) are also associated in minor amounts. The ore bands range from 5 m to about 40 m in length and from a few cm to about 5 m in thickness. Cr_2O_3 in the ores varies from 46% to 62%, MgO 4-16%, TiO_2 0.05-0.9%, Fe_2O_3 0.04-8%, FeO 9-27%, Al_2O_3 5-16% and SiO_2 0.5-0.8%.

In the eastern greenstone belt the Sukinda valley ultramafic complex contains chromite ores in association with IOG rocks. The chromiferous ultramafic belt in Sukinda Valley contains almost all types of chromite ores – massive, banded, spotted, powdery, disseminated, both fine and coarsely crystalline brown friable and placer types. The chromite ore bodies are also co-folded with serpentinized dunite-peridotite and websterite. Orthopyroxenite and gabbroic rocks have intruded the altered ultramafics and chromitites. In the southernmost Kathapal area extensive hydrothermal alteration of the ores have produced various Cr-bearing silicates like uvarovite (garnet), kammererite (chlorite), tremolite, chalcedony etc. Rhythmic banding and graded layering are also present in the chromitites (Baidya, [63] , Chakraborty and Baidya,[64]). Banerjee [65] observed a southwesterly plunging regional synform in the Sukinda ultramafic belt including the chromite ore bodies. Basu et.al., (1997) found the occurrence of two metabasaltic rocks – one at the base of the chromiferous ultramafic body and the other at the core of the regional synform. The contact between the ultramafic and the lower metabasalt is highly fractured and brecciated. Chakraborty and Chakraborty [67] described gradation of massive chromitite to thinly laminated variety containing silicate laminae of serpentinized olivine. Mondal et.al.[68] from geochemical studies suggested that the chromitites and associated ultramafics in the Sukinda and Nuasahi massifs crystallized from a low Ti but high Mg siliceous magma or boninite. Sukinda Valley chromite ores contain Cr_2O_3 48-61%, Fe_2O_3 0.05-3.2%, FeO 9.8-12.9%, Al_2O_3 10.6-15%, TiO_2 0.15-0.28%, SiO_2 0.5-0.9% and MgO 11-16%.

The chromite deposits of Baula-Nuasahi area of Mayurbhanj district, Odisha, are also associated with IOG ultramafic-mafic rocks in about 5 km long belt further north-northeast of the Sukinda area. The trend of the same greenstone belt is changed from ENE to nearly north-south in this area. Baidya et.al., [69] identified three major suites of plutonic rocks in this complex – the first suite is composed of interlayered enstatitite, websterite (± olivine), dunite, chromitite, hurzburgite and orthopyroxenite; the second suite comprising gabbro, norite, anorthosite, and bands of titaniferous magnetite; the youngest and third suite represent dykes and sills of dolerite and clinopyroxenite. The chromite ore bodies are hosted by the ultramafics of the first suite. These ultramafics are in many places transformed to serpentinite, talc-serpentine schist, talc-tremolite schist and talc-chlorite schist. The chromite ores are massive, schlieren and spotted types mainly. The ore bands are often co-folded with the host ultramafics. Structural continuity is retained between the adjacent IOG quartzite and the schistose ultramafics. The major chromite ore bodies (bands) are Durga lode, Laxmi lodes -1 and -2, Shankar lode and Ganga lode. The chromitite bands range in thickness from 1.5 m to about 4 m. Massive chromite ores contain 46-63% Cr_2O_3, 1.5-6% Fe_2O_3, 7-30% FeO, 0.12-1.3% TiO_2, 7.2-11.5% Al_2O_3, 1.7-17% MgO and 0.01- 1.77% SiO_2. The Shankar lode near the eastern gabbro-contact is highly brecciated and containing profuse sulfide minerals along with significant concentration of platinum group elements (described later in this paper). Mondal et. al.[70] found that in the massive chromitite blocks of the Shankar lode the chromite is Fe rich ferrianchromite/ferritchromit which possibly formed due to hydrothermal alteration of the original assemblages. The gabbroic matrix material of the Shankar lode in the breccia zone as well as the adjacent gabbroic rock of Nuasahi gave U-Pb zircon ages of 3123 ± 7 Ma and 3119 ± 6 Ma and also yielded whole rock Sm-Nd isochron age of 3205 ± 280 Ma (Augé et.al.[71])

3.3. Titaniferous Magnetite Ores

These orthomagmatic ores are characteristically associated with gabbro-norite-anorthosite suite of rocks which belong to a part of the eastern greenstone belt. Ore deposits are found in Kumhardubi, Betjharan, Dublabera, Baula and Nuasahi areas in parts of Jharkhand and Odisha. Baidya [72] observed good petrological and structural similarity of the magnetite bodies of Betjharan, Kumhardubi, Dublabera areas with the greenstone rocks of the Gorumahisani IOG. Ore bodies occur as lenses, veins and massive bands. In Kumhardubi the rock types are gabbro, granodiorite, granite and dolerite. Magnetite occurs as coarse crystals within gabbroic host which is crudely foliated having NNE-SSW strike and 56^o dip southeasterly. In Betjharan the major rock types are gabbro and anorthosite which have NE-SW strike and 61^o-67^o dip towards SE.

In Dublabera area magnetite bodies are hosted by gabbroic rocks in close association with granite-gneiss which is again transgressed by some small gabbro and dolerite dykes. Besides pyroxene, feldspar and magnetite these gabbroic rocks also contain minor amounts of pyrhotite, pyrite, chalcocite and covellite.

In Baula and Nuasahi areas titaniferous magnetite bodies occur as subparallel bands within gabbroic rock in the northeastern part of the Nuasahi chromiferous ultramafic complex. The magnetite bands generally ranges from a metre to about 20 m. The strike of the magnetite bands is NW-SE and they dip around 70^o northeasterly. Dunn [52], Roy [73], Dasgupta [74] and Banerjee [75] reported significant concentration of vanadium in these titaniferous magnetite ores. The Kumhardubi magnetite contains 80.13-90.21% ($FeO+Fe_2O_3$), 5.76-12.85% TiO_2 and 1.18-1.71% V_2O_5 as reported by Banerjee [75] from EPM analysis. Mineralogical studies by Baidya [72] have revealed presence of magnetite, ilmenite, hercynite and silicates like pyroxene, plagioclase, amphibole, biotite as major minerals, with minor to trace amounts of quartz, chlorite, apatite, sphene, zircon, rutile, hematite, chalcopyrite, pyrrhotite and pyrite. The magnetite ores contain 32.75-52.85% ($FeO+ Fe_2O_3$), 3.02-4.04% (Al_2O_3), 1.33-2.33% (SiO_2), 10.35-25.74% (TiO_2), 0.148-0.208% (V_2O_5), 0.01-0.13% (P_2O_5) and 0.57-1.51% (MgO). SEM-EDX analysis has also revealed that vanadium, besides in magnetite (0.13-0.66%), is also fixed in the structures of ilmenite (0.09-0.12%) and hercynite (0.01-0.18%) which is very important from metallurgical point of view.

3.4. Gold Mineralization

Gold mineralization is associated with both eastern and western greenstone belts. In the eastern greenstone belt and near Gorumahisani iron ore mines gold mineralization is reported from Kundarkocha and Digarsahi areas of the Singhbhum district, Jharkhand. The gold-quartz veins are associated with IOG rocks like metamorphosed ultramafics and komatiitic rocks (talc-tremolite-schist and talc-chlorite-schist), fuchsite-quartzite, biotite-chlorite-quartzite, BIF, carbonaceous and sulphide-bearing phyllites, mica-schist, metamorphosed calc-magnesian rocks, banded cherts etc. Dunn [52] suggested that the gold-quartz veins are parallel to the sharply folded or kinked monoclinal structure of the associated schists. Baidya [76] observed at least three phases of tectonic deformation. The gold-quartz veins and lenses are mainly localized along the F_2 axial zones. The gold-quartz veins vary from a few mm to nearly 2m in thickness which in general decreases both laterally and at depth. The gold-quartz lodes mostly occur at the contact of nearly black carbonaceous phyllite (footwall) and the green cherty phyllite (hanging wall). The lodes are mostly dark grey/bluish grey in colour where gold occurs as hair-thin veinlets or fine disseminated crystals. Besides gold the associated primary ore minerals are chalcopyrite, pyrrhotite, arsenopyrite, pyrite, sphalerite, sylvanite,bravoite, gersdorffite, enargite and scheelite. The sulphides are minimum in the lodes but abundant in carbonaceous phyllite. In the gold-quartz lodes the gold-content varies mainly between 5 gms and 20 gms per tonne.

In the western greenstone belt and in the southern part of the Noamundi synclinorium gold mineralization occurs as gold-quartz veins hosted by IOG metavolcanics (mainly metatuffs) in Gopur area of Keonjhar district, Odisha. The veins have mainly followed the prominent schistosity of the host rocks having NE-SW strike and dip around 70^o southeasterly. The mineralized zone is about 1.2 km in length (Sahoo et.al.[77]). The gold-quartz lodes contain, besides smoky grey quartz, other minor minerals like pyrite, pyrrhotite and ilmenite. Auriferous quartz veins contain 109-309 ppb gold whereas the gossan samples have 245-400 ppb gold. However, the official report of the Directorate of Mining and Geology, Government of Odisha, in the year 1996, during prospecting and exploratory drilling has established that the main quartz reef of Gopur area exhibits persistent gold value of 1 gm/tonne and they have also identified a rich auriferous lode of 60 m length in the southern block with gold values varying from 2.5 to 10 gm/tonne in a vein of average 1 cm width. In BH-9 they have found a 2.5 m thick lode with gold value 2.14 gm/tonne and in BH-11 another lode of thickness 1.0 m has gold value 5 gm/tonne.

3.5. Platinum Group Elements and Cu-Ni-Mineralization

In the chromiferous ultramafics of the Baula-Nuasahi area in the eastern greenstone belt occurrence of platinum group elements (PGE) in trace amounts (Pt less than 10 to 40 ppb and Pd less than 4 to 8 ppb) were reported by Page et.al. [78]. Nanda and Patra [79], on behalf of the Geological Survey of India were engaged in prospecting work for PGEs in this belt. The present author and coworkers established the economic prospect for Pt-Au-Ag mineralization in the chromite-sulphide association of the breccia zone in Nuasahi (Das et.al.[80]). Mondal and Baidya [81] reported four platinum group minerals (PGM) viz. Sudburyite (Pd Sb), Michenerite Pd (Bi Te), Palladian melonite (Pd Ni)Te_2 and Irarsite (IrAsS) –Hollingwirthite (RhAsS) from the chromite-sulphide association of this breccia zone. Baidya et.al. [69] also reported 0.2-9.6 ppm Pt, 3.0-11.8 Pd, 0.0003-0.0028 ppm Ir, 0.1-1.3 ppm Au and 2.4-6.7 ppm Ag, 0.05-0.25% Cu and 0.025-0.762% Ni in the brecciated sulphide-rich Shankar chromite lode. Later detail mineralogical, geochemical and petrogenetic works have been done by several workers viz. Mondal et.al. [82], Auge et.al.[83], Mondal et.al.[70], Mondal [84,85], Auge et.al.[86].

Whole rock analysis of the chromite-suphide-rich brecciated ore shows 45 ppm to 2.5% Cu, 160-1834 ppm Ni and 29-195 ppm Co, whereas the adjacent orthopyroxenite at the footwall of the breccia zone gives 110-169 ppm Cu, 540-640 ppm Ni and 71-104 ppm Co (Mondal et.al.[82]).

The lateritic nickel ore deposit (about 150 million tonne) with cut-off grade 0.5% Ni in and around Kansa area of the Sukinda ultramafic belt has formed through prolong weathering of olivine and serpentine of the ultramafics and ultimately precipitated with goethite and Mn-oxides in the limonite profile (Das et.al[85]), Sahoo et.al.[88], Ziauddin et.al.[89]). Nickel is also present in the secondary silicate minerals and iron oxides of the underlying clay-serpentinite (saprolite) zone. Das et.al.[87] show significant concentration of nickel in the constituent minerals of the nickeliferous laterite: Lithiophorite (Average NiO% 12.72), Magnetite (Av. 1.13%), Goethite (0.02-0.84%), Hematite (0.16-1.15%) and chromite (Av. 0.01%).

Fig. 2. presents the schematic diagrams of the crustal evolutionary stages with formation of various ore deposits. Fig. 2A shows the situation before 3800Ma when the East Indian Shield representing one of the oldest continental blocks was principally composed of undifferentiated hot and dense ultramafic-mafic lithosphere over which some primitive silicic bodies were floating like low density metallurgical slags. These primitive silicic slags (PSS) possibly represented the earliest evidences of continental crust.

Around 3800 Ma ago the lithosphere was differentiated into mafic and ultramafic parts (Fig.2B). In the depressed regions of the mafic lithosphere the earliest sedimentary basins were developed where the OMG sediments were deposited. The OMG sediments were derived by reworking of both mafic crust and the PSS. Geochemistry of the OMG sediments also indicates mixed provenance of the clastics both from more silicic continental crust as well as mafic crust. Asthenospheric convection possibly caused sagging of the overlying lithosphere and subsequent formation of the sedimentary basin. The OMG rocks possibly bear the evidence of the earliest greenstones including primordial BIF (Misra et.al., [24]).

Between 3800-3500 Ma with continued viscous drag and sagging (sagduction) of the lithosphere the OMG rocks, PSS and mafic crust, all were subjected to deformation, metamorphism, intense mixing and partial melting giving rise to OMTG tonalite diapirs (Fig.2c). The lower mafic crust was metamorphosed to amphibolites. Large scale granitic activity and cratonization between the span 3500-3200 Ma led ultimately to formation of Singhbhum Granite Phase-I and Phase-II (SBG-A) forming a much thicker continental crust overlying the lower high grade mafic crust (Fig.2D). SBG-A still preserves xenolithic relicts of OMG and OMTG. This was the initial stage (Stage-I of Fig.2D) prior to the formation of greenstone belt sensu stricto. Formation of SBG-A made the upper continental crust sufficiently rigid for rifting, development of the greenstone belts and iron ore

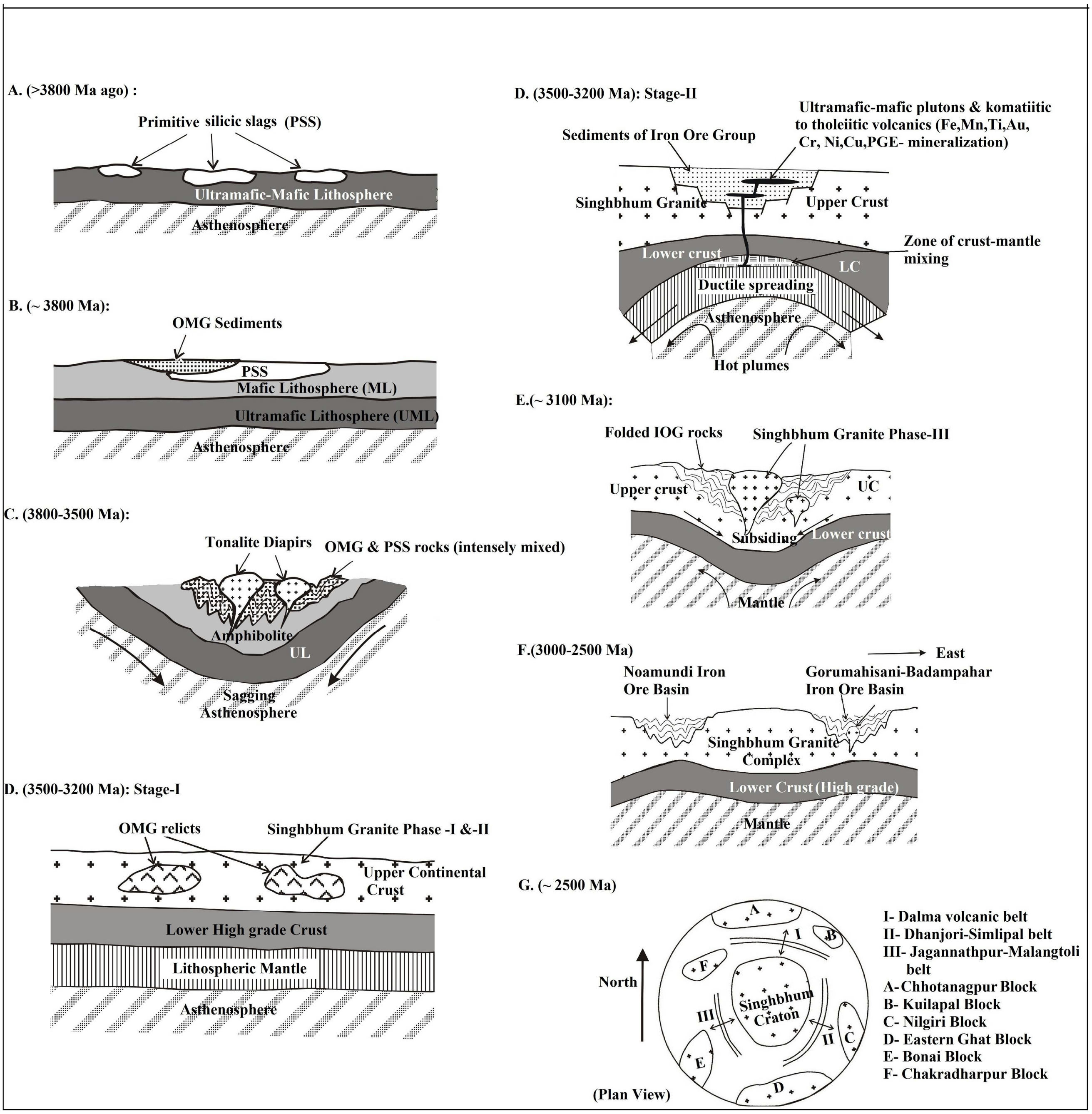

Fig. 2. *Archean tectonic and metallogenic model for the East Indian Shield.*

basins in the subsequent stage. Two major NNE-trending greenstone belts and iron ore basins were formed on the east and west of the Singhbhum granite craton. Ascending hot plumes from the asthenosphere caused ductile spreading in the mantle lithosphere leading to extensional fracturing and rifting in the overlying rigid crust with the formation of greenstone belt and iron ore basin (Stage-II of Fig. 2D). The lavas and the tuffs of the IOG were evolved from the zone of crust-mantle mixing and intimately associated with both continentally derived and volcanogenic sediments. These lavas, sediments and some concomitant mafic-ultramafic plutons ultimately formed the ore deposits of Fe, Mn, Cr, Ti, V, Cu, Ni, Au and PGEs associated with IOG rocks. Iron ore deposits of Gorumahisani, Sulaipat, Badampahar, Tomka-Daitari; Iron-Manganese ore deposits of Joda, Noamundi, Bichakundi, Bamebari, Khondband, Guruda, Joribar, Thakurani hills, Barsua, Koira, Kiriburu, Bolani, Lutuburu, Pansiraburu, Gua, Ghatkui, Chiria etc.; chromite deposits of Sukinda valley (Kathapal, Kalrangi, Sukrangi, Saruabil, Kaliapani areas), Baula, Nuasahi, Jojohatu and Roro buru areas; titaniferous vanadiferous magnetite deposits of Baula, Nuasahi, Kumhardubi, Betjharan, Dublabera areas; Cu-Ni-sulphides and PGE-mineralization in Baula, Nuasahi areas all are with in the IOG rocks and genetically related to these greenstone belts. The present author also considers that gold mineralization in Kundarkocha and Digarsahi areas and the nearby iron ore deposits of the Gorumahisani-Badampahar areas are both genetically related to the same Archean greenstone belt (Baidya [90,76]). The high density basic-ultrabasic volcanic in the rifted crust caused sinking and subsidence of the iron ore basin with deformation and low grade metamorphism of the sediments and volcanic, which continued upto around 3100 Ma. Partial melting of the continental crust during further subsidence of the iron ore basin in depth ultimately produced Singhbhum Granite Phase-III (SBG-B) which intruded the folded greenstone rocks (Fig. 2E) and formed the much thicker granitic crust.

From 3000 Ma to about 2500 Ma deformation, metamorphism of the IOG rocks continued in multiple phases, the tectonic activity in the two grrenstone belts gradually ended with closing of the iron ore basins on the east and west of the Singhbhum granite batholith (Fig. 2F).

Near the Archean-Proterozoic boundary and around 2500 Ma ago the East Indian Shield became tectonically active again with formation of three mobile belts surrounding the Singhbhum granitic craton (Fig. 2G) – Singhbhum mobile belt (SMB) on the north, Dhanjori-Simlipal belt (DSB) on the east and Jagannathpur-Malangtoli belt (JMB) on the west and southwest. The volcanics and sediments of these mobile belts ultimately produced mineralization of Cu, Mo, Ni, Pb, W, Fe, Ti, V, Au, U, P, REEs and PGEs in various parts during early and middle Proterozoic times, the details of which are beyond the scope of this paper.

Acknowledgments

I must thank my beloved students and research scholars, Rupam Ghosh and Riya Mondal for the preparation of diagrams and typescript of this paper. Logistic supports and sincere cooperation of M/S: Orissa Mining Corporation, Ferro-Alloy Corporation, Indian Metals and Ferro-Alloy Corporation, Tata Steel Ltd., Ghanashyam Mishra & Sons Pvt. Ltd., Mineral Exploration Corporation of India during fieldwork of the present author in different times are also gratefully acknowledged. Financial assistance from UGC (New Delhi) and Ministry of Steel, Govt. of India for different research projects of the present author have also supported to the field and laboratory studies.

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