Chapter 8
Summary and conclusion

The district Vizianagram, (A.P) manganese ore deposit in the khondalite–
charnockite terrain of Eastern Ghats Mobile Belt is about 60 km distant from the
Visakhapatnam city. The present study area is bordered by the Srikakulam and
Visakhapatnam districts. The manganese ore bodies are mainly concentrated between the
18° 12' - 18° 30' N latitude and 83° 20' - 83° 45' E longitudes in a linear belt in the study
area along Chipurupalle, Garbham, Garividi, Sadanandapuram and Koduru blocks
(Figure 1.2 and 2.2). The study area falls in Dharwar system of India which is synonium
for the Archaean and represents the oldest Super Group of geological Formations of India
(Fermor, 1909). Metasedimentary manganese deposits of small to moderate size are
widespread in the Eastern Ghats belt that covers a large sector of the east coast of India.
The region is a part of the East Gondwana along with Antarctica and Srilanka where
reassembly of East Gondwana has juxtaposed the EGB against the parts of East
Antarctica between 40° and 70° East Latitude (Yoshida, 1995) configured the region
Dasgupta et al, 1993), the dominant rock type of this belt is the khondalite Group
composed to khondalites senso-stricto pelitic rocks metamorphosed to granulite facies, all
hosting the manganese deposits. The lithology of the study area is represented by
granulite facies of the khondalites which undoubtedly are the host rocks of the
manganese ores in the terrain (Rao, 1954, 1960) and the ores occur primarily with cale-
granulites less often with quartzite and still less with the garnet-sillimanite-gneiss
(Siddiquie and Bhat, 2010). The Calc-silicate-granulites and quartz feldspathic gneisses
host the Mn-silicate carbonate rocks in Kotakara–Garbham area of Vizianagram,
(Mukhopadhyay et al, 2005). The present Mn- silicate, Mn-carbonate and Mn-oxide ores
located in the high grade, pelitic and calc-silicate granulites and garnetiferous quartzites
field work also made it out that the manganese ores in the area occur primarily in
association with Calc-Granulites, less often with other garnet-sillimanite-gneiss and
quartzite members of the khondalite group. The lithology in the present study area are
dominantly mixed metapelites with clear mapable bands of quartzite and calc-granulites and the 2nd group as charnockites mainly the massif types. The most common features of the ores and host rocks are the layered nature, gneissic banding and blasto-bedding boudin structures, concordant or banded ore horizons with discordant secondary ores horizons. The evidences of folds, faults and gneissic banding are in accordance with Dasgupta and Sengupta (1995), Bhattacharya (1997) and Siddiquie (2004). The presence of overturned folds (Figure 2.3) and the ores with the gneissic banding (Figures 3.4a-c) are some evidences from the study area. The occasional blasto bedding structures and metamorphic rhythmic succession of the supracrustal rocks are well preserved in the terrain suggesting the isochemical metamorphism of the khondalites. The shelf carbonates sequence represented by the calc-granulites and presence of rhodochrosite in the primary ores of the study area.

The primary ores of district Vizianagram, (A.P) along with the calc-granulites and other khondalite members have preserved important mineralogical trails in support of the initial sedimentary protolith and the later metamorphism followed by supergene enrichment. The primary manganese ores (metamorphosed or metasedimentary ore) consisting mainly of manganese silicates and minor manganese oxides occur conformably enclosed in the pelitic khondalites, calc-silicate granulite and weathered quartzite. While as the secondary ores bodies of supergene nature are discordant with the host rocks through the terrain. Manganese oxides with variable silicate admixtures constitute the predominant ore characterized by the presence of braunite, vredenburgite, jacobsite, hausmannite and rhodochrosite and with associated pyrolusite, cryptomelane and quartz, apatite etc. The secondary ores are dominantly represented by the supergene mineral assemblage of pyrolusite, cryptomelane, psilomelane, haematite with accessory quartz and apatite etc, revealing the metamorphism of a manganiferous protolith followed by the supergene alteration. Further, manganese carbonate-oxide deposits, with or without silicates, occur as isolated lenses in the oxide deposits. Mn-silicate-carbonate rocks presumably derived from carbonate protolith occur in regionally metamorphosed terrains ranging in grades ranging from greenschist to granulite facies (Dasgupta, 1993; Plimar and Lovering, 1983; Gnos and Peters, 1995, 2006). Metasedimentary deposits occur in high grade granulite terrains in shallow-water shelf regimes (Roy, 1981) which in accordance with the present findings is conclusive for the genesis of the manganese
ores of district Vizianagram, (A.P). Metamorphosed manganese deposits from Koduru and Garbham areas consisting of manganese silicates like bixbyte, braunite, hausmannite, rhodonite, spessartite, hollanidine, jacobsite and vredenburgite as primary manganese oxides and silicates; pyrolusite, cryptomelane, psilomelane, ramsdellite, lithiophorite were also detailed by previous workers (Sivaprakash, 1980; Krishna Rao, 1954a, 1954b, 1960; Rao, 1976; Siddiquie and Bhat, 2010). Generally the present manganese ores of district Vizianagram, (A.P) are inhomogenous with siliceous, aluminous, ferruginous and carbonaceous components indicating a mixed source of the elements and diverse mineral assemblages as deciphered from the bulk ore geochemical and mineralogical characteristics detailed chapters 4 to 6. Econically the primary ore samples are low grade Mn ores with high Si, Al, Fe, P and Ti as compared to the secondary ores which are high in Mn weight percentage but low in Si, Al, Fe and Ti. The ores shows significant variation in chemical composition especially with respect to Si, Mn, Fe and Al among major elements. The Ti, Al and Mg contents are comparable with the respective values in the khondalites. The Si and Al concentration in the host rocks while as that of Mn in the primary ores are the clear geochemical specialization. The precipitation and deposition of Mn with the co-supplied detrital components of Si, Al, Fe, Ti is evident in the study area as seen in correlations Figures 5a. The exogenic trace elements like Cu-Ni-Pb-Zn have positive correlation with Mn is due to their common source. The general enrichment of district Vizianagram manganese ores (A.P) in the elements like Mn and Cu-Ni-Pb-Zn as compared to the back ground of the host rocks with elevated Si, Al, Fe and Ti contents also indicates intense delivery of hydrothermal material into the depositional basin with the co-supplied terrigenous material that led to the formation of the initial Mn rich sedimentary protolith. The high Mn/Fe ratios of the district Vizianagram manganese ores (A.P) is similar to the general Archaean manganese ores and is due to fractionation indicating the longer transport of Mn than Fe and a clear distinction from typical deep marine and hydrothermal. The most probable source of Fe are the ferruginous host rocks of the terrain than the direct hydrothermal source. The ternary diagram of Mn-Fe- (Ni-Cu-Co) ×10 of Bonatti et al (1972) and Crerar et al (1982) as shown in (Figure 5.21) shows the detrital-hydrogenous genesis of the present ores. Positive correlation of Fe with Co and V (Figures 5.10-5.11) are in accordance with hydrogenous environment of Burns and Brown (1972). However in Fe-Si×2-Mn ternary diagram of Toth (1980) the present manganese ores do not fall in typical field of
hydrothermal manganese ores. Si-Al-Fe are positively correlated as shown in Figures 5.17a and 5.17h and were supplied by terrigenous sources as shown in Figure 7.1. The precipitated heterogenous Mn-silicate-carbonate sequence in the shelf zone and the associated sedimentary sequence were subjected to multiple episodes regional metamorphism leading to the formation of primary manganese ores of low grade nature from the Mn rich sedimentary horizons with high Si, Al, Ti and Fe. At this stage the heterogenous manganiferous protolith and the associated sedimentary sequence were transformed into metasedimentary group resulting into the formation of metamorphosed manganese ores (primary ores) and the host khondalites as calc-granulites and Garnet-Sillimanite Gneiss. The granulites grade metamorphism declared in the region is evident in the both the field and hand specimens as well as the optical and XRD results (Figures 4.7-4.9) of the primary ores. The primary ore mineral assemblages in the study area include the diagenetic carbonate like rhodochrosite to high grade ore minerals like spessartite, rhodonite, vredenburgite, haumannite and jacobsite. The abundance of garnet, sillimanite, quartz and apatite and in the host rocks also suggests the high grade metamorphism. The development of the metamorphic ore minerals like vredenburgite, jacobsite and haumannite (Figure 4.6) confirms the high grade metamorphism. The geochemical analysis of thirty ore samples from the six blocks of district Vizianagram, (A.P) shows higher values of Si, Al, Fe, Na, Mg and K in the primary ores while as the higher values of Mn, P, Ca, Ti and Ba are seen in the secondryy ores as shown in table 9 and Figures 5.1-5.5. The distribution pattern of minor elements like K$_2$O, Na$_2$O, MgO, CaO, BaO and TiO$_2$ and P$_2$O$_5$ in Vizianagram manganese ores vary in their concentration within limited range (Tables 10, 11 and 12). The overall ore shows higher concentration of potassium, but average Na$_2$O, CaO, MgO, BaO and TiO$_2$ goes around 1% as seen in table 12. In terms of the major element composition, the primary ores are close to the calc- granulites with reference to Al, Fe and Ti contents. The ores has a mixed source of hydrothermal, oceanic and terrigenous components as evident in the positive correlations of Mn-Ni-Cu-Zn and discrimination plots and ternary plots of Si-Al-Mn (Figures 5), Mn-Al-Fe (Figure 5.12), Mn-Al-Fe (Figure 5.13), Al-Ti (Figure 5.14), Fe-Mn-Si (Figure 5.16). The primary manganese ores are enriched in Si, Fe, Ba, P and Ni, Cu, Co and V in comparison to other manganese ores and are considered as primary metamorphosed ore while as the manganese enriched ores of higher oxides are secondry in nature and are of supergene nature formed from the pre-existing primary or metamorphosed ore was also
worked out by previous workers (Rao, 1976; Roy, 2000; Siddiquie and Raza, 2008; Siddiquie and Bhat, 2010). The original sediments probably contained some amount of phosphorous (Sivaprakash, 1980; Bhattacharya et al, 1984; Siddiquie and Raza, 2008; Siddiquie and Bhat, 2010) and more phosphorous in the form of apatite appears to have been introduced into the manganese ores through granitic and pegmatitic activities (Rao.S.V.G. et al, 1981: Acharya et al, 1990, 1994b; Siddiquie and Bhat, 2010). Manganese ores have evolved in a few important phases of metallogenesis in the region and the manganese ores in district Vizianagram, (A.P) are co-genetic as evident from the collective field evidence and the geochemistry and mineralogical modules of the ores and host rocks. The various conclusive remarks of the present piece of research work are as follows;

The manganese ores of district Vizianagram, (A.P) seems to have evolved in a few important phases of co-precipitation and sedimentation as Mn-rich sediments followed by their diagenesis, regional metamorphism and later supergene enrichment. These phases as evident in the studied mineralogical assemblages of all the types of ores in the study area and the bulk geochemistry and the stratigraphic, structural and tectono-metamorphic evidences in the field. The diagnostic plot and discriminations diagrams seen in Figures 5.10-5.14 and 5.30-5.33 indicate the hydrogenous, shallow-shelf sedimentary-diagenetic genesis of the present manganese ores. The dissolved oceanic Mn was dominantly contributed by remote marine hydrothermal sources and was carried to the shelf zone due to its high solubility and longer transportation as compared to its co-generated Fe counterpart which gets deposited near the vent. The Mn remained in the dissolved state as Mn$^{2+}$ in the oxygenated surface waters of the ocean and in Mn$^{4+}$ in the reduced deep water. The two water columns are demarcated by the redoxcline across which the Mn alternates as Mn$^{2+}$ and Mn$^{4+}$ across the redoxcline for most of its life span till it reaches the sediment surface in the shelf zone where the Mn$^{2+}$ is deposited as MnO$_2$ over the shelf carbonate platform as shown in the hypothetical genetic model in Figure 7.1. The influx of elision, gas and water fluids along a fault zone from the sedimentary sequences of the then sedimentary basin, which resulted in specific physicochemical conditions in the bottom and silt waters; this, in turn, provided conditions for the accumulation of the elements of anoxic environments and retention in the sediments of Mn and trace elements precipitating from hydrothermal plumes. The precipitated MnO$_2$ reacted with the
available Si, Ca, Al and Fe in the system of Mn-rich sediments leading to the formation of earlier Mn-silicate and carbonate protolith. During this stage of Mn mineralization the Si, Al, Ca, Fe, Ba, P and Ti from the terrigenous sources was consumed in the formation of the manganese silicates and carbonates.

The manganese ore mineralogy, geochemistry and the lithological characteristics of the host rocks indicate that the Vizianagram metasediments and the manganese ores of the khondalite Group are clearly a metamorphosed or metasedimentary sequence of manganese ores and host rocks in accordance with (Roy, 1981; Siddiquie, 2004; Siddiquie and Bhat (2008 and 2010) formed from an older sedimentary protolith (Siddiquie, 2004; Siddiquie and Raza, 1990).

The initial manganiferous sedimentary protolith was deposited in a stable shelf environment with a mixed source of Mn dominantly from hydrothermal source with subordinate contribution from terrigenous source as shown in the hypothetical genetic model (Figure 7.1). The ores show sedimentary hydrogenous nature with respect to high Mn and Ba values, positive correlation of Mn with Ba-Co-Ni-Zn in accordance with Nicholson (1986 and, 1992). Ba/Sr values also indicate sedimentary nature in accordance with Fan (1994).

Some deep and remotely generated marine hydrothermal plumes were enriched in Mn, Cu, Ni, Pb and Zn. These elements were carried in solution state by the oceanic water and were delivered to the shelf zone during favourable conditions of their precipitation and deposition. The presence of remote hydrothermal springs supplying Mn and some other elements and generating plumes with elevated contents of these elements in deep waters is obvious.

From the mineral-chemical attributes of the manganese deposits, the author proposed that the oxide ores were formed when anoxic bottom water enriched in Mn$^{12}$ was upwelled on the continental margin and mixed with oxygenated surface water (Figure 7.1). The process initiated most probably in the late Proterozoic in the light of geochronology of the region coupled with the present evidences. The geochronological data on the rocks of Eastern Ghats belt are meager and show a wide scatter. The wide range of dates has been attributed to superposed granulite and amphibolites facies events and the accompanying structural re-working (Mezger and Cosca, 1999; Sengupta et al, 1990 and. 1999). Nevertheless, the available geochronological data clearly point to an
Archaean event during 2.8 and 2.6 Ga, which can be taken as the minimum age of sedimentation of the khondalite Group.

- Manganese carbonates were diagenetically derived from these initial Mn-oxides by reaction with calcareous material in the shelf zone probably under evaporative conditions. Continental weathering acted as a part of possible source for manganese and iron, supplied through acidic surface water and ground water to the depositional palaeo-basin. Relatively high amounts of Si, Al and Ti as well as good correlations between SiO₂ and Al₂O₃ and Al₂O₃ and TiO₂ in the Vizianagram manganese ores may be due to the admixture of detrital material during precipitation as depicted from the discrimination diagram of Choi and Hariya (1992).

- The post depositional regional metamorphism have erased the depositional and sedimentary signatures of the ores as well the host rocks to a greater extent but the geochemical and mineralogical signatures reveal their genesis with the tectonic and other geochemical, atmospheric and basin conditions during their deposition and post depositional stages. Metamorphosed manganese minerals from the study area include developed during the metamorphic stage of the manganese ores include braunite, bixbyite hausmannite, rhodonite, spessartite, hollandite, jacobsite and vredenburgite are in accordance with previous workers (Sivaprakash, 1980; Rao, 1954 and1960; Rao, 1976; Siddique and Bhat, 2010). The elevated contents of Si, Al, Fe and Ti are evident. Featured and elevated concentration of Mn against the background host rocks indicates the formation of manganese rich ore minerals in specific bands with in the earlier combined system of manganiferous sedimentary protolith. The ores have attained the concentration of Mn with the development of the metamorphosed mineral assemblages. It is during this stage of ore formation that Mn-silicates were formed at higher rate instead of the earlier Mn-Carbonates of diagenetic stage which was consumed in the decarbonation process and subsequent genesis of Mn-silicates.

- During the post-metamorphic period, prolonged exposure of the deposit to atmospheric oxygen and meteoturic waters has caused the primary minerals to undergo supergene alteration. Most of the primary manganese oxide minerals are totally obliterated by weathering and supergene processes. The manganese silicates like spessartite are also affected. Under supergene conditions, due to strong oxidation effects, the manganese oxides of lower valency states (primary minerals) were transformed into manganese oxides of higher valency states e.g. pyrolusite, cryptomelane and
romanechite. Development of cryptomelane/romanechite and goethite from garnet can be cited as an example. During this supergene process, elements such as Mn, Fe, P, Al and Ti are enriched and Mg, Ca and Si are leached from primary manganese minerals. During the supergene process, elements such as Mn, Fe, P, Al and Ti are enriched and Mg, Ca and Si are leached from primary manganese minerals. The economically important Vizianagram manganese ore deposits were formed by oxidation of pre-existing metamorphosed Mn-oxide (with Mn$^{2+}$ and Mn$^{3+}$) and Mn-silicate rocks (Roy, 1981). The evidence in favour of the weathering and alterations in the studied manganese ore deposit is the laterite area characteristically concentrated in the upper zone and manganese in the lower zone of the weathered profile (Figure 2.3f). The rocks most amenable to supergene concentration of manganese in the weathering zone are Mn-rich carbonates followed closely by Mn-silicate-carbonates. Manganese silicate carbonate admixtures were produced as a consequence of influx of detritus and hydrogenous constituents during sedimentation. Mn oxides are either formed in situ by oxidation of the carbonates ore through dissolution, limited vertical and lateral migration and re-precipitation (Roy, 1981).

- The mineralogical and chemical characteristics observed in these rocks reflect heterogeneity in the metapelite composition and indicate more than one source for the parent sediments, predominantly basic in nature. Geochemical characteristics of the host rocks suggest that the provenance for these rocks was a mixed source of basic rocks and tonalite/trondhjemite probably the Archaean crust. Geochemical characteristics of the host rocks shows that the provenance for these host rocks of the manganese ores was a mixed source of basic rocks and tonalite/trondhjemite, probably the Archaean crust (Raju and Rao, 2001).

- The premetamorphic sedimentary protolith package of pelites, arenite and carbonate is indicative of their formation in a stable shelf milieu. The khondalites are were most probabl deposited in PCM environment with iron rich shale-greywacke-arkose sequence as the source rock with some due contribution from tonalitic crust and granitic intrusion in the Archean crust as indicated by the binary plots and ternary diagrams for the present khondalites and charnockites (Figures 6.8-6.19).