

CHAPTER 6

DISCUSSION AND CONCLUSIONS

The focus of this study was to define a possible protolith succession for the host rocks to the manganiferous metasediments at Serra do Navio. It was also the aim to provide a depositional model for the succession and determine the extent of metamorphism. Because several features may have to be taken into account to deduce a genetic model, this chapter will summarize the results of previous chapters and integrate them to build a comprehensive model.

6.1 Possible protolith succession

Petrographic and whole rock geochemical studies identified five main lithologies present at Serra do Navio. These are, stratigraphically from bottom to top: biotite schist, graphite schist, Mn-carbonate schist, Mn-calcite marble and rhodochrosite marble. The preservation of compositional lamination and consistent lithostratigraphic succession between the drill cores clearly illustrate that these rocks formed from the metamorphism of a sedimentary protolith succession.

It is suggested that biotite schist derived from either pelitic a sediment, greywacke or pyroclastic rocks. The well-preserved compositional banding reveals that the protolith was heterogeneous in composition. The whole rock geochemistry of biotite schist is marked by elevated SiO_2 , TiO_2 , Al_2O_3 , Zr, Sc concentrations and ΣREE . This is typical of siliclastic sediments including deep-sea turbidities and greywackes (McLennan et al., 1990).

Graphite schist occurs in laterally discontinuous units across the three drill cores (Fig. 6.1). It is geochemically identical to biotite schist, but petrographically distinguished by the presence of graphite. Scarpelli (1973) proposed two possible modes of origin to explain the presence of graphite, (1) decomposition of carbonates during metamorphism,

and (2) the metamorphism of organic material. However, the former explanation does not hold, as carbonate minerals are abundant in rocks that are Mn-rich but devoid of graphite, whereas graphite abounds in Mn-poor lithologies that are very similar in composition to biotite schists. This suggests that the presence of graphite is associated with primary deposition of organic material rather than attributable to metamorphism of carbonates. Hence graphite schist is thought to have formed at the expense of an organic rich pelitic protolith, most probably carbonaceous shale.

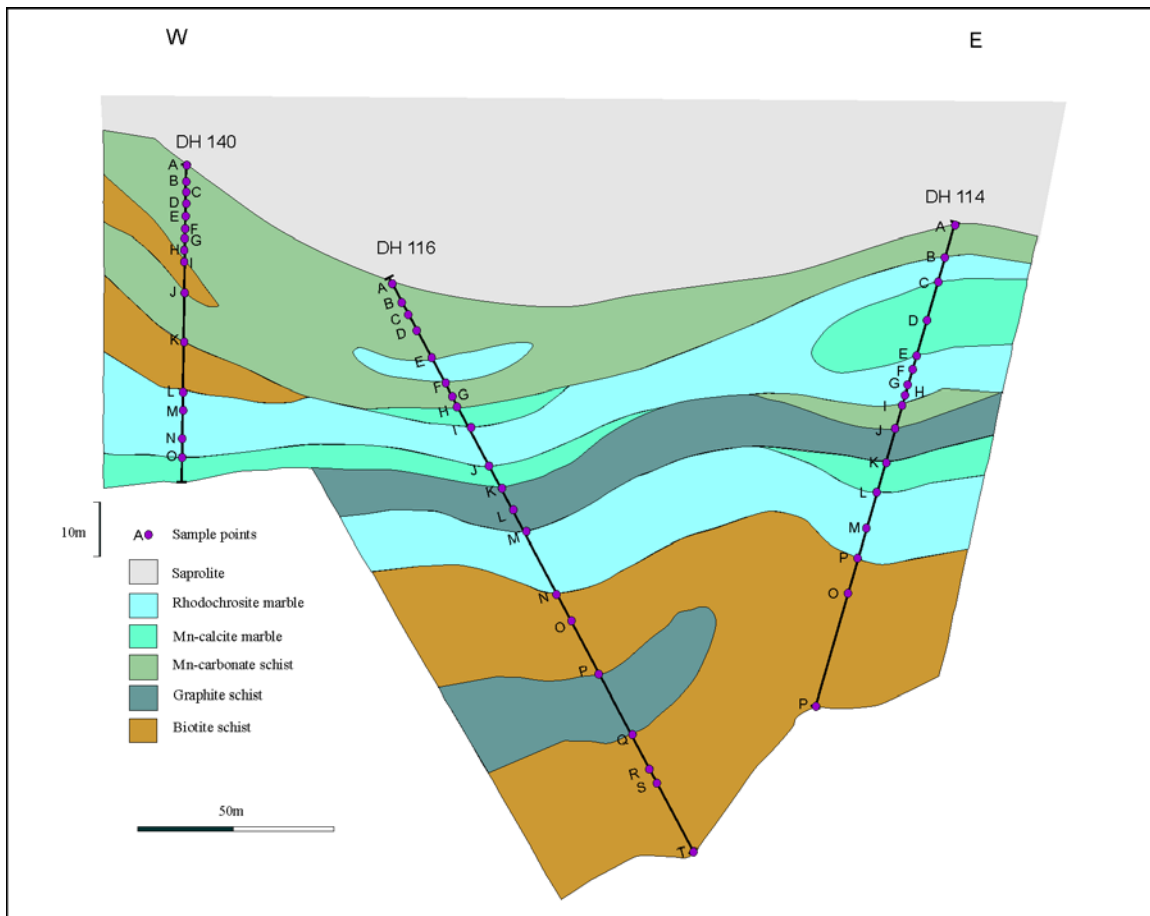


Fig.6.1: Profile across the three drill cores at the Serra do Navio deposit

Sub-equal proportions of carbonate and SiO_2 characterize the Mn-carbonate schist, which is regarded as a lithology that is transitional between Mn-carbonate rocks and siliciclastic rocks. This lithology defines laterally continuous units across the three boreholes though discontinuous units may be present (Fig. 6.1). A metamorphic mineral assemblage of

tephroite, rhodonite, spessartine and carbonate minerals (rhodochrosite and Mn-calcite) characterizes this lithology. The geochemistry reflects enrichment in MnO and SiO₂ with only very minor Al₂O₃, TiO₂, Zr and Sc. Tephroite, rhodonite and spessartine account for the SiO₂ content while the MnO is hosted by Mn-carbonates as well as the aforementioned silicates. Spessartine, as well as minor biotite and chlorite, account for the Al₂O₃ content. The mineral assemblage is interpreted to be derived from a protolith that was a mixture of Mn-carbonates, chert and very minor clay/alumo-silicates. The Mn-carbonate schist, apart from its elevated SiO₂ content is similar to Mn-calcite marble and rhodochrosite marble. This is used to argue that the silica content in the Mn-carbonate schist derived from chert rather than siliciclastic influx, and a manganiferous chert is identified as the most likely protolith.

Abundance of Mn-calcite as well as Mn-silicates and some minor alumino-silicates (spessartine, biotite, chlorite and amphibole) is characteristic of Mn-calcite marble i.e. it is similar to Mn-carbonate schist but is more enriched in both carbonate and Mn. In the stratigraphic column this lithology occurs as thin laterally discontinuous horizons that are repeated several times in the succession (Fig.6.1). The lithology is regarded to be transitional between Mn-carbonate schist and rhodochrosite marble. The original protolith may have been a manganiferous carbonate rock with minor admixture of clay and chert.

Rhodochrosite marble represents the Mn-rich end member of the depositional environment with alumino-silicate minerals and SiO₂ (chert) virtually absent in a lithology dominated by coarsely recrystallized manganese carbonates. This lithology occurs as two laterally continuous units in all the sampled boreholes and has a gradational contact with Mn-calcite marble (Fig. 6.1). Minor spessartine and chlorite are present, but almost all MnO content can be attributed to rhodochrosite. This is reflected by the whole rock geochemistry that is marked by anomalous high concentrations of MnO and LOI (representing CO₂). Concentrations of Co, Ni, Zn, V and a distinct Ce* anomaly give evidence of efficient scavenging by Mn⁴⁺-oxyhydroxide precipitates. These synsedimentary precipitates were diagenetically transformed into Mn²⁺ carbonates. It is

interesting to note that Al_2O_3 , TiO_2 , Zr and Sc contents, all elements that represent siliciclastic input, are very minor in concentration. Rhodochrosite marble is thus formed originally as Mn^{4+} oxyhydroxide mud, devoid of siliciclastic detritus and chert, but probably rich in organic matter. This assemblage was diagenetically transformed into Mn-carbonate mud rock. Because of its almost monomineralic nature, this lithology became only recrystallized to a marble during metamorphism.

6.2 Depositional model

In order to construct a comprehensive depositional model, the following observations are of particular interest:

- The succession studied in the Mina F12 portion of the Serra do Navio deposit records the transition from siliciclastic (greywacke or shale or pyroclastics) to Mn-carbonate deposition. Mn-carbonate deposition is modulated by the deposition of chert and interrupted by episodic deposition of carbonaceous siliciclastics, most probably carbonaceous shale. Three depositional stages are thus thought to account for the lithostratigraphic succession studied at the Serra do Navio. These are deposition of siliciclastic sediments, deposition of chert + manganese and deposition of organic matter-rich sediments.
- Mn-rich sediments define laterally continuous sedimentary units.
- The chert rich lithologies mark the transition from siliciclastic to chemical deposition but are already dominated by chemical precipitation with only very minor siliciclastic influx.
- There is a notable absence of MnO enrichment in siliciclastic rocks (i.e. siliciclastic deposition and Mn deposition are drastically different) and Mn-rich rocks contain only very minor amounts siliciclastic detritus.
- Mn-carbonate lithologies are marked by negative $\delta^{13}\text{C}$ values and a positive Ce anomaly, strongly suggesting that Mn was deposited as Mn^{4+} oxyhydroxide sediment that was diagenetically transformed into Mn carbonate.

- It appears from the geochemistry that there is a rapid transition between the deposition of siliclastic sediments and chemical precipitation (chert and manganese).

Based on the above observations, a metallogenetic model can be proposed based largely on that defined for Phanerozoic shallow-marine deposits (Frakes and Bolton, 1992) and manganese carbonates/manganiferous chert deposits of the Birimian Supergroup in Ghana (Nyame, 1998) that are of similar age and tectonic setting to the Serra do Navio deposit. A depositional environment in tectonically active back arc or intra arc basin may be suggested for the Serra do Navio deposit, analogous to the Nsuta deposit in the Birimian Supergroup in Ghana (Van Bart, 2001). Siliclastic sedimentation may be explained by turbidites and volcanoclastics derived from the exposed island arc, now represented by the Jornal Formation (Fig. 6.2). These siliclastics/volcanoclastics transformed into biotite schists during metamorphism. Transition from siliclastic deposition to Mn-carbonate deposition may be explained by rapid transgression associated with rapidly declining influx of siliclastic detritus and possibly sluggish water circulation. Dysaerobic or anaerobic conditions developed in deeper water environments, allowing remobilization of Mn from sediments or transport of hydrothermal Mn from the deeper water column onto the shelf. Wherever Mn-rich deep, upwelling water mixed with oxygenated water Mn precipitation could take place (Fig.6.2). In the absence of siliclastic detritus, Mn was effectively concentrated. Chert precipitation appears to be associated locally with the deposition of Mn-carbonates. This may be tentatively attributed to mixing of silica saturated water masses of different temperature, pH and salinity.

Manganese was precipitated as Mn^{4+} oxyhydroxides that were diagenetically transformed into Mn-carbonates. Negative $\delta^{13}C$ values of these Mn-carbonates indicate that organic carbon was deposited with the original metalliferous precipitate. The organic carbon acted as a reducing agent to form Mn^{2+} carbonates, which incorporated carbonate from both organic carbon and inorganic carbon present in pore water solutions in dysaerobic diagenetic conditions (Okita et al., 1988). The formation of Mn-carbonate from

diagenetic transformation of Mn-oxyhydroxides is supported by positive Ce anomalies recorded for the Mn-carbonate rocks.

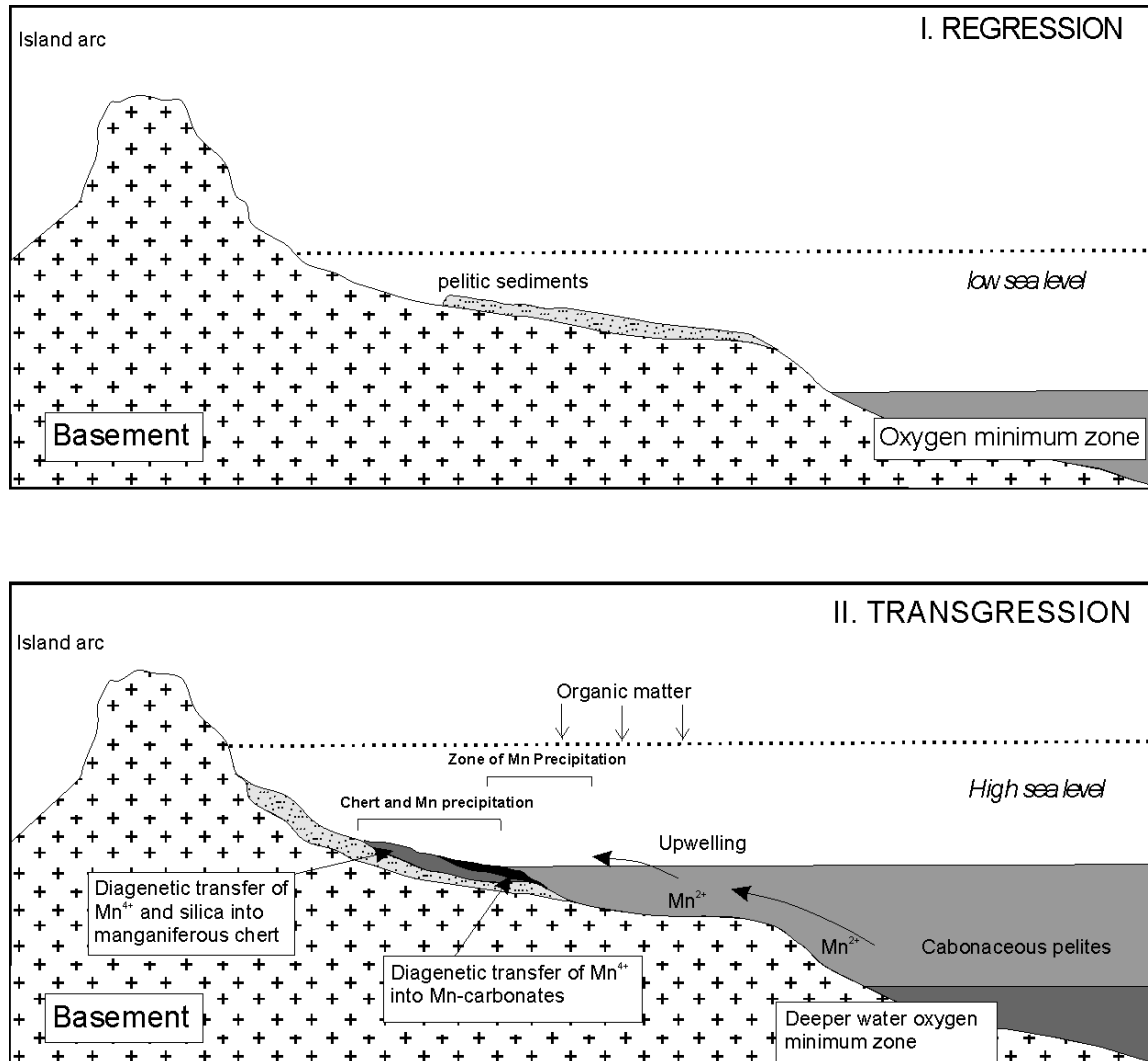


Fig. 6.2: Idealized depositional model of the host rock succession at Serra do Navio. Pelitic sediments are deposited first, followed by chert and Mn, then Mn only. Carbonaceous sediments accumulate in deeper water environments, under dys- to anaerobic conditions. Model based on Frakes and Bolton (1992).

Carbonaceous shale at Serra do Navio forms a very distinct laterally continuous unit (Fig.6.1). Organic matter-rich sediments generally accumulate in the deeper water column where conditions are dys- to anaerobic. Consequently, it is suggested that deposition of carbonaceous shales at Serra do Navio record the deepest depositional environments (Fig.6.2). A similar model that accounts for such a distal, deeper water facies deposition of organic matter-rich sediments has been proposed by Leube et al.

(1990) for chemical and siliciclastic sediments of the Birimian Supergroup. An almost identical model can be applied to the rocks at the Serra do Navio deposit (Fig. 6.3). In this model the siliciclastic/volcaniclastic sediments accumulate proximal around an active volcanic arc (Fig.6.3). Manganese and chert are then deposited on the shelf, where siliciclastic detritus does not reach. The relative position of manganese and chert remains uncertain in this model, but it appears as if manganese would accumulate proximal to organic matter-rich sediments to account for the apparent abundance of organic matter in the Mn-rich precipitates. Carbonaceous sediments accumulate as distal equivalents of the chemical precipitates under dys- to anaerobic deep-water conditions (Fig 6.3).

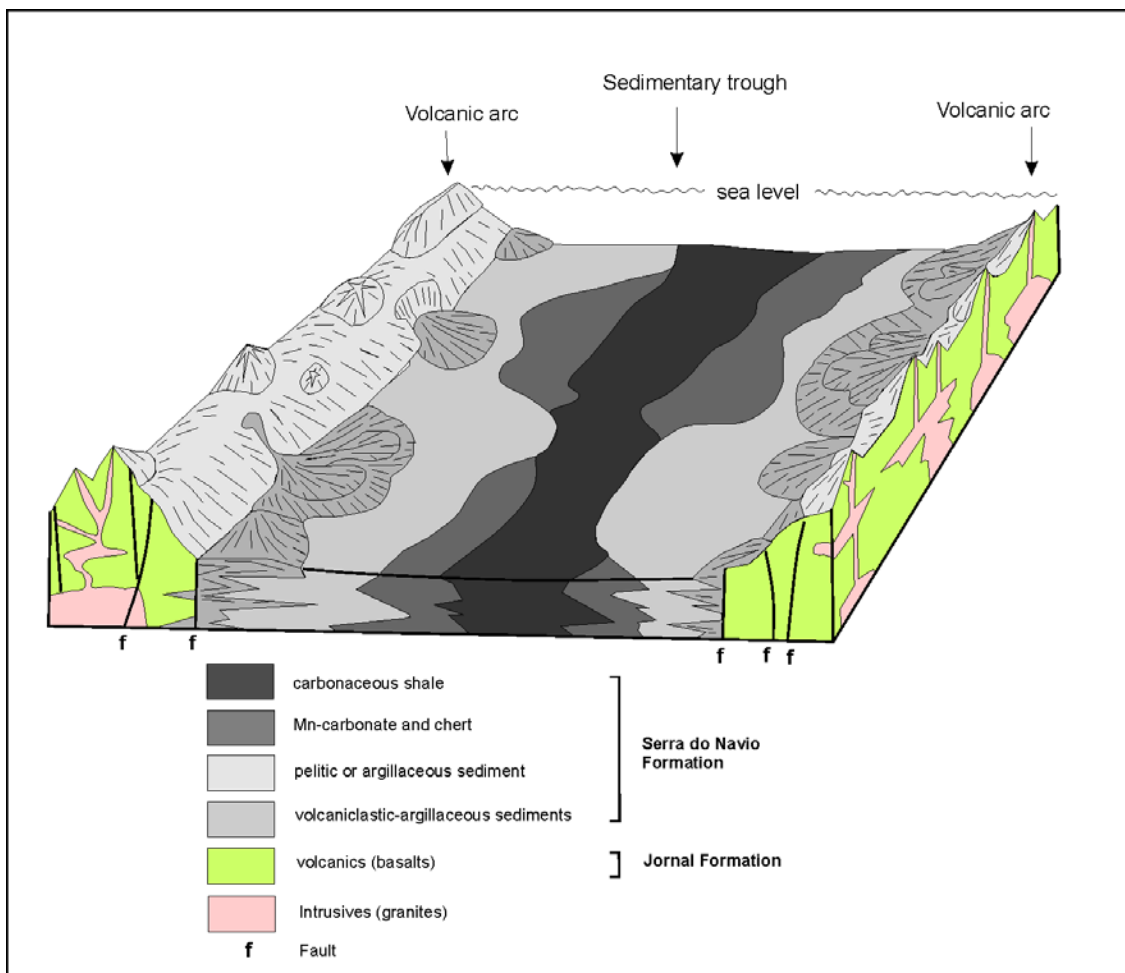


Fig.6.3: Idealized model for the deposition and facies relationships of the rocks at the Serra do Navio deposit. Model modified after Leube et al. (1990).

The depositional model proposed for Serra do Navio does not only correlate well with Mn-carbonate and manganiferous chert deposits of Paleoproterozoic age (Fig. 6.4), but

also aggrESS very well with a genetic model recently proposed for small Mn-carbonate deposits hosted by black cherts of Phanerozoic age (Munteanu et al., 2004).

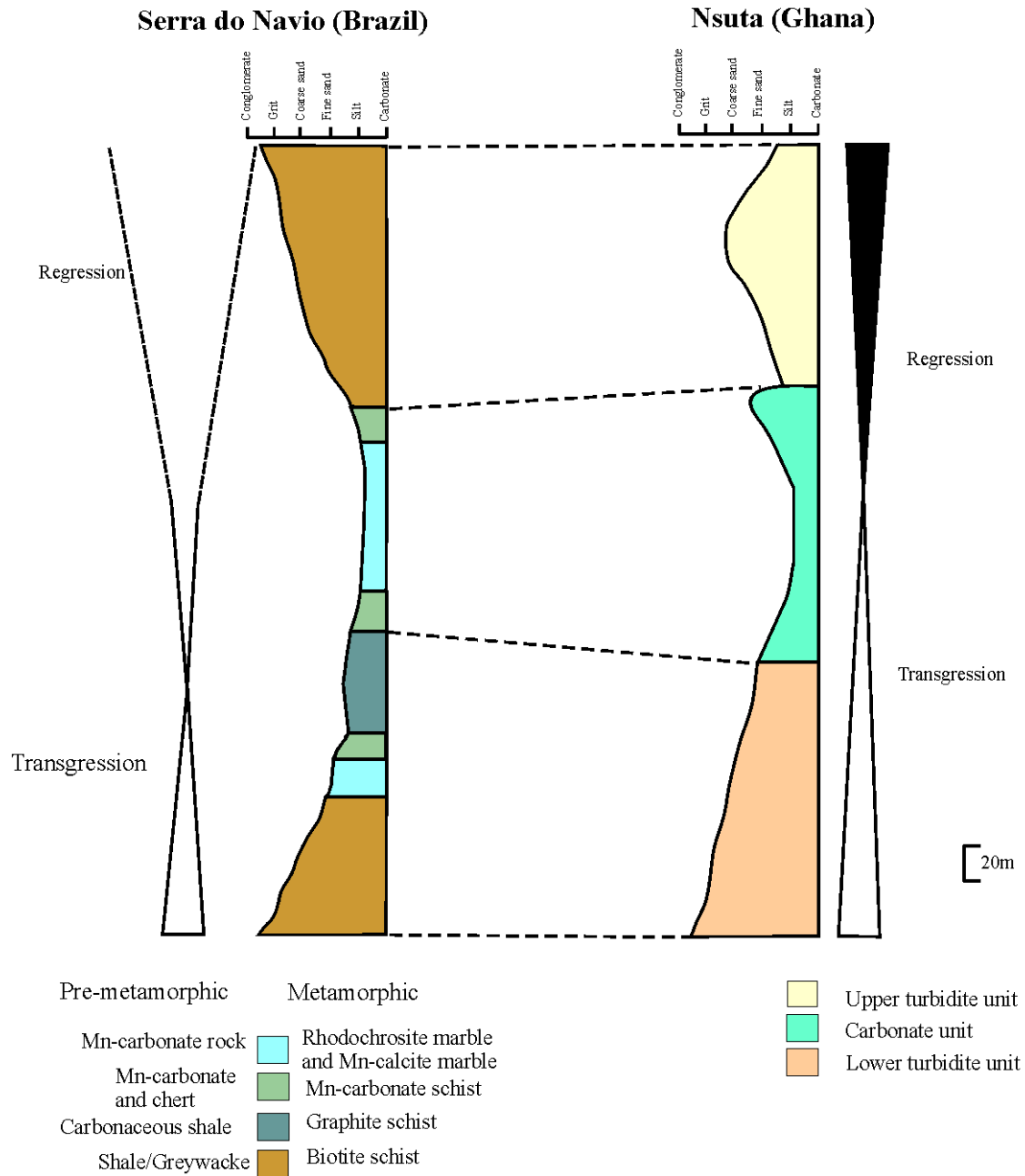


Fig.6.4 Idealized section from the Serra do Navio correlated with a true stratigraphic section from the Nsuta deposit, Ghana (Van Bart, 2001) with an interpretation of predicted sedimentary sequences that constitute the deposits. NB: The regressive sequence at Serra do Navio is left open because it is not known whether siliciclastic sediments are continuous above the carbonates.

6.3 Metamorphism

Scarpelli (1973) has suggested 3 metamorphic phases – an older dynamic metamorphic event followed by thermal metamorphism and a younger dynamic metamorphic event, all of amphibolite grade. The current investigation has largely confirmed observations of Scarpelli (1973) even though lower peak metamorphic conditions are determined.

The first metamorphic event is characterized by development of pervasive foliation in the alumo-silicate rocks as well as recrystallization in the carbonate rocks, indicative of extensive deformation in a compressive tectonic regime. This compression is tentatively associated with complex NW folding during the ca. 1.9 – 2.1 Ga Trans-Amazonian Orogeny (Teixeira et al., 2000). Minor folding and formation of syntectonic spessartine porphyroblasts are also characteristic of this stage of metamorphism that is responsible for the progressive transformation of Mn-carbonate minerals to produce Mn-silicates (rhodonite and tephroite) by decarbonation reactions (see section 3.6). Fluid inclusion studies in spessartine garnets have constrained the P-T conditions at 1 – 2 Kbar and ~ 400 - 500 °C assumed to be representative of peak metamorphism. Amphibolite facies peak metamorphic conditions were suggested by Scarpelli (1973) but the occurrence of CH₄ rich inclusions described in this study from peak metamorphic spessartine seem to favor low – medium grade conditions of metamorphism, possibly of upper greenschist facies.

Retrograde metamorphism is characterized by the development of chlorite at the expense of biotite in the alumo-silicate rocks, and at the expense of spessartine porphyroblasts in Mn-rich lithologies. The replacement of Mn-silicates by a late generation of manganiferous carbonates is also regarded as a retrograde metamorphic effect. Retrograde metamorphic reactions thus indicate the introduction of fluids containing both H₂O and CO₂. These fluids may have been introduced along late fracture-hosted veinlets that are now filled by quartz, chlorite, carbonate and minor sulphides minerals.

6.4 Conclusions

Petrographic, mineralogical and chemical evidence indicate that the host rock succession at Serra do Navio is unequivocally sedimentary in origin. Five lithological types have been identified, namely: biotite schist, graphite schist, Mn-carbonate schist, Mn-calcite marble and rhodochrosite marble. Biotite schist is interpreted to have been derived from pelitic sediment, greywacke or pyroclastic rocks. Graphite schist formed at the expense of an organic-rich pelitic protolith, most probably carbonaceous shale. Mn-carbonate schist is assumed to have been originally manganeseiferous chert whereas Mn-calcite derived from manganeseiferous carbonate rock with minor admixture of clay and chert. Rhodochrosite marble formed originally as Mn⁴⁺ oxyhydroxide mud, devoid of siliciclastic detritus and chert, but probably rich in organic matter. This assemblage was diagenetically transformed into an Mn-carbonate mud rock.

The proposed metallogenetic model postulates that the protolith to biotite schist derived its siliciclastic/volcaniclastic sediments from an island arc. Manganese and chert precipitated in anaerobic deep-water environments in the absence of siliciclastic detritus. Carbonaceous shale accumulated where conditions were dys- to anaerobic in the deepest depositional environments. The metallogenetic model proposed for the Serra do Navio deposit is in excellent agreement with other well-studied Mn-carbonate deposits of Paleoproterozoic age and manganeseiferous chert deposits of Phanerozoic age.

The Serra do Navio deposit has experienced a significant metamorphic overprint of upper greenschist facies. Peak metamorphic conditions are constrained at temperatures of ~ 400 - 500°C and pressures of 1 – 2 kbars.