Chapter 6

Genesis and Geotectonic History

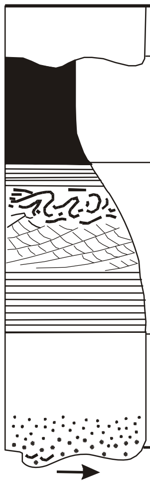
6.1 Depositional Environment of the Lower and Upper Sedimentary Units

The greywacke succession of the lower and upper sedimentary units was most probably deposited by turbidites as indicated by normal graded beds with sharp erosional bases, the presence of Bouma cycles, sole marks, soft sediment deformation structures and rip-up clasts *(Walker and Mutti, 1973; Prothero and Schwab, 1996).*

Turbidites in general are regarded as deep-water deposits associated with submarine fan complexes. However, Walker *(1992)* suggests that the turbidity current *process* can take place at any depth, but for the deposit to be preserved as a turbidite, it must not be reworked by later current or wave action. This probably implies minimum water depths of 250-300m (i.e. below storm wave base) *(Walker, 1992).*

Each turbidity flow represents a "catastrophic" event resulting from either tectonic movement and/or sediment slumping. Failure of large sediment accumulations in shallow water is one of the most important prerequisites for turbidity currents *(Einsele, 1991).* It is important to note that the presence and degree of grading in a turbidite bed is strongly controlled by the availability of a range of grain sizes. Well-sorted material in the source area does not contribute to distinctly graded beds *(Einsele, 1991).*

Turbidity currents are commonly referred to as “density currents” that move downslope on the ocean floor, driven by gravity that acts on the density difference between the current and the surrounding sea water *(Walker, 1992).* According to Edwards *(1993)* turbidity currents are density flows where grain suspension is mainly supported by the upward component of fluid turbulence. Bouma *(1962)* recognised that turbidite sequences consist of a “deposition type” of five “intervals” nowadays commonly referred to as the Bouma cycle (Fig. 6.1).



GRAIN SIZE	BOUMA (1962) DIVISIONS	INTERPRETATION	LITHOFACIES AT NSUTA
Mud	E Laminated to homogenous mud	Deposition from low-density tail of turbidity current ~ settling of pelagic or hemipelagic particles	Massive siltstone, sometimes finely laminated with very fine sand.
Silt	D Upper mud/silt laminae	Shear sorting of grains & flocs	
Sand	C Ripples, climbing ripples, wavy or convolute laminae	Lower part of flow regime	
	B Plane laminae	Upper flow regime plane bed	Fine to medium sand, poorly sorted, greywacke
Coarse sand	A Structureless or graded sand to granule	Rapid deposition with no traction transport, possible quick (liquefied) bed	Very coarse to coarse-grained greywacke

Figure 6.1. The Bouma cycle after Edwards (1993).

The turbidite beds at Nsuta commonly display incomplete Bouma cycles (Fig 6.2) with only Bouma divisions "A", "B" and "E" present. Most of the thicker turbidite beds at Nsuta commence with a sharp basal contact that often contains rip-up clasts and flame structures originating from division “E” of the previous cycle. The basal division “A” of a cycle is medium to coarse-grained and massive, and grades up into a finer parallel-laminated division “B” (Fig. 6.2). Deposited on top of division "B" is a structureless/laminated siltstone that defines division “E” (Fig 6.2).

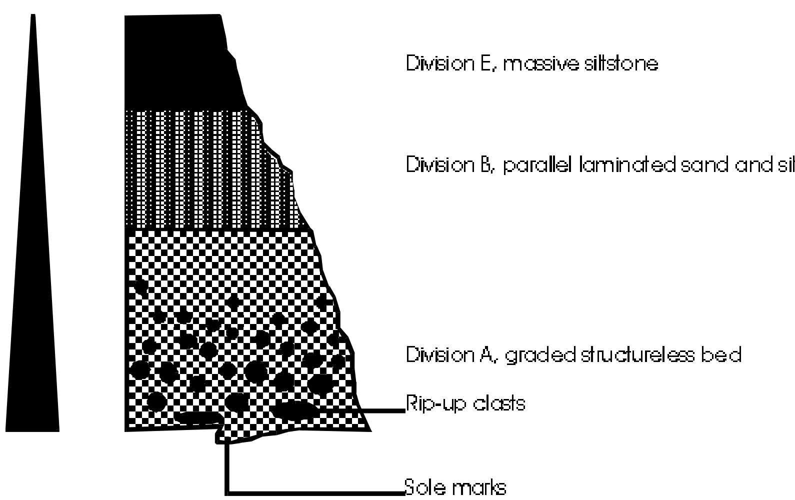


Figure 6.2.Typical Bouma cycle at Nsuta. Only divisions A, B, and E are developed. Note rip-up clasts at the base of "A". These clasts are derived from the "E" division of the immediately underlying turbidite flow.

The deposition of the siliciclastic succession hosting the manganese carbonate orebody at Nsuta is attributed to a mid- to lower submarine fan environment, based on the following observations:

- Interlayering of medium- to coarse-grained and fine-grained sediments in upward-fining cycles on various scales. This is a feature typical of turbidite sequences deposited in middle submarine fan environments *(Walker and Mutti, 1973; Walker, 1978; Prothero and Schwab, 1996)* (Fig. 6.3).

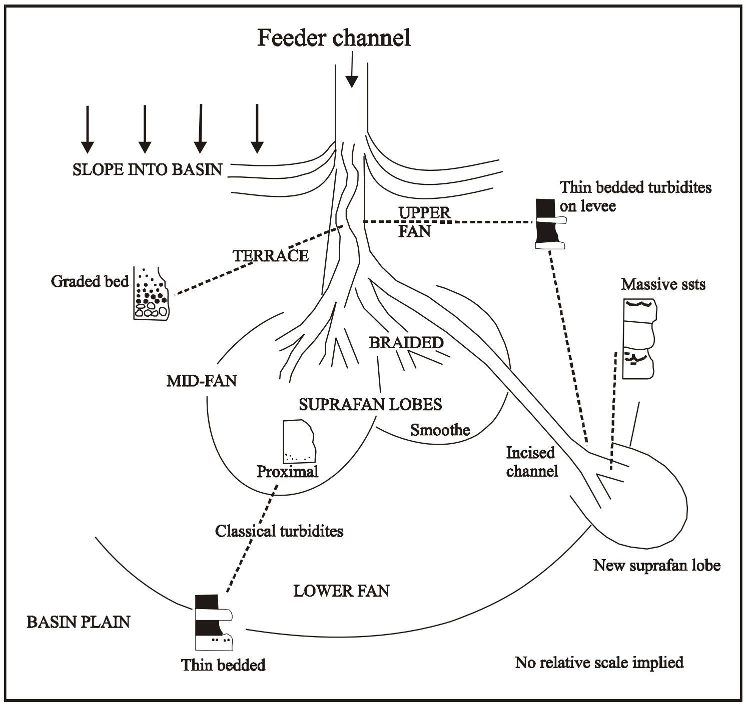


Figure 6.3. Model for sedimentation of Nsuta turbidite succession in a submarine fan (modified after Walker, (1978)). Mid fan and lower fan environments predominate at Nsuta. An incised channel was observed at Hill D north (BH4756) and has associated levee and overbank deposits. The carbonate unit would have been deposited in the lower fan environment. The majority of turbidite flows at Nsuta occur on the interface of the mid- and lower fan, and are classified as "classical" turbidites.

- The turbidites consist mainly of medium- to coarse-grained greywackes grading into siltstone or phyllite, with Bouma units A, B, and E present. The beds can thus be classified as being composed of "classic" Bouma cycles according to the classification of Walker *(1992).* Such Bouma cycles typically occur between mid and lower submarine fan environments (Fig. 6.3) *(Walker, 1992)*.

- Two distinct types of turbidity flows are present in the Nsuta succession. The first type consists of coarse sand particles (greywacke) grading up into a silty unit (siltstone) and display erosive lower contacts, with rip-up clasts and flame structures. In contrast, the second type consists of thinner cycles composed of fine/very fine sand and silt and do not show an erosive lower contact. Einsele *(1991) and* Walker *(1992)* ascribe these two distinct styles of deposition to high- and low- density turbidity currents. High-density turbidity currents (represented by the first type) can reach high velocities and carry relatively coarse-grained sand, pebbles, and intraclasts. The turbulent nature of such turbidites causes erosion of sea floor sediments over extensive areas. Low-density turbidity currents represented by the second type of beds, can only keep silt and clay particles in suspension because of their low flow velocities, and as a result have a very poor erosional capacity.
- A thick, massive greywacke deposit identified in the upper turbidite unit in drill-core 4756 (Fig. 6.4) is interpreted as a turbidite fan channel deposit in the mid to lower fan environment. Walker (1992) suggests that such thick amalgamated turbidite beds (Bouma cycles) are commonly associated with turbidite channels that can be many meters deep. Successive deposits amalgamate to produce composite beds, different from the monotonous interbedding of argillite and greywacke characteristic of classical turbidite successions. Prothero and Schwab *(1996)* suggest that turbidite fan channels are similar to those of alluvial fans, and have distinctive levee and overbank deposits, like those observed in fluvial systems (Figs. 6.4 and 6.5).
- The thick phyllite beds (Hill B) in the upper turbidite unit are interpreted as argillaceous levee deposits that flank either side of the turbidite channel. According to Einsele *(1998)* turbidite channel deposits in the upper and middle fan regions are accompanied by levees which may rise above the surrounding sea floor by 10 to 100 m.

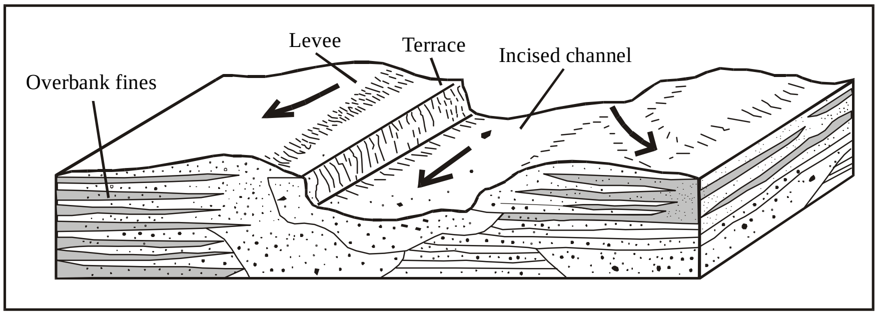


Figure 6.5. Incised channel fill, levee, and overbank deposits of the mid to lower part of a channelized fan (modified after Einsele, 1998). A thick, massive greywacke unit observed at Hill D north is thought to represent the infill of such a channel. Levee deposits are observed at Nsuta as thick argillaceous units.

A rather similar depositional setting to that described above has also been reported by Leube et al. *(1990)* for the siliciclastic sedimentary units that are interbedded with volcanics of the Birimian succession in general. According to this model *(Leube et al., 1990)* the Birimian sedimentary rocks were deposited adjacent to sub-parallel chains of volcanic island-arcs in intervening elongated sedimentary basins. These basins could have been several hundred kilometers long and may have attained depths of a few hundred meters. In this scenario, volcaniclastic sediments occur as minor constituents within the volcanic belts but make up the bulk of the fill of the sedimentary basins *(Leube et al. 1990).*

According to Leube et al. *(1990),* argillites represent the normal, i.e. constant background sediments in the depositories, whereas the coarser detrital sediments and volcanics were brought in sporadically by discrete and more localised events (in time and space) such as volcanic eruptions and turbidity currents. Based on lithological composition, Leube et al. *(1990)* propose an idealised sequence of facies from the volcanic belts towards the centres of the sedimentary basins (Table 6.1). Results of the present study found nothing that would argue against this general depositional model of Leube et al. *(1990)* (Table 6.1). The main point of this model is turbidity currents, which carried predominantly pyroclastic and epiclastic sediments down the slopes of the volcanic island arcs to form immature greywackes, siltstones and shales, but also true volcaniclastic rocks more proximal to the volcanic source *(Leube et al. 1990)*. True volcanic rocks, including lava flows, tephra and tuffs, may also have contributed significantly to the basin fill.

Table 6.1. Different facies of the Birimian Supergroup and their characteristic lithological associations (modified after Leube et al., 1990).

Facies	Lithology	Depositional environment
Volcanic/ volcaniclastic	Presence of lava essential; volcaniclastic rocks (pyroclastics or epiclastics) may or may not be present. Rare argilitic sediments.	Water/air interface of volcanic islands or volcanic ridges.
Greywacke (turbidite related)	Reworked, allochthonous, notably quartz-enriched volcaniclastic rocks displaying graded bedding	Turbidites at lower end of slopes of volcanic ridges
Volcaniclastic argillite	Interbedding of volcaniclastic rock (predominantly sand to silt sized, non- or little transported pyroclastics) and argillitic rock with the former dominant in thickness and proportional abundance. Rare interlayers of lava.	Depository proximal to volcanic island or ridges.
Argillite/ volcaniclastic	As above, but a preponderance in thickness and proportional abundance of argillites.	More distal portions of the depository
Argillite	Argillites, often finely laminated and graphitic.	Low energy environments in the most distal portions of the depositories.
Chemical sediments	Chert, carbonate, manganese, organic carbon.	Structurally weak regimes in transitional zones between belts and basins

6.2 Depositional Setting of the Manganese Carbonate Ore Bed

The sedimentary succession at Nsuta can also be evaluated applying simple sequence stratigraphic principles (Fig. 6.6). Transgressive and regressive cycles are controlled by eustatic sea level changes that directly influence the clastic sedimentation rate into a basin. Transgressions are associated with increasing accommodation space in the basin (relative sea level rise) and thus result in upward-fining sequences. Regressions, on the other hand, are associated with decreasing accommodation space in the basin (relative lowering of sea level) and result in gradually upward-coarsening sequences as seen in the upper turbidite unit. The onset of a transgression and end of a regression are often marked by an unconformity resulting from negative accommodation space in the basin *(Van Wagoner et al. 1998)*. As mentioned previously, the lower turbidite unit fines

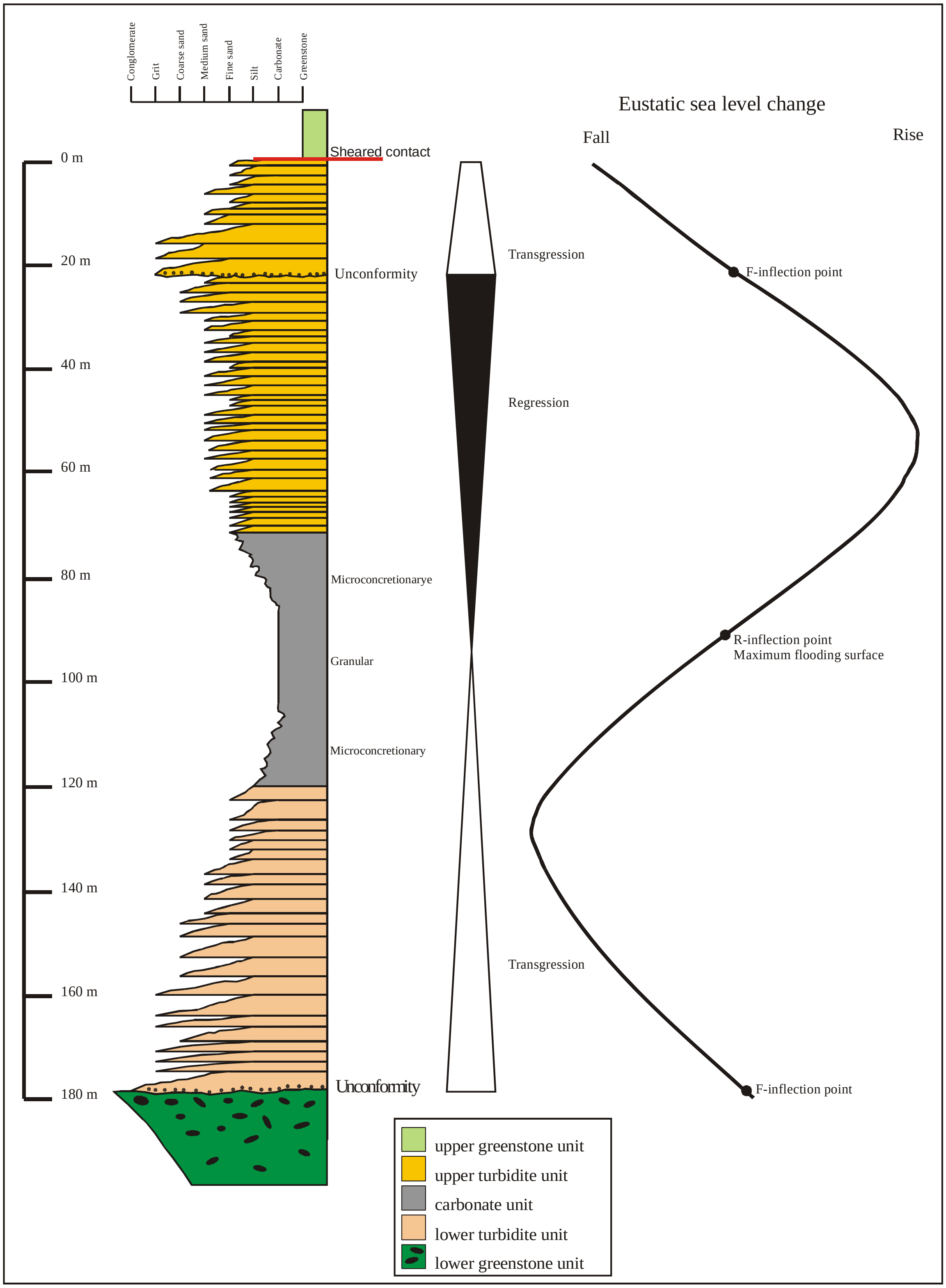


Figure 6.6. Stratigraphy of the Nsuta manganese deposit with an interpretation of sequences and a relative sea level curve..

gradually and may thus mark a major transgression (Fig. 6.6). During this transgression the depositional basin is apparently starved of clastic material, a precondition for the development of the manganese carbonate orebody which contains no siliciclastic detritus.

The manganese carbonate orebody occupies the central position in the entire turbidite sequence, and is thought to mark maximum flooding surface at the peak rate of sea level rise. Evidently, the influx of siliciclastic detritus decreased gradually and became insignificant as the central part of the manganese carbonate bed was deposited.

The lower and upper contacts of the carbonate bed into the surrounding turbidites are marked by the occurrence of carbonate microconcretions. Studies on modern *(Huckriede and Meischner, 1996)* and ancient *(Gutzmer and Beukes, 1998)* marine manganese carbonate sediments suggests that such microconcretions grow just below the sediment-water interface during very early diagenesis. The microconcretions display irregular concentric growth zones (Fig. 3.4d) and a fibrous radial internal texture. There is no evidence that these microconcretions have been reworked so that they almost certainly represent in-situ formed concretionary structures.

The carbonate unit itself was most probably formed in a very quiet deep water environment. Negative $\delta^{13}C$ values of the manganese carbonate *(Nyame, 1998)* indicate that organic carbon was involved in the formation of the carbonates. This normally happens where manganese is originally deposited as Mn^{4+} oxihydroxide together with organic carbon. The organic carbon then acts as reducing agent to form Mn^{2+} carbonates which incorporate carbonate derived from oxidizing organic carbon *(Gutzmer & Beukes, 1998)*. This process normally takes place in dysaerobic diagenetic conditions *(Okita et al., 1988).*

Manganese deposition continued well into the upper turbidite unit (Fig. 4.4). The latter marks renewed regression and influx of siliciclastic detritus. This regression may have been the result of an eustatic drop in sea level, or relative tectonic uplift. Initially, argillaceous and silty material is reintroduced, followed by fine sand and silt, and finally coarse sand, in an upward coarsening succession (Fig 6.6). A coarse granulestone unit in the succession may mark another sequence boundary in the succession and the onset of another upward-fining transgressive cycle (Fig. 6.6). The record of this second transgressive cycle remains incomplete due to subsequent shear deformation along the contact of the upper sedimentary unit with the overlying upper greenstone unit (Fig. 6.6).

6.3 Metamorphic Alteration

The greenstones appear to be the most suitable rocks with which the pressure and temperature conditions of metamorphism in the Nsuta area can be constrained. Two metamorphic assemblages were identified in the lower greenstones; namely:

(1) quartz-albite-chlorite-carbonate ± epidote

(2) quartz-albite-actinolite.

These are typical low-grade mineral (greenschist facies) assemblages of mafic rocks. The presence of sericite and biotite in assemblage (1) and (2), respectively, is probably related to later potassium metasomatic alteration. The presence of epidote in some rocks in assemblage (1) is related to relatively high (Ca + Al)/(Mg + Fe) mole ratio and is thus related to the whole rock composition *(Spear 1993).*

Assemblage (2), which shows the presence of actinolite, can be explained by a number of factors *(Spear 1993)*, such as a high FeO/ (CaO + Al_2O_3) mole ratio, or a H_2O dominated fluid. The fact that assemblage (1) is observed near carbonate-dominated lithologies (Mn carbonate), suggests that the composition of the metamorphic fluid controlled the stable mineral phases for the greenstones. These results indicate that it is impossible that the regional metamorphic grade at Nsuta reached amphibolite facies as suggested by John et al. *(1999).* Amphibolite facies metamorphism described by John et al. *(1999)* is more likely to be present in the form of contact metamorphic aureoles in areas away from Nsuta, but is not present at Nsuta. John et al. *(1999)* also suggest that the constant peak metamorphic pressures found in the southern Ashanti belt (Fig. 6.7), implies that the entire area represents the same crustal level and, therefore, must have experienced similar high-grade metamorphic conditions. However, constant pressures do not rule out local contact metamorphic effects and pressure estimates in general are highly inaccurate *(Spear, 1993).*

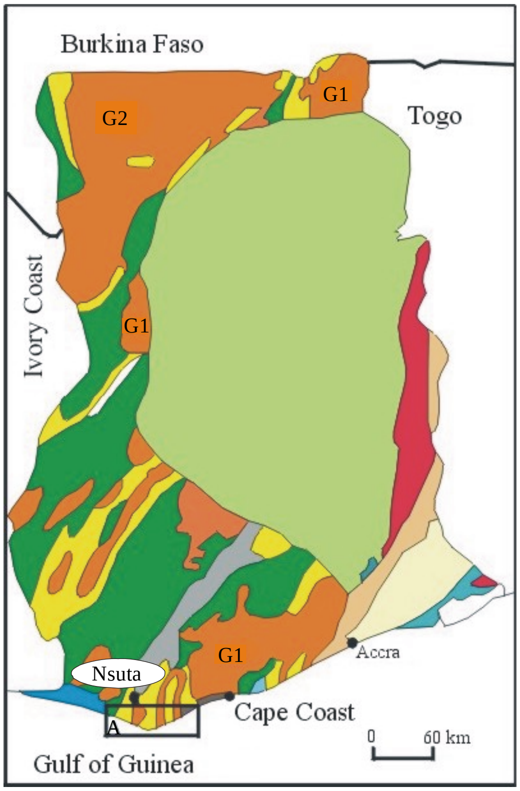


Fig. 6.7. Geological map of Ghana showing the area in which John et al. (1999) conducted a metamorphic study of Birimian strata in the extreme southern limit of the Ashanti belt to the south of Nsuta.

Perhaps more realistic for the Nsuta area are is the results of Kleinschrot et al. *(1994),* who suggest that at the peak of the prograde metamorphic evolution, P-T conditions corresponding to greenschist facies (± 500^{O}C at 5kbar) were obtained in the area. This observation is supported by Nyame *(*1998) who provides evidence for the preservation of primary sedimentary structures and textures in the manganiferous phyllites and manganese carbonate ore; features that would almost certainly have been destroyed if amphibolite facies metamorphism were reached.

The occurrence of metamorphic minerals, like spessartine garnets, cross-cutting distinct sedimentary laminations may be consistent with low temperature transformation of materials that were initially of sedimentary origin *(Nyame, 1998)*. Minerals such as muscovite, chlorite and spessartine garnet commonly found in the argillites, greywackes and carbonate ore possibly formed from mineral reactions involving clay minerals, silica and/or Mn carbonates. Spessartine-rich garnet, for instance, are known to form at low temperature (250-300^{O} C) and pressure in chemically favourable rocks *(Nyame et al., 1998).*

To summarise, it is possible that certain parts of the southern Ashanti belt have experienced amphibolite facies metamorphic conditions in contact metamorphic aureoles of intrusive granitoid bodies. However, whether these conditions can be extrapolated to the entire southern Ashanti belt and especially the Nsuta area, appears more than doubtful. At Nsuta, peak metamorphism almost certainly only reached greenschist facies and more detailed work is required to understand the metamorphic history of the Ashanti belt as a whole.

6.4 Structural Deformation

A total of 351 bedding orientations were acquired during field mapping. All measured bedding orientations indicate that the strata have a dominant strike in a NNE-SSW direction (Fig. 6.8). On a stereoplot the data clearly represent a dominant structure (related to F_1) while the scattered data are attributed to a less dominant second structure (related toF_2) (Fig 6.9). Interpretation of Figure 6.9 allows for two possibilities, a) only one fold limb was measured or b) due to isoclinal folding, the interlimb angle is zero degrees which would result in data from both limbs plotting in the same position on the stereoplot. Neither of the two possibilities enable construction of an F_1 fold axis.

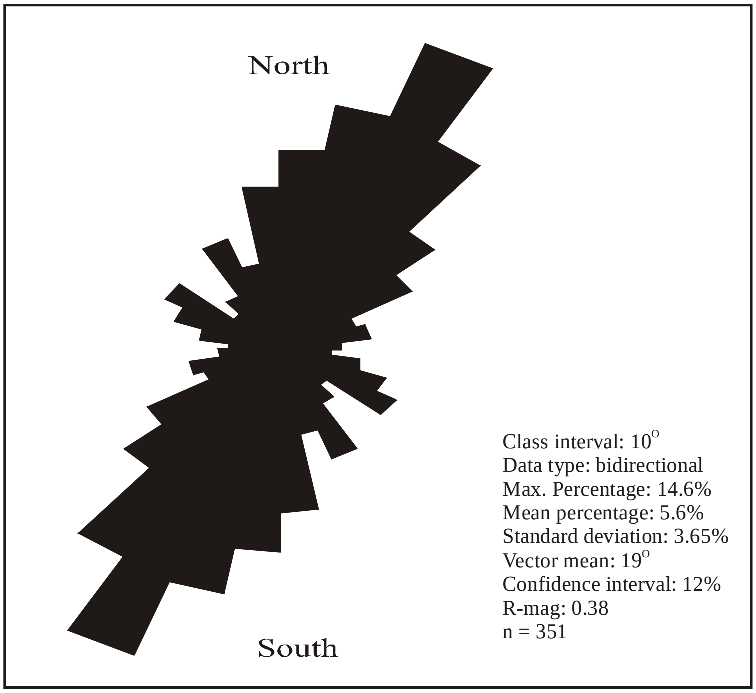


Figure 6.8. Rose diagram illustrating all measured strike directions of bedding planes at the Nsuta deposit.

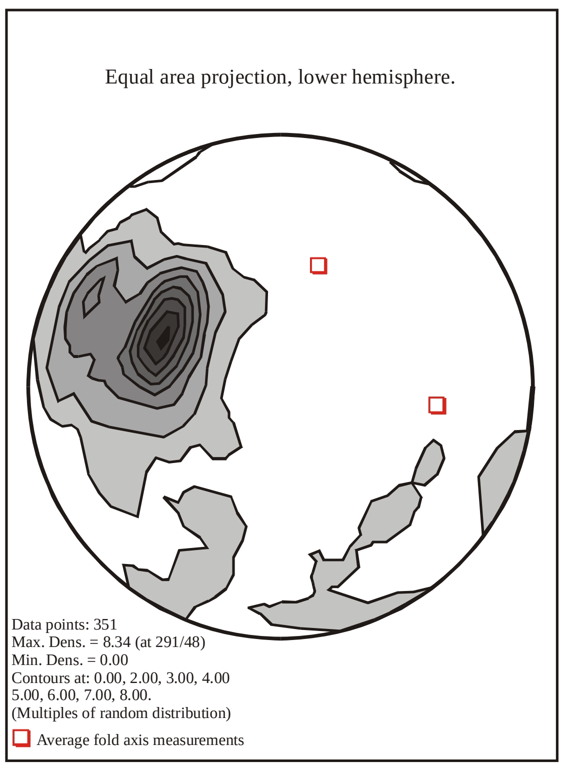


Figure 6.9. Contoured composite stereonet projection of poles to bedding with constructed fold axes plunging NNE (F_1) and E (F_2).

The geological map (Fig. 5.1A) and structural analyses suggest the following deformational history for the strata in the Nsuta mining concession:

- F_1 isoclinal folding with fold axis trending NNE-SW.
- Thrust faulting, most probably related to F_1, bringing the lower greenstone unit in contact with the upper greenstone unit (Fig. 6.10).
- Oblique cross folding with F_2 fold axis oriented E-W
- Normal faulting (E-W), affecting the orebody between mining areas in different hills (Fig 5.1A).
- NNE-SSW extensional faulting causing rotation of Hills D north and D south (Fig 5.5).

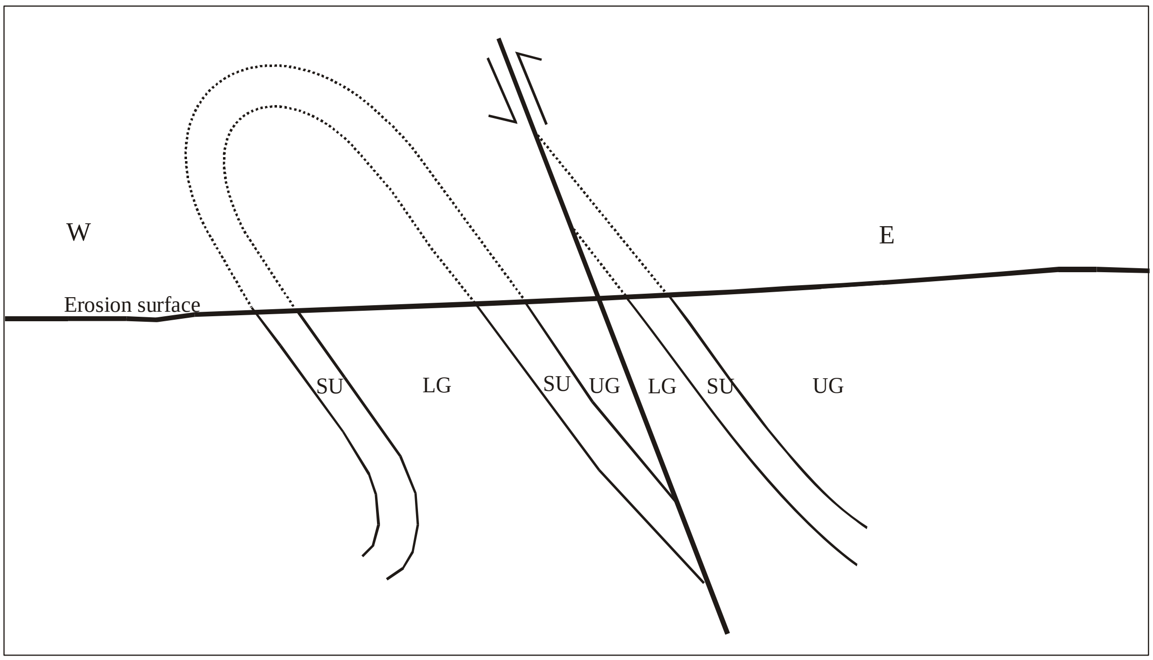


Figure 6.10. Illustration of a steep thrust crosscutting the limb between an anticline and syncline, bringing the lower greenstone unit (LG) in contact with the upper greenstone unit (UG). Relative displacement of the sedimentary unit (SU) is also indicated.

A simplified interpretative structural map (model) of the mine suggests that the eastern segment of the mine merely represents one limb of an anticlinal structure that has been thrusted in a westerly direction (Fig 6.10). Thrusting may have been syn- or post-F_1 folding and apparently propagated along the limbs between anticlines and synclines.

E-W oblique-slip normal faults appear to become listric with depth and are responsible for segmenting the deposit into the series of hills (fault blocks) that are mined today (Fig. 6.11). These faults are systematically arranged from north to south and are assumed to propagate in a southerly direction since anticlinal and synclinal axes all plunge to the north. In effect, the concession could be seen as consisting of a series of half-graben structures (Fig. 6.12). This style of faulting can only be a small-scale representation of a larger system that must exist on a regional scale. Field evidence suggests that there is differential tilt between imbricate fault blocks on the mine, a feature typical of listric faulting at depth *(Wernicke and Burchfiel, 1982; Wernicke, 1984).*

The direction of downthrow is towards the south, thus enabling the blocks to display successively steeper tilts towards the south. This phenomenon permits preservation of stratigraphy towards the south but exposure and erosion of stratigraphy in the north (Fig. 6.12). If the western side of the concession represents an anticline, then rotated anticlinal blocks should be preserved on the western side of Hills A and B at depth below surface. It may represent a prospective area for extension of the manganese orebody (Fig. 6.11 and 6.12).

6.5 Plate-Tectonic Setting of the Nsuta Manganese Deposit

The geotectonic evolution of the Birimian Supergroup is a controversial topic, with three major models being proposed at present, namely:

- Intracontinental rifting *(Leube et al., 1990).*
- Convergent ocean-plate margins *(Attoh and Ekwueme, 1997).*
- Continent - continent collision *(Hirdes et al., 1996).*

It is beyond the scope of this dissertation to define an unambiguous geotectonic setting for the Birimian Supergroup in general, as field observations were restricted to the Nsuta deposit. Thus one can only select a model that appears more consistent with observations made on the mine and build the plate tectonic setting of Nsuta manganese deposit into that. At present, the most widely

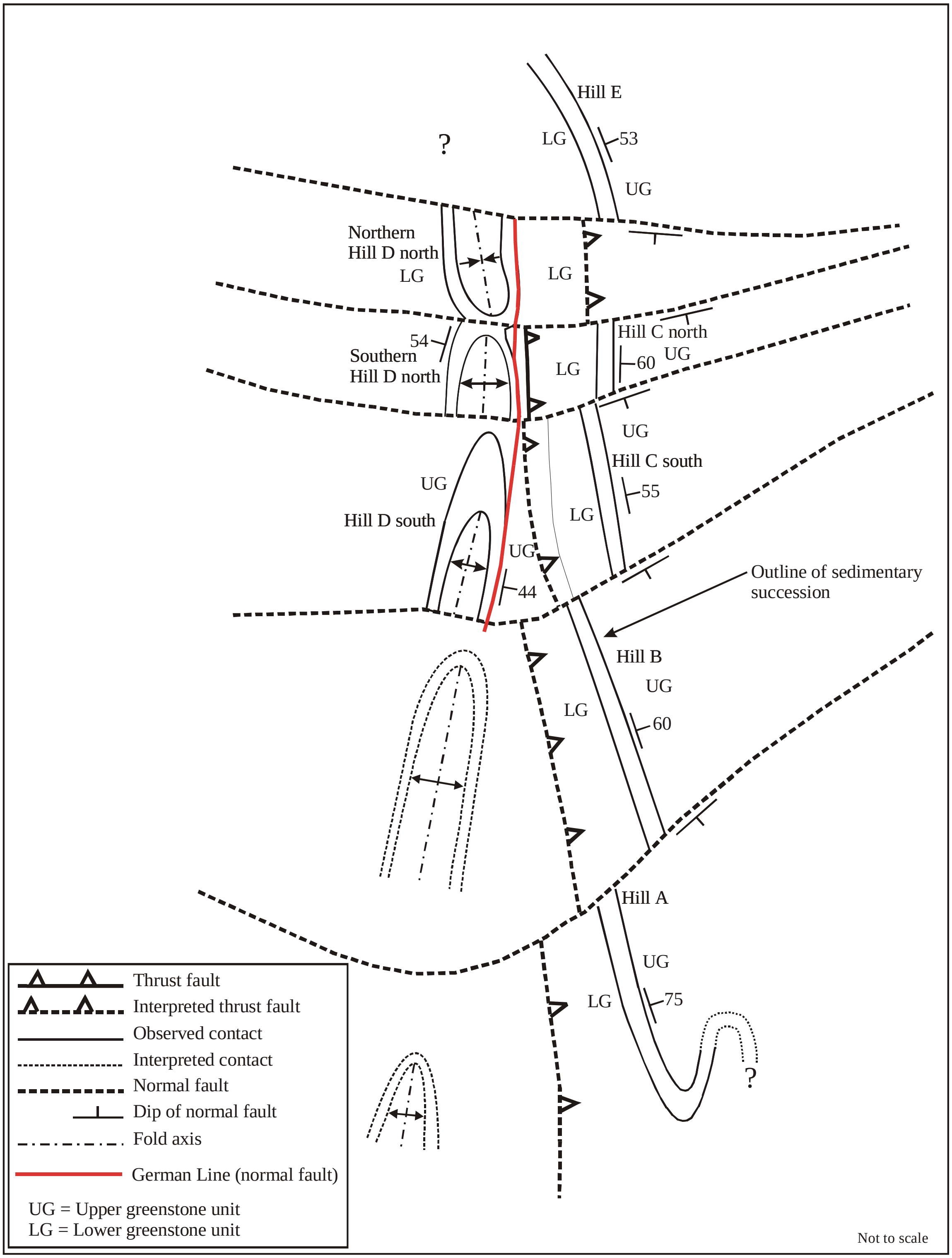


Figure 6.11. Plan view sketch model of the structural geology of the Nsuta deposit.

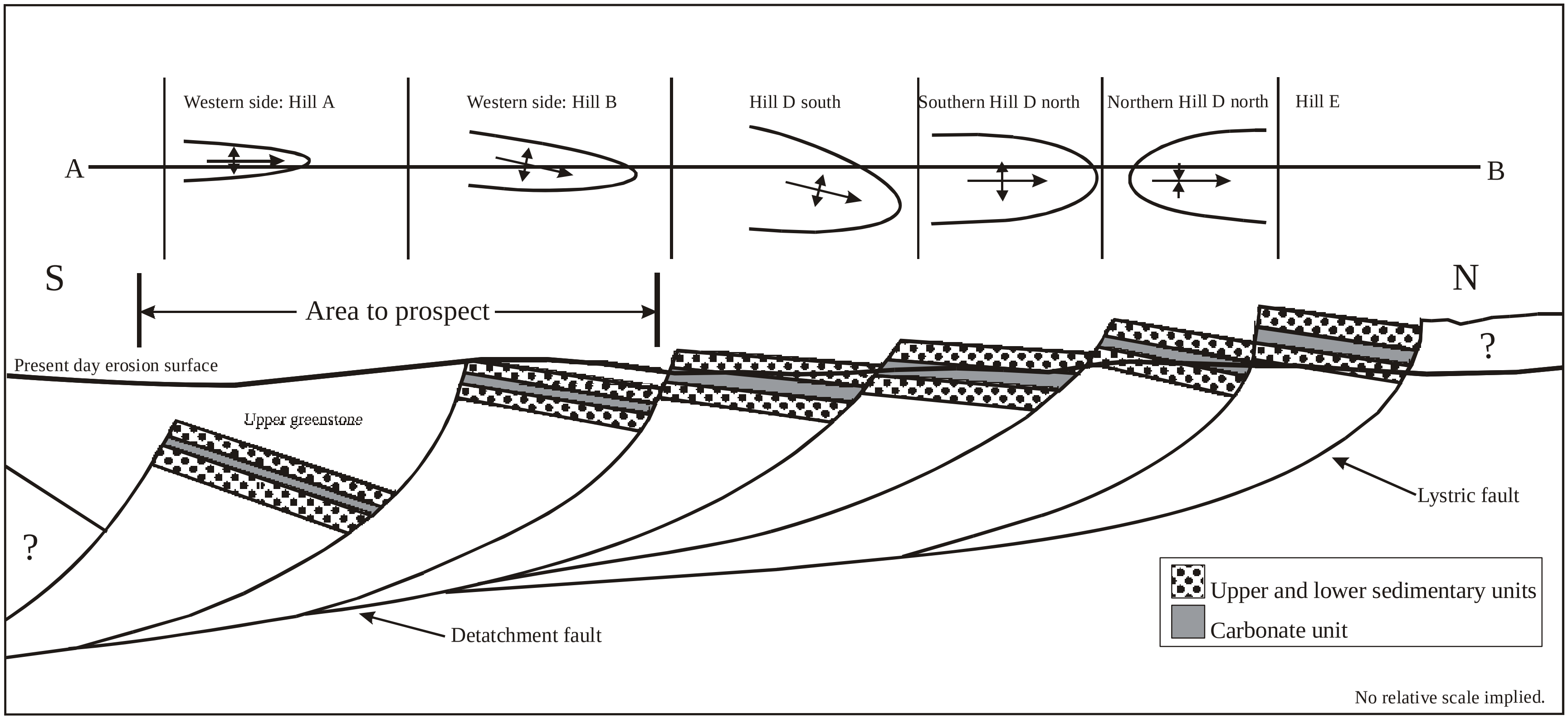


Figure 6.12. Interpretative sketch of the western side of the Nsuta deposit. Top sketch is plan view of a series of faulted F_1 folds. Bottom sketch is a cross-section along line A-B of plan view sketch. Note that successively more of the ore-bearing succession is preserved towards the south of the mining area due to downwards displacement by listric faulting i.e. the potential of finding ore beneath cover increases towards the south.

supported model appears to be the one by Hirdes et al. *(1996)* that envisages continental collision and accretion of island arcs and oceanic plateaus onto the Archean Man Shield. This model was selected as basis for the following discussion. The model *(Hirdes et al., 1996)* suggest that the Birimian Supergroup constitutes juvenile continental crust that formed as island arcs and intervening sedimentary basins which were accreted onto the Man Shield. This process constitutes one half of a Wilson cycle that culminated in continental collision and the Eburnean tectonothermal event or orogeny. The age and duration of this major orogenic event can be constrained between 2.18 Ga (early Birimian volcanism) and 1.97 Ga (post-tectonic mafic dykes) (Table 2.1). The early stages of this collision process is marked by subduction of oceanic crust beneath the Man Shield, and calc-alkaline magmatism to produce volcanic island arcs and early Dixcove granitoid intrusives at 2.18 Ga (Table 2.1 and Fig. 6.13 A-B).

Associated with island arc volcanism is backarc spreading and the opening of elongated sedimentary troughs that were successively filled by volcanics, volcaniclastics and immature siliciclastics derived from penecontemporaneous volcanic rocks. Turbidite deposition in submarine fan environments was favoured by steep topographic relief due to rapid tectonic uplift associated with the build up of volcanic arcs (Fig 6.13B).

Active tectonics and volcanism supplied abundant immature siliciclastic material that was shed into the adjoining backarc basins. Any tectonic disturbance to unconsolidated sediments would have produced turbidites. Chemical sediments, including the Nsuta Mn-carbonate orebody, constitute a minor but conspicuous component in the backarc basin fills. They were efficiently concentrated wherever siliciclastic influx was cut off. Such conditions may have been most prevalent during maximum rates of relative sealevel rise in the central part of backarc basins i.e. most distal to the source of siliciclastic detritus (Fig 6.13B).

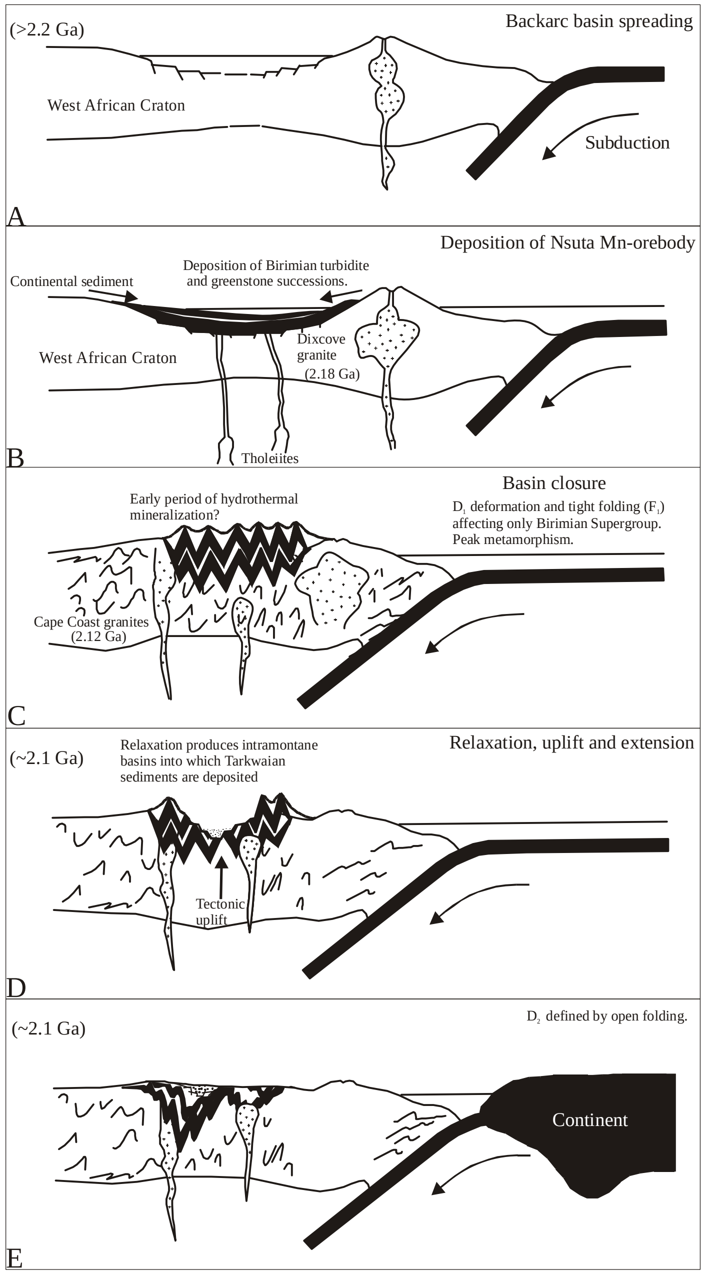


Figure 6.13. Proposed model for the geotectonic evolution of the Birimian Supergroup in a backarc basin setting *(modified after Windley, 1977).* A. Early stages of subduction and backarc basin development. B. Calc-alkaline volcanism and deposition of Birimian sediments and lavas; intrusion of Dixcove granites into the volcanic belt. C. The onset of the Eburnean tectonothermal event by basin closure initiating D_1 deformation that influences only the Birimian Supergroup. D. Crustal relaxation associated with uplift, formation of narrow intramontane basins, and deposition of eroded material into these basins to form the Tarkwaian Group. E. Late stages of deformation (D_2) jointly influence Birimian and Tarkwaian rocks. Termination of Eburnean tectonothermal event at ~2.05 Ga is constrained by post-peak metamorphic vein-hosted gold mineralization in the Ashanti Belt.

Taking the above into account, a local geotectonic model emerges for the volcanosedimentary succession that hosts the Nsuta manganese deposit. The lower greenstone unit is composed essentially of reworked volcaniclastics that give evidence of active volcanism proximal to the site of deposition. This lower volcaniclastic unit is unconformably overlain by a thick upward-fining succession of turbidites that was deposited in response to a marked marine transgression. These turbidites almost certainly represent more thoroughly reworked and weathered volcanic material similar to that of the lower greenstone unit, intermixed with organic matter, derived from early marine microbes that may have thrived in the backarc basins.

Deposition of the manganese carbonate orebody is interpreted to reflect maximum transgression and starvation of the basin from detrital influx. Different opinions exist as to the source of the manganese. Most authors favour synvolcanic hydrothermal emanations as the most likely source of manganese *(Kleinschrot et al., 1994; Nyame, 1995; Yeh et al., 1995; Nyame, 1998; Mücke et al., 1999).* However, the manganese ores have no geochemical attributes of marine hydrothermal manganese deposits *(Nyame, 1998)*. Thus it appears more likely that not only hydrothermal solutions, but also meteoric and groundwater contributed to transport of manganese into the backarc basins.

Field observations suggest that the manganese carbonate orebody was deposited as one continuous bed that may interfinger with turbidites only towards its extremities. This implies that the main carbonate bed and orebody formed over extensive areas on the floor of a backarc basin. This conclusion differs from that of Nyame *(1998)* who proposed that the manganese carbonates occur in several small distinct lenticular bodies that interfinger along strike with turbidite units. These bodies conform to the different hills on the mine. However, Nyame *(1998)* did not take the complex structural history of the Nsuta area into account, a history that readily explains the locally lenticular appearance of the orebody. These "lenses" appear to be the result of early E-W striking normal faults that simply offset the strata at irregular intervals along strike between the various hills.

After deposition of the manganese orebody, renewed regression was responsible for the deposition of the upward-coarsening lower part of the upper turbidite unit. This regressive cycle is topped by a second transgression depositing the upper part of the upper sedimentary unit. The upper greenstone unit appears para-allochthonous, its actual relationship to the underlying sequence remains uncertain due to the sheared contact with the underlying sedimentary unit. Birimian volcanism and associated backarc basin infill may have ceased as early as 2.15 Ga in the Ashanti Belt.

Backarc basin closure, uplift and erosion of the Birimian volcanics and sediments are a logical consequence of continuous compression and subduction during the Eburnean Wilson cycle (Fig. 6.13C). It is suggested that the Birimian rocks, including the Nsuta succession, were intensely deformed during this first phase of Eburnean deformation (Fig. 6.13C). F_1 isoclinal folding observed at Nsuta is attributed to this phase of deformation. The age of basin closure and initial deformation may be reflected by the intrusion of Cape Coast granitoids at 2.12 Ga (Fig. 6.13C).

Uplift associated with this initial phase of deformation may have caused the opening of small, elongated intramontane basins where extensional forces prevailed in the overall compressional regime *(Leube et al. 1990; Bossière, 1996).* These intramontane basins were filled by Tarkwain siliciclastics (Fig. 6.13D), derived from erosion and weathering of a Birimian-aged hinterland between 2.13 ± 3 and 2.09 ± 2 Ga. *(Hirdes and Davis, 1998).* The presence of paleoplacer gold deposits in the Banket Series of the Tarkwaian Group confirms that at least some hydrothermal gold in the Birimian Supergroup pre-dates deposition of the Tarkwaian Group and acted as source for the Tarkwaian sediments.

Further phases of deformation affected the Birimian as well as the unconformably overlying Tarkwaian. These phases of deformation must therefore post-date deposition and diagenetic lithification of the Tarkwaian siliciclastics i.e. must be younger that 2.09 ± 2 Ga. **(**Figure 6.13 E). Unfortunately the structural history of the Ashanti belt on a regional scale still remains unclear and no explicit comparison to the observations at Nsuta can be drawn. From results presented in this study and literature data *(Leube et al. 1990; Eisenlohr and Hirdes, 1992)* it appears likely that tight folding observed at Nsuta is restricted to the Birimian Supergroup but that less intense open folding affected both Birimian and Tarkwaian rocks. This conclusion is tentative and should be confirmed by detailed structural studies in the outcrops generated by gold mining of the Tarkwaian Group near Tarkwa.

Recent geochronological studies suggest that a second phase of structurally controlled hydrothermal gold mineralization took place at ~2.06 ± 6 Ga *(Oberthür et al. 1998; Pigois,op. cit.)*. Gold bearing quartz-carbonate veins and stockwork of this age not only crosscut the Birimian Supergroup, but also the Tarkwaian Group *(Pigois, op. cit.)*. Similar quartz-carbonate veins at the Nsuta deposit post-date peak metamorphism and the Eburnean-age deformation events.

It appears likely that recrystallization of granular carbonate ores to high-grade granoblastic rhodochrosite along veins and pods is associated with this later event of hydrothermal fluid flow. The end of the Eburnean orogeny is only constrained by the intrusion of 1.97 Ga mafic dykes that crosscut the deformed and metamorphosed Birimian and Tarkwaian strata. These dykes show up very clearly on the aeromagnetic maps of the Nsuta area (Figs 2.10 and 2.11). In the vicinity of Nsuta, east-west oblique-slip listric faulting post-dates intrusion of these mafic dykes (Fig 2.11B) and are thus not associated with the Eburnean orogeny but reflect a later tectonic event. The deposit is also affected by NNE-SSW striking normal faulting that is even younger that the E-W faulting. The exact ages of these events remain uncertain. However, they appear to be related to extensional tectonic regimes which may in turn be of Pan African age or related to the breakup of Gondwana.

Deep lateritic weathering and formation of high-grade managnese oxide ores formerly mined at Nsuta are certainly associated with the old African land surface that formed after the breakup of Gondwanaland in the Late Jurassic to Early Cretaceous times. Tertiary uplift of the continent resulted in incision of the old African peneplane by rivers *(McFarlane, 1976)*. The presently dissected appearance of the orebodies could thus be regarded as erosional remnants of the old African land surface.