At present, the fauna of subzone A (Table.2.9a) is therefore characterised by the presence of the: amphibians *Kestrosaurus, Trematosuchus* and undescribed primitive brachyopids (Shishkin, *pers.comm.*); and archosauriformes believed to be congeneric with the European genus *Garjainia* (Welman *pers.comm.*). The associated fauna includes: the cynodonts *Cynognathus* and *Trirachodon kannemeyrii*; the captorhinid *Thelegnathus oppressus*; the bauriid therocephalian *Sesamodon*; small lungfish assigned to the genus *Ceratodus*; and indeterminable members of the r[illegible]chosauria (Gow *pers.comm.*). To date no dicynodonts are known from the subzone.

Studies of this faunal assemblage, particularly the amphibians (Hancox *et al.*, 1995; Shishkin & Welman, 1995) have shown this fauna to be more primitive than any previously discovered in the *Cynognathus* Assemblage Zone and this finding has important implications for the relative dating of the *Cynognathus* Assemblage Zone.

b) Subzone B

Geographically, subzone B outcrops from south of Thaba Nchu in the north to Steynsburg in the west and Lady Frere in the east. The most southerly occurrence of the subzone occurs in the area surrounding Tarkastad. The lower boundary is taken as the FAD of the capitosaurid amphibian "*Parotosuchus*" *africanus*, which co-incides with the FAD of the dicynodont *Kannemeyeria* (Fig.2.85). Both of these FADs co-incide lithologically with the top of a laterally persistent sandstone within the lower half of the Burgersdorp Formation.

The upper boundary is marked by the LAD of "*Parotosuchus*" *afri*[illegible] *Kannemeyeria* and *Thelegnathus* and the FAD of *Parotosuchus morgani* s.[illegible]. This contact may be an erosional remnant at places, but where fully preserved, co-incides lithologically with the base of the second prominent sandstone horizon within the Burgersdorp Formation that Groenewald (1996) refers to as the Andriesberg Member. To the west of Rouxville and on the Aliwal North-Bethulie road, the upper lithological contact is formed by a single sheet sand deposit of the

Bamboesberg Member of the Molteno Formation, and at Aliwal North district subzone B is directly overlain by two sandstones of the Bamboesberg Member.

During the course of collecting in subzone B (Appendix 3) numerous lungfish tooth plates were collected on the farms Grootdam and Winaarsbaken in the Burgersdorp district. At these localities lungfish fossils occur within facies Se_l along with numerous fragmentary amphibian remains assignable to *"P"africanus* (Shishkin *pers.comm.*). The lungfish specimens may be assigned to the catch all genus *Ceratodus*, but are of markedly different size (up to 50mm) from those in subzone A, and quite possibly represent a different species of the genus.

The fauna of subzone B (Table.2.9c) equates to the classical *Cynognathus* Assemblage Zone fauna as documented by Kitching (1977) and includes the: amphibians *"P".africanus*, *Batrachosuchus* and an unidentified brachyopid (Shishkin *pers.comm.*); dicynodonts *Kannemeyeria* and *Kombuisia*; archosauriforms *Erythrosuchus* and *Euparkeria*; cynodonts *Cynognathus*, *Diademodon*, and *Trirachodon*; therocephalian *Bauria*, captorhinids *Thelegnathus* and *Myocephalus*; rhynchosaurs *Howesia* and *Mesosucuhus*; and lungfish *Ceratodus*.

A number of the forms from subzone B show an advanced state of evolution over their predecessors in subzone A. The zone index amphibian *P.africanus* is advanced over the state found in *Kestrosaurus* (Hancox *et al.*, 1995) showing the trend towards closure of the otic notch as well as in the advanced nature of the construction of the basicrani and lower jaw (Shishkin *pers.comm.*). *Erythrosuchus* is advanced over the state found in the archosauriform from subzone A (Welman *pers.comm.*) as is *Trirachodon berryi* when compared to *T.kannemeyerii* (Welman *pers.comm.*). The brachyopid amphibian from the zone is also believed to be advanced over the state found in the lowermost subzone (Shishkin *pers.comm.*). Considering the wealth of procolophonid material from the subzone (Gow, 1978), a comparative study of material from subzone A and B would be very useful.

The abundance of forms in this subzone may be a real increased abundance over subzone A or may be due to a collecting bias, in as much as for most of the history of the zone these were the only known exposures. If the former is the case then the radiation of new forms following the proposed end Permian extinction, began during subzone A times and reached its peak in the Karoo Basin during subzone B.

c) Subzone C:

The new faunal assemblage discovered during the course of this study in the upper part of the Burgersdorp Formation, in the south of the basin, is assigned to subzone C. Geographically this subzone is restricted to exposures in the Bamboeshoek Valley and its surrounds in the Eastern Cape Province and the strata containing this fauna have a maximum preserved thickness of only ±130m.

The basal boundary is taken as the FAD of the amphibian *Parotosuchus morgani* sp.nov., and this coincides with the FAD of the dicynodont *Angonisaurus*, as well as the first appearance of the shansiodontids. Because the Molteno Formation is barren of tetrapod fossils, the upper boundary of subzone C cannot be based on a FAD, and must for practical reasons be based on the LAD of *Cynognathus* Assemblage Zone fossils. This coincides lithologically with a barren zone towards the top of the Burgersdorp Formation, but in places may also be defined by the basal sandstone of the Bamboesberg Member.

The new components of this fauna are described earlier in this chapter and include the capitosaurid amphibian *Parotosuchus morgani sp.nov.*, as well as stahleckeriid (*Angonisaurus coxi*) and shansiodont dicynodonts. At present the total fauna from this subzone (Table 2.6a) includes the above mentioned forms, the cynodonts *Cynognathus*, *Diademodon* and *Trirachodon*, and indeterminable material assigned to the archosauriformes.

The palaeoflora of this subzone includes: podocarp wood; a new seed genus; the horsetail *Calamites*; and a new fern similar to *Dicroidium superbum*. It is different to that from subzone B, where *Dicroidium hughesii* is the only species of *Dicroidium* known, and is more similar to that of the overlying Bamboesberg Member of the Molteno Formation. It is also of interest to speculate on the changes in internode size, and plant size for the specimens of *Calamites*. Those from subzone A are small and seem to become larger through to subzone C (Fig.2.76). A similar change in the overall size of the palaeoflora is evidenced from the Katberg Formation through the lower, middle and upper Burgersdorp Formation. This trend is however based on limited evidence at present, and should be further investigated before being used for biostratigraphic applications or palaeoclimatic reconstructions. The study of the biostratigraphy of the palaeoflora of the Burgersdorp Formation is still in its infancy, but preliminary results suggest that the palaeofloral signatures may prove very useful.

Table 2.7 summarises the faunal assemblage characteristic of the uppermost Burgersdorp (*Cynognathus* Assemblage Zone) in the south of the basin compared to the fauna of subzones A and B. These differences become important in Chapter Four when considering the basinal development of the Karoo Basin during the Triassic.

2.7.2.3 Discussion on *Cynognathus* Assemblage Zone biostratigraphy

Apart from the tentative suggestions of Watson (1942) and Cooper (1982), the *Cynognathus* Assemblage Zone has not previously been sub-divided, and at present no formal subdivision is accepted (Kitching, 1996). Hancox *et al.* (1995) proposed an informal threefold biostratigraphic subdivision based on the spatial and temporal distributions of the zones amphibians. Recent collecting and taxonomic studies by independent authors have substantiated the threefold subdivision of the *Cynognathus* Assemblage Zone proposed by Hancox *et al.* (1995).

This study has also allowed the confusion regarding the biostratigraphic ranges of a number of individual genera to be corrected. *Kannemeyeria* has in the past been thought to be diagnostic of the lower and middle parts of the *Cynognathus*

Assemblage Zone (Kitching, 1977), and has its FAD has been proposed to equate to the base of the *Cynognathus* Assemblage Zone. When the *Cynognathus* Assemblage Zone was only known from the subzone B deposits, this was indeed the case. The discovery of a lower subzone (Welman *et al.*, 1991) and new upper subzone, in which *Kannemeyeria* does not occur shows that this form is stratigraphically restricted to the middle part of the *Cynognathus* Assemblage Zone (subzone B). The proposed presence of *Kannemeyeria* in the upper part of the biozone (Keyser & Smith, 1977-78) may be due to the fact that they were working in the middle of the basin, where subzone B is directly overlain by the Bamboesberg Member of the Molteno Formation, or in that the postcrania on which the range was based actually belong to one of the new dicynodont genera from subzone C. There is at present no biostratigraphic overlap between the range of *Kannemeyeria* and the new dicynodonts from subzone C.

Spatially *Kannemeyeria* is known from Tarkastad in the south to Burgersdorp in the west and Lady Frere in the east. The most northerly documented occurrence of *Kannemeyeria* is at Thaba Nchu mountain (Welman *et al.*, 1991), where a single specimen occurs just below the Indwe Sandstone Member of the Molteno Formation (Kitching *pers.comm.*).

Cynognathus and *Diademodon* occur throughout the range of the *Cynognathus* Assemblage Zone, and these two genera have been proposed to be long range conservative taxa (Cooper, 1982). Further studies of these forms may show whether species diversity occurs within the proposed subzones, or whether they truly are long range conservative forms. Such a study is currently underway for the cynodont genus *Trirachodon* (Hopson & Welman *pers.comm.*), and preliminary results indicate that the northern species of this genus are more primitive than those from the southern reaches of the basin (Welman *pers.comm.*).

To avoid confusion when dealing with earlier subdivisions proposed in the literature, the present subzones are here correlated to their historical equivalents. At the time of Watson's (1942) subdivision, subzones A and B (Hancox *et al*, 1995) were unknown. subzone A therefore occurs stratigraphically below Watson's zone A. Watson's (1942) zone A, in which both *Kannemeyeria* and *Erythrosuchus* are present, may be equated to subzone B. His zone B may with some modification be tentatively correlated with the uppermost parts of subzone B and the lower part of subzone C.

Cooper, (1982) stated that the lower half of the Burgersdorp Formation yielded the type fauna of his *Kannemeyeria* Zone, whereas the upper part yielded only *Cynognathus* and *Diademodon*, which he believed persisted into his overlying *Tetragonias* Zone. The *Tetragonias* zone was based on the faunas of East Africa and was characterised by the FAD of the shansiodont index genus *Tetragonias*, psuedosuchian thecodonts, chiniquodontid and traversodontine cynodonts, as well as the last cynognathid, trirachodontine and diademodontine cynodonts.

Cooper's (1982) *Kannemeyeria* zone may be directly equated to subzone B. *Angonisaurus* occurs together with *Tetragonias* in the Manda Formation and although *Tetragonias* is not known from the *Cynognathus* Assemblage Zone, the newly described shansiodontid is similar. The presence of *Angonisaurus*, coupled to the FAD of shansiodont genera and an associated fauna dominated by cynognathid, diademodontid and trirachodontid cynodonts allows for subzone C to be equated to the *Tetragonias* Zone of Cooper (1980).

Welman *et al.* (1991) believe that the fossiliferous horizons in the Burgersdorp Formation the northern part of the basin were the equivalents of the upper part of the Formation in the south. That this is not the case is proved by regional stratigraphic studies, and by the primitive nature of the fauna from the north. The majority of the fauna documented by Welman *et al.* (1991) may be included within subzone A.

3 MOLTENO FORMATION

3.1 Introduction

In this Chapter, the general geology of the Molteno Formation is discussed and the Bamboesberg and Indwe Sandstone Members are documented in terms of their lithology, palaeontology and spatial and temporal variability. A neostratotype for the Bamboesberg Member is proposed and the Member is formally defined (Appendix 5) following the guidelines set out in SACS (1987).

The two units of the Molteno Formation under investigation, namely the Bamboesberg and Indwe Sandstone Members, are the same as those recognised by Turner (1975a), Christie (1981) and MacDonald (1993) for this region of the Eastern Cape (Table 1.3c) and are the only two Members formally recognised by the South African Committee for Stratigraphy (SACS, 1980). The strata above the Indwe Sandstone Member were also studied during the course of fieldwork, but a number of the informal units (Table 1.3b,c) defined by Turner (1975a), Christie (1981), and Christie & MacDonald (*in prep.*) could not be recognised. The strata above the Indwe Sandstone Member differ fairly considerably on a regional scale and new nomenclature would have had to be erected to define this sequence of rocks, especially in the Bamboeshoek Valley where the succession is formed by a complex transitional phase from the Indwe Sandstone Member through to the Elliot Formation. A detailed study of these strata was beyond the scope of this work and, as mentioned in Chapter One, for the purpose of this thesis the strata of the Molteno Formation above the Indwe Sandstone Member are grouped together and referred to as the "Transitional" Member (Turner, 1975a).

3.2 General Geological Description

The Molteno Formation overlies the Burgersdorp Formation (Beaufort Group) and forms the basal subdivision of what was previously termed the "S[illegible] Group". In the south of the basin, the lower contact is take[illegible] of the

Bamboesberg Member of the Molteno Formation (Turner, 1975a) and is currently defined as a transitional zone with the Burgersdorp Formation, some 100m thick (Johnson & Hiller, 1990). In the north of the basin, the basal contact occurs between the Burgersdorp Formation and the Indwe Sandstone Member (Fig.1.1) and is in most places sharp and erosional. The upper boundary of the Molteno Formation as defined by DuToit (1954), Ryan (1963), Botha (1952, 1968), Haughton (1969), Turner (1975a) and Christie (1981) is regarded as being gradational and conformable with the overlying Elliot Formation.

Geographically the Molteno Formation outcrops over an area of some 25000km^2 (Turner, 1983), extending from the Eastern Cape Province, northward through Lesotho and into the Free State, and eastward into Natal (Fig.3.1). The most extensive and stratigraphically complete exposures of the Formation occur in the northeastern Cape, south of the towns of Aliwal North and Matatiele (Fig.3.2). Geometrically the Molteno Formation is wedge shaped in south-north cross section and has previously been sub-divided into three sedimentary packages (Turner, 1983), all of which thin northwards away from the proposed source area (Fig.1.1). These three sequences approximately equate to the Bamboesberg, Indwe Sandstone and "Transitional" Members as used in this thesis. Within the upper of these three main packages, a number of smaller cycles have been recognised (Turner, 1975a; Christie, 1981, 1986; Cairncross *et al.*, 1995).

No single type locality has been proposed for the entire Formation, and instead a composite type was proposed, with each Member assigned a type locality (Turner, 1975a; Christie, 1981). The type locality for the Bamboesberg Member is situated in the hills above Grootdoringhoek Pass and that for the Indwe Sandstone Member, directly behind the town of Indwe itself (Fig.1.2).

The strata of the Molteno Formation are not structurally complex, being deformed only into broad, open anticlines and synclines. These structures trend north and northeast and have a horizontal to sub-horizontal attitude, with an inward dip towards Lesotho. Dolerite sills and dykes, ranging in thickness from a few centimetres to several hundred metres, are the main cause of structural complexities, inducing gentle easterly and westerly dips to the strata. This is especially the case in the area between Sterkstroom and Indwe, where the Glen Grey dolerite swarm (DuToit, 1905a) accounts for nearly all observed displacement. These dolerite intrusions also discolour and metamorphose the lithologies into which they intrude to varying degrees. The proximity to large intrusive dolerites has particular impact when dealing with the rank of the coal of the Formation, or when sampling rocks for palynological studies.

A small amount of faulting is believed to have occurred prior to dolerite emplacement (Turner, 1971; MacDonald, 1993). These authors note that such faults do not exceed a few kilometres in length and rarely have displacements exceeding 30m, except at Jamestown and to the north of the town of Indwe, where throws are believed to have exceeded 300m (MacDonald, 1993). Turner (1983) however states that there is a distinct absence of intrabasinal faulting in the Molteno Formation. No evidence of major faulting was observed during the course of this study.

3.2.1 Thickness

Because the upper and lower boundaries of the Formation are not well defined, numerous discrepancies occur in the literature as to the maximum preserved thickness of the Molteno Formation. This is compounded by the fact that the maximum thicknesses recorded in the literature come from different parts of the basin, where the Formation may be composed of various Members, or limited parts thereof. The primary controls on the thickness of the Formation are believed to have been erosional (Turner, 1975a) and non-depositional (Christie, 1981).

Schwartz (1903) records the earliest thickness measurements for the entire Molteno Formation of between 610-762m at Matatiele. DuToit (1905a) gives a maximum thickness of 488m for the Formation, but later increased this to 580m, for a section at Elliot (DuToit, 1911). Similar maximum thicknesses of 609m

(Haughton, 1969) and 605m (Christie, 1981) are recorded for the area between the towns of Indwe and Cala. MacDonald (1993) gives a slightly higher maximum for the Formation of 650m in the southeast of the basin. Turner (1975a, 1978, 1983) believed that early thickness estimates of the Molteno Formation were exaggerated due to the incorporation of parts of the Elliot Formation and provided a reduced figure of 460m for the southeast of the basin. Christie (1981) notes that Turner (1975a) did not correctly place the upper boundary in terms of the parameters that he outlined for its identification, and therefore underestimated its true thickness.

A number of other maximum thickness figures that appear in the literature suffer from the fact that they are not dealing with the entire Formation. Dunn's (1873, 1878) recorded maximum thickness for the Coal Measures" of 305m near the town of Molteno encompasses only the upper part of the Bamboesberg, the entire Indwe Sandstone and lower parts of the "Transitional" Members, as does Robinson's (1969) figure of 385m for the area to the south of the town of Molteno. DuToit (1905b) records thicknesses for the Formation of 305m south of Aliwal North to between 45-75m at Aliwal North (DuToit, 1905b). MacDonald's (1993) figure of 90m at Aliwal North accords well with this. Turner (1975a) gives a maximum thickness of 30m for the Formation in the north of the basin near the town of Bethlehem. In the northern margins of the basin, only the Indwe Sandstone and parts of the "Transitional" Member are preserved.

As noted previously, the spread of thickness estimates for the Molteno Formation is primarily due to the confusion regarding the placement of the lower and upper contacts. The placement of the lower contact is defined in this Chapter, and its nature is more fully discussed in Chapter Four. Prior to presenting the maximum thicknesses recorded during this study, it is necessary to briefly present the criteria used for the placement of the upper boundary.

For the purpose of this investigation the upper contact of the Molteno Formation was taken as the top of the uppermost coarse sandstone within the Molteno Formation. This sandstone lies above the dinosaur tracks reported on by Raath *et* *al.* (1991) and co-incides with an important palaeontological break, in that tetrapod bone is unknown below the contact, whereas directly above it, fossils assignable to the *Euskelosaurus* Assemblage Zone (Kitching & Raath, 1984) (Table.1.2) are abundant. These criteria are similar to those used by Turner (1975a) and Christie (1981), except for their use of the red colour of the Elliot Formation in their placement ot the boundary. Colour is not considered significant in the placement of the contact, as red colouration occurs in the fine components throughout the "Transitional" Member.

Thicknesses recorded for the entire Molteno Formation during the course of this study range from 550-605m in the Bamboeshoek Valley, to 240m south of Aliwal North. North of Rouxville, the three main sequences are still preserved, but with a very reduced thickness of between 15-35m. North of Vanstadensrus, the Molteno Formation is represented by only by the Indwe Sandstone and "Transitional" Members, and at places in the north, only by the Indwe Sandstone Member. In the north of the basin measured thicknesses of between 12-15m were recorded on the farm Fraaiuitsicht (Rosendal district) and on the Senekal-Ficksburg road.

From the above thickness measurements it is evident that the Molteno Formation is thickest in the southeastern parts of the basin and thins gradually in a north and northwesterly direction until the area surrounding Aliwal North, where a rapid decrease in thickness occurs. In the area surrounding the town of Rouxville, the Bamboesberg, Indwe and "Transitional" Members are dramatically reduced in thickness, with regards to their southern sections, with the whole Molteno Formation being only ±25m thick. North of Rouxville, the Formation maintains a fairly constant thickness, thinning from ±25m to 10m over a distance of some 250km. The thickness figures for the Molteno Formation recorded during this study accord fairly well with those of DuToit (1911), Haughton (1969) and Christie (1981) for the south of the basin, but differ from the figure of 460m supplied by Turner (1975a). Measured thicknesses in the middle and north of the basin accord well with the figures of DuToit (1954), Haughton (1969) and MacDonald (1993) for the area around Aliwal North and Turner (1975a) for the northern margin.

3.2.2 General lithology

The Molteno Formation is composed predominantly of sandstone with subordinate siltstone, mudstone and coal. In the past the Molteno has often been lithologically distinguished from the overlying Elliot and underlying Burgersdorp Formations solely on its predominantly arenaceous character. Sandstone percentage is however variable throughout the Formation and ranges from almost 100% for the Indwe Sandstone Member in the north of the basin, to only 20% for some of the argillaceous units of the "Transitional" Member in the south of the basin.

In many places, the sandstones grade vertically into siltstone and mudstone, creating fining upward sequences between 5-50m thick. Grainsize for the sandstones varies from fine to very coarse, with pebble to cobble size intra- and extra-formational clasts dispersed throughout. Extra-formational clasts are predominantly blue-white quartzites of the Cape Supergroup (Rust, 1959, 1962). The intra-formational clasts are predominantly siltstone and mudstone, although reworked silicified wood also occurs. The sandstones are generally yellowish grey (5Y 7/2), pale yellowish brown (10YR 6/2), moderate yellowish brown (10YR 5/4), to pale blue (5PB 7/2) and very light grey (N8) in colour. The majority of fossils in the sandstones are fragmentary megaplants, imprints of stem axes and well preserved horsetail casts. At a few localities fossil fish are preserved in the sandstones (Cairncross *et al.*, 1995), however none were discovered during this study.

Individual fining upward cycles are usually topped by siltstones and mudstones, which range in colour from dark grey (N3) to light olive grey (5Y 6/1), and dark reddish brown (10R 3/4) to dusky red (5R 3/4). The fines usually contain the best preserved fossil megaplant material and are also known to contain insect fossils (Cairncross *et al.*).

A number of coals seams occur in the Molteno Formation and these have previously been recorded by DuToit (1905), Turner (1971, 1975a), Christie (1981), Heinemann (1988) and MacDonald (1993). The stratigraphic occurrence of these seams is not well understood and is discussed later in this Chapter. Coals are normally only sporadically developed and are often only carbonaceous mudstones. Although mined in the past, and currently to power a brickworks, they are of little to no real economic potential. The coal is predominantly durain to clado-durain and is high in ash content, with values ranging from 50-60% for the raw material (MacDonald, 1993). The rank of the coal decreases from east to west.

The mean palaeocurrent directions for the Molteno Formation in the south of the basin range between 015° (Turner, 1975a) and 330° (Christie, 1981). Turner (1975a) gives a figure of 310° for the mean in the north of the basin which, when combined with his mean for the south, gives a basinal mean of 330°.

3.3 Bamboesberg Member

3.3.1 General geological description

The Bamboesberg Member (Turner, 1975a; SACS, 1980) is the basal Member of the Molteno Formation and lies stratigraphically between the Burgersdorp Formation (Beaufort Group) and the Indwe Sandstone Member of the Molteno Formation (Fig.1.1; Table 1.1). Where the Member is preserved to its maximum extent, the basal contact is usually sharp and erosional. The top contact is at all localities marked by the base of the overlying Indwe Sandstone Member and in many places co-incides with a concentration of extra-formational clasts informally named the "Kolo Pebble Bed" (Turner, 1975a) (Table 1.3a,b).

The Member is named after the Bamboesberg Mountains in the Eastern Cape Province, and the type section is located within this mountain range at Grootdoringhoek Pass (Fig.1.2). MacDonald (*in prep.*) proposed two reference stratotypes for the Bamboesberg Member, the first at Cala Pass, and the second some 20km southeast of the town of Molteno. Presently there is no type area for the Bamboesberg Member, however the the Bamboeshoek Valley to Bushmanshoek

Pass are is proposed in this thesis (Appendix 5). A brief description of the sedimentology of the Bamboesberg Member at the type locality is given by Turner (1975a) and for the area around Indwe and Cala by Christie (1981). The geographic outcrop area of the Bamboesberg Member has been fully mapped during this present study (Fig.3.2) and extends from north of Queenstown in the south, to Vanstadensrus in the northwest, and from Cala in the east to the Steynsburg-Molteno district boundary in the west (Fig.1.2).

Lithologically, the Member is composed of up to five stacked fining upward sequences, each of which is composed of laterally extensive sandstones, capped by thin lenticular siltstones, mudstones and rare coal. Sandstone is the dominant lithology in the Member and may form as much as 99% of the sequence in the southeast of the basin (Christie, 1981). Values up to 92% were recorded during this study, although, more typically, sandstone percentage ranges from 65-80% for the Bamboesberg Member. The sandstones are generally yellow grey (5Y 8/1) to light grey (N7-N8) in colour when fresh, and light olive grey (5Y 6/1) when weathered. The coarser sandstones frequently have a glittery appearance, caused by the secondary overgrowth of quartz, which makes field estimations of grain size difficult.

No true conglomerates were recognised in the Bamboesberg Member, although in places the bases of fining upward sequences may locally contain well rounded extra-formational clasts of blue and white quartzite. Such clasts may also occur scattered throughout individual sandstone units. Granite pebbles have been recorded in the past (Haughton, 1924) however none were observed during the course of this study. These extra-formational clasts are the most useful indicator of source area provenance, and also play an important role in deciphering the basinal fill history of the Bamboesberg Member. Intra-formational clasts of siltstone and mudstone also occur distributed throughout the sandstones.

Two coal seams have previously been recognised within the Bamboesberg Member, and these are variously referred to as the Suurkop Coal (Turner, 1975a) and the

Indwe and Guba seams (Christie, 1981). The stratigraphic affinities of these coals are not clear in the literature, a fact further compounded by the presence of numerous minor seams in the upper parts of the Bamboesberg Member. The nomenclature, stratigraphic position and importance of these coals is discussed later in this chapter.

The siltstones and mudstones vary from dark greyish olive green (5GY 3/2), dark greenish grey (5GY 4/1) to light olive grey (5Y 6/1 - 5Y 5/2) in colour dependant on the amount of included carbonaceous material and the redox state. In the lower part of the Bamboesberg Member the fines may also be dark reddish brown (10R 3/4) to dusky red (5R 3/4) in colour.The carbonaceous mudstone ranges from dark grey (N3) to grey black (N2) to greenish black (5G 2/1). The coal in the Member is black (N1). Well preserved fossil megaplant remains are frequently concentrated on bedding plains, as well as randomly interspersed within the siltstones and mudstones.

3.3.2 Thickness

As defined in the previous section, the Bamboesberg Member is restricted to a relatively small area along the southern rim of the main Karoo Basin, extending some 160km north of its most southerly outcrop near Queenstown. Previous workers present a wide range of maximum thicknesses for the Bamboesberg Member, dependant on where in the basin they were working. Rust (1959, 1962), Turner (1975a) and MacDonald (1993) give maximum thicknesses of 257m, 162.8m and 240m respectively for Bushmanshoek Pass in the south of the basin. Christie (1981) provides a maximum thickness of 120m at Cala Pass in the southeast and MacDonald (1993) a maximum thickness in the west of 101m. This thickness was based on borehole SF1/85, drilled to the west of the town of Molteno.

The Bamboesberg Member furthermore follows the regional trend of the Molteno Formation in thinning rapidly from south to north (Fig.1.2; 3.3a). Turner (1975a) documents thickness changes for the Member from 115 m in the area to the south of the towns of Indwe and Cala, to approximately 70 m at Indwe. He also records figures of 128m to the east of Elliot and an anomalous low of only 31m southeast of Maclear. Christie (1981) gives figures of between 115-128m (average of 90m) for the Bamboesberg in the southeast of the basin near the towns of Indwe and Cala, and notes that the Member thins rapidly northward, being only 70m in the area to the north of the town of Indwe. MacDonald (1993) gives an average of 150m for the Member in the south of the basin, noting that it thins to less than 100m in places. Johnson (*pers.comm.*), notes that thicknesses variations from 175-235m seem to characterise the Bamboesberg Member in the Indwe to Sterkstroom area, whereas his average for Aliwal North is only 25m.

Although thickness changes occur throughout the spatial range of the Bamboesberg Member (Fig.3.3a,b), most of the thickness discrepancies that occur in the literature may be accounted for by the fact that a number of previous workers have misplaced the upper and lower boundaries of the Member. This factor has tended to increase or decrease the thickness to varying extends. Due to the indeterminate nature of the basal and upper contacts, most of the thicknesses supplied in the literature must be viewed with some suspicion, unless firm reasoning is given for the choice of lower and upper boundaries.

Due to the proposal in this thesis of Bushmanshoek Pass as a neostratotype for the Bamboesberg Member (Appendix 5), it is necessary to briefly discuss the thickness figures provided for this area. Rust's (1959, 1962) figure of 257m is considered to be too high, as his placement of the lower boundary was actually within the Burgersdorp Formation and he therefore increased the thickness by some 30m. A re-calculation of his figures without the included Burgersdorp section provides a total of 227m. Turner (1975a) gives the lowest figure for the Pass (section 72), being only 162.8m. This figure is felt to be an under-estimation due to his placement of the Indwe Sandstone Member low in the succession here, as well as his uncertainty regarding the basal contact. Adding the extent of the top Bamboesberg sandstone and overlying carbonaceous mudstone at this section would increase this figure by some 30m to 192.8m. MacDonald (1993) gives a figure of 240m for the Bamboesberg Member in Bushmanshoek Pass, but does not state what parameters he used for defining the upper and lower boundaries. Measured thicknesses recorded for Bushmanshoek Pass during this study are 194.67m, 198.4m and 206m respectively. Thickness ranges for Bushmanshoek Pass may therefore be realistically grouped between ±192-215m, making this section the thickest preserved sequence of the Bamboesberg Member anywhere in the basin (Fig.3.3).

Measured thicknesses for the Bamboesberg Member were recorded at a number of localities throughout the basin (Fig.1.2) and this data was supplemented by a single core (SF1/85) drilled by the Council for Geosciences. This core was originally believed to have intersected upper Burgersdorp Formation strata (MacDonald, 1993). Re-examination of the core found that the red mudstone that MacDonald (1993) used to define the uppermost Burgersdorp, actually occurs within the lower part of the Bamboesberg Member and is underlain by a coal bearing sandstone. Thus the entire Member was not drilled and the preserved thickness of the Bamboesberg Member in this core is 103.36m.

Measured thickness variations for the Bamboesberg Member are presented in Figure 3.3, which clearly shows that the Bamboesberg Member thins east, west and north from a maximum thickness of ±215m in the Bushmanshoek Pass area. Between Bushmanshoek Pass and the type section at Grootdoringhoek Pass, the Member is only partially preserved at surface, and only drilled to a depth of ±104m west of the town of Molteno. At the type section at Grootdoringhoek Pass (some 30km west of the town of Molteno) the Member is 85m thick, thinning to only 60m at its westernmost occurrence on the farm Hillside (Steynsburg district), where the Member is preserved in its entirety as an uplifted outlier. To the east of Bushmanshoek Pass, the Member does not outcrop at surface until near the town of Dordrecht and borehole data is not available. In this area the thickness and contact relationships of the Bamboesberg Member are greatly affected by massive dolerite intrusions of the Glen Grey Sheet (DuToit, 1905) and by the regional easterly dip. Borehole data from Christie (1981) suggests that the thinning in this area was structurally controlled. At and around Cala, the Member has a fairly constant thickness of between 110-120m. On the preserved eastern margin thicknesses of between 60-80m are recorded (Christie, 1981). North of Bushmanshoek Pass, the Member is not preserved at surface until south of Aliwal north, where the thickness is between 40-60m. The south to north thinning from Bushmanshoek Pass to south of Aliwal North is fairly rapid (Fig.3.3b), with the thickness falling from ±215m to ±70m over a distance of 100km. A rapid thinning occurs at Aliwal North, and just to the north of the town, the Member is only 22m thick. The most northerly occurrence of the Bamboesberg Member occurs between Zastron and Vanstadensrus, where the Member is preserved as a single 3m thick fining upward sequence of sandstone through to coal.

From the recorded thickness measurements it is evident that the Bamboesberg Member thins rapidly in a south to north direction, as well as thinning consistently east and west from a maximum thickness in the Bushmanshoek Pass area. It therefore seems that the basin was deepest in the Bushmanshoek Pass area and that the south to north, and symmetrical east and west thinning may be accounted for by original basin topography.

3.3.3 Sedimentology

3.3.3.1 Lithofacies descriptions

For the Bamboesberg and Indwe Sandstone Members, full lithofacies descriptions are given, but extended interpretations are presented only where they differ significantly to those found in the Burgersdorp Formation. As for the previous Chapter, facies are broadly defined following the scheme of Miall (1977, 1978, 1996).

A) Sandstone Facies (S)

Sandstones are volumetrically the most abundant lithology in the Bamboesberg Member. Grainsizes within the sandstone facies range from fine to very coarse sand and individual grains may be angular to well rounded. Feldspar tends to be more angular than quartz of a similar size. Pebbles and cobbles occur sporadically within most facies but are more usually associated with the coarser sandstones. Sorting is variable dependant on facies type, but in general the fine to medium grained sandstones are poorly to moderately sorted, whereas the coarse sandstones are well to very well sorted. Extra-formational clasts are predominantly blue/grey quartz arenites, brown lithic arenites and minor amounts of vein quartz. Soft sediment deformation (Figs.3.4, 3.5) is rare in the fine grained sandstones of the Bamboesberg Member, being more abundant in the coarser fraction. They occur as convolutions composed of regularly spaced folds which die out upwards and downwards within a bed and do not cross bounding surfaces (Fig.3.6).

a) <u>Heterolithic Scour Fill</u> (Se$_h$)

Facies Se$_h$ is a matrix supported, heterolithic lag and scour fill sandstone facies, with both intra- and extra-formational clasts present together (Fig.3.7). This facies equates to the rock pebble conglomerate (Cp) of Christie (1981), but because true conglomerates are not present in the Bamboesberg Member, these pebbly sandstones are rather included under the sandstone facies.

The matrix consists of poor to very poorly sorted medium to coarse-grained feldspathic sandstone. Intra-formational clasts consist mainly of subangular to subrounded discs of mudstone, siltstone and fine grained sandstone, sometimes with included fossil plant material. These fossils are mostly fragmentary leaves, stems and small logs, which form part of the lag fabric. Megaplant fossil remains occur as two-dimensional impressions or as three-dimensional compressions. The compressions may be either coalified or completely altered to haematite, and the original material tends to weather out, leaving behind a three dimensional mould.

Extra-formational clasts are predominantly rounded to well rounded pebbles of blue/white quartz arenite, although subangular clasts are also documented. Vein quartz is rare and chert was not recorded for the Bamboesberg Member, although chert is known from the overlying Indwe Sandstone Member (Turner, 1975a). Clast size averages 12cm, with the largest recorded clast size being 65cm. The clasts have intermediate to long axis (I/L) ratios of between 0.46 and 0.95 and short to intermediate axis (S/I) ratios of between 0.22 and 0.78 (Appendix 7). These ratios fall predominantly within the oblate and equant fields of the shape classification of Zingg (1935).

Lag set thicknesses range from 30-80cm (average 40cm) and are discontinuous, extending laterally no further than 15-20m. The base of a set is undulatory in nature and may take the form of an erosional surface of limited relief. This facies is generally unstratified, although crude internal stratification was documented.

Facies Se_h is interpreted as channel lag and scour fill deposits formed in response to scouring of the sides and floor of the channels as they shifted across a well vegetated braidplain, with pebbles being deposited following peak flow. The build up of a basal lag of coarse detritus would tend to increase the channel bed surface area and frictional resistance, thereby bringing about a decrease in flow velocity, in turn resulting in the deposition of finer grained material as interstitial matrix.

b) Intraclast Conglomerate (Se_i)

The intraclast conglomerate facies (Fig.3.8) differs from the heterolithic scour fill in that extra-formational clasts are not present and the clasts are exclusively of siltstone and mudstone. Intraformational fossil plant debris may also be present, but is subordinate in amount. In most cases facies Se_i is preserved at the base of massive, horizontal and cross-stratified sandstone sets, as discrete lag deposits (Fig.3.9), as well as randomly dispersed throughout sets. Se_i grades both vertically and laterally into other facies types, particularly St_i and Sh_b. This facies is therefore only locally developed, normally at the base of a larger architectural element, and for this reason Miall (1996) abandons it as a discrete facies. Set sizes range from 10cm to more than 50cm.

Dependant on the nature of the hosting architectural element, the matrix ranges from medium to coarse grained, poorly to moderately sorted sandstone. Clasts are predominantly disc-shaped with diameters between 1-30cm, although usually no more than 5cm, and frequently less than 2cm in size. Clast sizes tend to be larger in the finer grained sandstones. In places the siltstone clasts preserve deformed internal lamina, which represent evidence of liquefaction prior to reworking.

Facies Sc_i is believed to be formed by the erosional scour of intraformational silts and muds, and their reworking prior to deposition. The presence of deformed laminae within the siltstone clasts, attests to soft sediment deformation prior to the clasts being incorporated into the sandstones. The fact that larger clasts tend to occur in the finer facies may be directly attributable to less abrasion and rounding under lower flow regime conditions.

c) <u>Trough cross-stratified</u> (St)

Facies St (Fig.3.10) occurs in fine to coarse grained sandstone and in many places has rounded to well-rounded extraformational quartzite clasts scattered throughout sets. These extraformational pebbles are more abundant in the coarser sandstone fractions. St is, sub-equally with horizontal stratification (facies Sh), the dominant facies type for the sandstones of the Bamboesberg Member. The percentage of St is however higher in the coarser sandstones of the Bamboesberg Member, whereas Sh is higher in the finer grainsizes.

Sets occur as wedge, tabular and channel fill scours and in many instances preserve concave down, erosive bases. Facies St may be further sub-divided into large (St_l) (Fig.3.11) and small scale sets (St_s). Large scale sets ($\geq$1.0m thick and up to 7m wide) and co-sets are more common in the coarser sandstones, whereas small scale, solitary sets (15-50cm thick and 30-50cm wide) are more abundant in the finer grained sandstones. In most cases solitary sets have a sharp basal bounding surface, and co-sets tend to mutually cross-cut one another. The foreset dip angle with the basal bounding surface is always less than 30° and averages between 10-15°. Mudstone and siltstone drapes may be interspersed between individual sets.

Facies St_l is generally accepted as being formed by three dimensional dune migration in the upper part of the lower flow regime (Harms & Fahnestock, 1965; Miall, 1996), where water depth exceeds 30cm. The large size of the co-sets and their lateral continuity suggests deposition by large dune field migration, in the upper part of the lower flow regime. St_s possibly owes its formation to the migration of large scale catenary ripples similar to those described by Williams (1971) and Jackson (1978b), or as proposed above for St_l but with decreasing water depth and flow regime. In the latter case the change from St_l-St_s represents a continuum of process.

d) Planar cross-stratified (Sp)

Facies Sp (Fig.3.12) is far less abundant in the sandstones of the Bamboesberg Member than either Facies Sh or St. This facies occurs most abundantly in the finer grained sandstones in the south of the basin, and may be the dominant facies type in the northern outcrop area of the Bamboesberg Member. Facies Sp occurs as individual sets between 8cm and 1m thick in fine to medium grained sandstones, which are moderately to well sorted. Lateral continuity is normally restricted to less than 5m, but in rare instances may reach 25m. Individual sets may be tabular or wedge shaped, with sharp, flat upper and lower boundaries. Facies Sp occurs randomly interspersed with facies Sh and St and as co-sets with facies St (Fig 3.13). Foresets may be either tangential or discordant and dip at a maximum angle of 16°.

Palaeocurrent directions measured from these sets are generally oblique or normal to the main flow direction as determined from more reliable indicators such as trough cross-stratification (Rust, 1972, 1978; Allen, 1982). Small scale co-sets, 8-25cm thick, preserve evidence of palaeocurrent direction parallel to the main flow.

Facies Sp in the Molteno Formation has previously been proposed to form by the migration of two dimensional, straight crested sandwaves (Cairncross, *et al.*, 1995). The dip of the foresets is indicative of simple transverse channel bars with active slip faces (Williams, 1966; Rust, 1978) Sets which exhibit near normal palaeocurrents are thought to represent transverse (cross channel) bar foreset migration during sand flat growth (Banks and Collinson, 1974), and may cross both the main channel and the braidplain. The origin and growth of such bars is explained in detail by Smith (1970, 1971). Small scale sets with palaeocurrents parallel to palaeoflow represent the migration of simple, two dimensional, straight crested sandwaves as previously documented for the Molteno Formation by Cairncross *et al.* (1995).

e) Massive Sandstone (Sm)

Facies Sm (Fig.3.14) consists of structureless, apparently structureless and faintly irregularly stratified sandstones, that occur locally near the base of sandstone sheets, or as thick (1-3m) individual sets. Grainsizes documented for this facies range from fine to coarse sand, and the facies is poorly to moderately well sorted. This facies may be fairly localised and laterally inextensive, or traceable down palaeoslope for distances of up to 100m. Intra- and extraformational clasts and carbonaceous material may be randomly distributed throughout sets, but do not form discrete layers. The basal contact of a set is usually sharp and erosive with the top contact abrupt or gradational into finer grained sandstone.

The erosive nature of their bases, the presence of rare well rounded quartz pebbles and numerous pellets of mud and siltstone, as well as the absence of sorting and grading, point to transportation by a single high energy (upper flow regime), but fairly short lived event, with rapid dumping of sediment. In the semi-massive facies, faint relict bedding may be due to the obliteration of internal structure by hydraulic creep or dewatering.

f) Horizontally stratified (Sh)

Sh (Fig.3.15) is the most abundant facies in the finer grained sandstones of the Bamboesberg Member. Locally this facies may account for up to 70% of the facies assemblage present. Facies Sh is preserved in fine-medium grained, poorly to moderately well sorted sandstones. As for the Burgersdorp Formation, facies Sh may be sub-divided into Sh_b,Sh_i and Sh_t dependant on where in a given sequence it occurs. Sh_i and Sh_t equate to the sub-horizontal and irregularly planar stratified sandstone (S_{ip}) of Christie (1981).

Facies Sh_b occurs as individual sets between 10-25cm thick and as co-sets up to 2.0m thick. The sets are laterally extensive, forming sheets up to 150m in length. Grainsize often decreases within a sequence and Sh_b may grade vertically into Sh_i, Sh_t or Sr. Laminae within sets are parallel, and at places are well delineated by discrete concentrations of heavy minerals (Fig.3.16), predominantly rutile and garnet.

Facies Sh_i and Sh_t are similar in nature, tend to occur as sets up to 25cm thick, and form co-sets up to 1.0m. This facies tends not to be as laterally continuous as facies Sh_b. The internal laminae are [illegible] as well defined and may be sub-parallel in nature, especially towards the top of a set, where Sh_t grades into overlying Sr. The dip on individual laminae reach up to 5°-10° in places, however they always flatten out prior to reaching a bedding plain.

The bedding plain surfaces of facies Sh_b and Sh_i frequently preserve current parting lineations (Fig.3.17). This is the primary sedimentary structure on which palaeocurrent trend is obtained for the finer grained sandstones of the Bamboesberg Member. Bed top surfaces are often highly micaceous and may also contain siltstone clasts and whole and fragmentary carbonaceous fossil plant material.

Facies Sh_{bs}, with bed top parting lineation are documented as forming under high velocity, laminar flow, by currents in the upper flow regime (Allen, 1964b; Picard & High, 1973). The upward decrease in grainsize and gradational change into other facies, including Sh_t and Sr, probably reflects a response to waning flow following peak discharge. Where the upper contact is sharp and there is little or no grainsize variation within a set, deposition is thought to represent a single high velocity event.

g) Ripple cross-stratified (Sr)

Facies Sr (Fig.3.18) is locally well developed in the Bamboesberg Member. This facies occurs exclusively in grainsizes ranging from fine to very fine sand and tends to be moderately to poorly sorted. Sets may be up to 50cm thick, but are typically between 5-20cm. Sets are not laterally continuous and may grade locally into St_s, thereby forming a continuum between St_l-St_s and Sr. Asymmetric current rippled bed top surfaces are locally well developed and ripples are predominantly of the linguoid type, with lesser sinuous and straight crested forms also preserved. Ripple amplitudes range from less than 1cm up to a maximum of 3cm, with wavelengths between 8-32cm, giving ripple indices of between 6-12.85.

Facies Sr is believed to form in the lower flow regime by sand ripple migration (Allen, 1971, 1982). The variety of internal structuring evident may be attributable to changes in flow velocity and sediment supply during deposition (Allen, 1982). Their positioning relative to other facies suggests that they are predominantly formed as bar top deposits due to changes in flow regime during shallowing, or during periods of high water level, when previously exposed bar tops become temporarily submerged.

B) Fines facies (F)

As for the Burgersdorp Formation, the term fines is used to cover lithologies ranging from very fine-grained sandstones to siltstones and mudstones. Mudstone and siltstone form a relatively minor component of the total facies assemblage of the Bamboesberg Member, but have received a fair amount of attention in the past due to the fact that they host the coal seams and the best preserved fossil material.

The fines are often massive (structureless) or horizontally laminated, with a small percentage of ripple cross-lamination. The siltstones and very fine sandstones are often micaceous and usually finely laminated to structureless. Except in the case of the proposed lacustrine deposits, they normally form laterally inextensive bodies less than 3.0m thick. The fines are often richly fossiliferous, with well preserved megaplant material concentrated on bedding plains. The mudstones are often massive and may be highly carbonaceous.

a) Matrix supported heterolithic clast accumulations (Fe$_h$)

Facies Fe$_h$ is unique to the Bamboesberg Member in the study area and consists almost exclusively of small ($\leqslant$2cm) intra-formational clasts of mudstone (subfacies Se$_i$) (Fig.3.19) but with rare quartz arenite pebbles up to 8cm also present (Fig.3.20) and the larger clasts may show rough imbrication. The matrix of this conglomeratic accumulation consists entirely of mudstone. Individual sets range in size from 4cm to 30cm and may be normally or inversely graded.

This facies is somewhat unusual in that very fine mudstone and quartz clast are preserved together. The normally graded beds are thought to be developed by suspension settling of mixed mud and mudstone clasts from sediment laden currents entering a standing body of water. The inversely graded beds with larger clasts and quartzite probably represent traction driven bedload deposits prograding into a standing body of water.

b) Massive (Fm)

Facies Fm includes structureless to faintly laminated fines (Fig.3.21) which may show faint colour banding. Facies Fm may occur as thick (1-2m), laterally extensive deposits or as thin (<20mm) deposits draped onto the tops of other facies, in which case the lower surface conforms to the gross morphology of the underlying bedform. Soft sediment liquefaction features are fairly common and faintly mudcracked bed-tops attest to very infrequent periods of desiccation. Well preserved carbonaceous fossil plant compressions are fairly common within this facies.

Facies genesis is thought to be due to the settling of suspended load fines from low energy currents in the lower part of the lower flow regime. This probably occurred in abandoned tracts and low lying areas within and surrounding the main flow locus.

b) Ripple laminated (Fr)

Ripple laminated fines (Fr) (Fig.3.22) with and without climbing lamination occur as thin (<15cm) isolated or laterally continuous sets up to 150m in length. This facies grades upward into facies Fm or Fh. In the upper part of the Bamboesberg Member, these deposits are often silicified to form chertified horizons, with well preserved fossil plant material on the bed tops.

Straight, asymmetric, sinuous crested and linguoid ripples are typically formed on the bed tops of such sets. Amplitudes range from 1-20mm. Straight crested ripples are formed at slightly lower flow velocities than linguoid ones, with sinuous crested forms believed to represent intermediate bedforms (Harms *et al.*, 1975). Climbing ripples are currently held to form by the migration and upward growth of ripples with excessive supply of suspended fine sediment (Allen, 1971) and are indicative of weak currents in the lower part of the lower flow regime (Reineck & Singh, 1973).

c) Horizontally laminated (Fh)

Facies Fh consists of horizontally to irregularly planar laminated fines (Fig.3.21) forming beds up to 20cm thick. Organic rich laminae and whole fossil plant compressions occur throughout. Facies Fh may have intercalations of very fine to fine-grained sandstone and at places may exhibit soft sediment deformation.

This facies is indicative of flow regimes too low to allow for traction movement (Hamns & Fahnestock, 1965) and are thought to represent back channel and braidplain suspension deposits in the lower part of the lower flow regime, where flow turbulence is insufficient for the formation of ripples.

e) Coal and Carbonaceous Mudstone (C)

Although it comprises less than 5% of the total facies abundance of the Bamboesberg Member, coal has been the subject of numerous studies since the earliest investigations of the Molteno Formation. Turner (1971) reviewed the early investigations undertaken between 1856 and 1948, as well as work carried out by Federale Mynbou in 1960-61 and the Geological Survey between 1965-67. Since this time, studies by Christie (1981), Heinneman (1986) and MacDonald (1993) have advanced the knowledge of the coal seams to the present state found in the literature.

Coal and carbonaceous mudstone (Fig.3.23a) in the Bamboesberg Member is typically horizontally zonated, with bands of dull (inertinite/fusinite) and bright (vitrinite) coal (Fig.3.23b) alternating with carbonaceous siltstone and mudstone. Seams up to 4.5m thick are documented at Indwe (Christie, 1981) however during the course of this study a maximum thickness of only 1.2m was recorded for seams in the Bamboesberg Member. The coal seams do not have basal underclays or rooted horizons and are typically thin and discontinuous, occurring as lenses up to 50m in length. Coal seam thickness is variable due to original palaeotopography, non-deposition and erosion. This is particularly true for the uppermost coal in the

Bamboesberg Member, which is often directly overlain by the erosive base of the Indwe Sandstone Member.

Coal samples were not analyzed for proximal, ultimate or maceral characteristics and the following coal properties are combined from reports by Christie (1981), Heinneman (1986) and MacDonald (1993). The coals are durain to cladodurain rich, with high ash values, ranging from 30-85% for the raw material. The mineral component consists of clay, calcium and magnesium carbonates, pyrite, marcasite and trace amounts of chloride, fluoride and phosphorous (Turner, 1971). They range in rank from low-volatile bitumous to anthracite and are generally fairly vitrinite rich. The fixed carbon content ranges from 30-81% (MacDonald, 1993).

Although the coal seams do not have basal underclays or rooted horizons, the excellent preservation of plant material within the carbonaceous mudstone intercalations suggest that they were at least part autochthonous in nature. The autochthonous organic component was most probably derived from plant material growing in and around the edges of standing bodies of water. The high ash contents of the coal is most likely due to the introduction of mineral matter during peat formation, by aeolian or fluvial processes.

The coal deposits and the intercalated carbonaceous mudstone are interpreted as backswamp peat deposits and areas of plant colonisation and compaction on abandoned terrace and braidplain hollows. The alternating bands of bright and dull coal are considered to be the result of fluctuations in the water table level. Bright bands are thought to represent times of high water table levels, while the dull bands and carbonaceous mudstone represent times of lower levels.

Apart from typical coal deposits, coalified stringers within the sandstones may also be included in this facies. Coalified logs occur within the sandstone horizons and layers of charcoal (fusain) are often associated with the coarse sandstone horizons within the Bamboesberg Member. The fusain within the sandstones may represent either reworked and oxidized peat accumulations, or evidence of a large palaeofire.

The occurrence of fusain in the upper part of the Bamboesberg Member at the same stratigraphic horizon over distances of tens of kilometres would tend to favour the latter.

3.3.4 Architectural element associations

As previously noted by Turner (1975a) and Christie (1981), the Bamboesberg Member is composed of a number of stacked fining upward sequences, each between 10-40m thick (Fig.3.24). Where fully developed and preserved, such a sequence grades upwards from medium-coarse grained sandstone through siltstone and carbonaceous mudstone or coal. Based on recent approaches in interpreting ancient sedimentary sequences (Allen, 1983; Miall, 1985, 1996) two main architectural element associations are recognised within the Bamboesberg Member. The first association occurs within thick, laterally extensive tabular sandstone bodies assemblages and the second predominantly within the sequences of fines that occur between the tabular, sheet sandstones (Fig.3.24). Within each of these associations, different architectural elements and facies associations are documented.

The tabular sandstones of the Bamboesberg Member are characteristically laterally continuous, sheet forms, ranging from 1.5 to 6 m in thickness and traceable regionally over several tens of kilometres. The basal contact of the sandstone units is usually sharp and flat, or gently undulatory, and is often overlain by a basal accumulation of facies Se_i or Se_h. Deeply incised cutbank structures do not occur. The top contact is also usually sharp, although it may also be gradational into fine sandstone or siltstone. Due to their regional extent, the nature of their internal architectural elements, their facies relationships and the occurrence of basal erosional surfaces overlain by facies $Se_{i,h}$, these laterally extensive tabular sandstone sheets are interpreted as bedload dominated channel fill deposits (element CHS of Miall, 1996) (Cant & Walker, 1976; Cairncross *et al.*, 1995). The fines facies associations are interpreted as braidplain deposits, with the coal and carbonaceous mudstone representing deposition in permanent, to semi-permanent bodies of water.

3.3.4.1 Channel fill systems (CHS)

The rebuilding of Boesmanshoek Pass during the latter half of 1991 yielded new exposures in road cuts that were ideal for the study of the architectural elements and facies relationships of the channel fill sequences. Due to the fresh nature of the exposures, most of the following descriptions are based on this locality, coupled with observations of spatial and temporal change from other parts of the basin.

The channel fill sequences form distinctive, laterally extensive, tabular sandstone sheets, that may be correlated over many kilometres. They are generally between 5-15m thick and are internally structured by three main architectural elements, minor channels (CH), downstream accreted macroforms (DA) and laterally accreted macroforms (LA) (Fig.3.25). The basal erosional surfaces of these channel complexes represent third order contacts (Allen, 1983), whereas the individual architectural elements are bound by second order surfaces.

a) Minor channel fills (Ch)

Minor channel elements (Ch) (Figs.3.25, 3.26a,b) within the overall channel complex (CHS) occur as lenses of sandstone, overlying a convex down erosional surface. In Bushmanshoek Pass, such minor channel fills are usually up to 15m wide by 1-1.5m thick, with width/depth ratios of between 10-15. The largest minor channel was recorded in the upper part of Cala Pass and measured 80m wide by 3.1m deep, giving a width to depth ratio of 25.80.

The basal contact to a channel fill sandstone is commonly flat or slightly erosive and convex down into the underlying facies. Sedimentary structures associated with the minor channel fills include basal sole structures and bed-top parting lineation and current ripples. Internally the fill is structured predominantly by medium to large scale St, Sh and lesser Sp. Evidence of penecontemporaneous soft sediment deformation and bioturbation occurs at places. Ferruginous concretions frequently occur on the top surface of the coarser grained channel fills. Facies Se_i or Se_h commonly occur above the basal erosion. Scour surfaces within the sandstones in many places contain siltstone clasts and whole fossil plant material. In order of abundance, sandstone facies found within the channel fill sequences are Sh=St, Se_i, Sp=Sm, Sr and Se_h. Fines facies preserved in-channel are predominantly Fh and Fm, with rare Fr. Coal is not usually preserved within this facies, although carbonized plant fragments and coalified logs may be preserved. Charcoal (fusain) is present in the finer grained units of the channel fills.

The basal facies Se_i or Se_h is typically overlain by facies St_l or Sh_b and grades upwards into facies St_s and Sh_l. Individual trough thicknesses and grainsize decrease upwards in a typical channel fill, with a progression from St_l to St_s. This decrease in set thicknesses and change from St_l to St_s is thought to be a response to a reduction in flow velocity, brought about by increased frictional drag, due to in channel bedload deposition. Facies St_s may also occur interspersed with other facies within the minor channel fill sequence. These deposits may be due to seasonal fluctuations in flow rates and water depths in the channel. These sequences are interpreted as complete channel fills formed during the lateral migration of the active channel tract across the braidplain.

Cosets of facies St up to 1.0m thick overlying facies Se_i or Se_h represent only partial channel fills, with the upper Sh and Sr facies not present. This lack of the upper part of the sequence may be due either to non-deposition or erosion during channel switching and the establishment of the succeeding channel base.

Facies Sp may be randomly interspersed throughout a typical channel fill sequences and represents the internal structure to numerous different architectural element types. Individual sets of facies Sp bounded by second order surfaces are interpreted as being the internal structure to both transverse and longitudinal/linguoid bars. The distinction between these two architectural elements is based on internal palaeocurrent direction (transverse/lateral or downstream accretion) and overall gross morphology.

In places, lateral restricted (<3m long), thin (<50cm), concordant, undeformed lenticular and tabular mudrock units occur interspersed within the channel sandstones. These units usually occur above class two bounding surfaces which define individual bars. They are internally structured by facies Fr and Fm and are interpreted as bar top and terrace deposits.

b) Abandoned channel fill systems (ACH)

A typical abandoned channel fill sequence is shown in Figure 3.27. The sequence is composed predominantly of finer grained sandstones than in active channel fills, together with intercalations of siltstone and mudstone. It is predominantly structured by facies Sr, Fh, and Fr. They are also the sites of rich plant accumulations and fusain, with numerous well preserved megaplant fossils on the bedding plains. The exceptional preservation of the fossil megaplant material in these deposits suggests plants may have colonised the channel prior to fill. The lack of associated leaves, stems and reproductive structures however favours at least a small amount of transport. Plant material most probably floated into a quite water setting, became waterlogged and settled from suspension along with the mud and silt fraction. In rare instances coal may also be preserved in this setting.

c) Laterally accreted macroforms (LA)

Laterally accreted macroforms in the Bamboesberg Member include transverse bars, sand-flats and rare overbank splays. Transverse bars (Fig.3.28) are tabular elements with sharp, basal and top contacts, and are laterally continuous across the width of individual channel fills. Splay sandstones interspersed within the braidplain fines (Bf) may also be transverse in nature (Fig.3.29). Solitary sets of facies Sp are attributed to high flow stage deposition by simple bar slipface migration. Palaeocurrent directions obtained from this facies show directions between 45-90° to the flow direction ascertained from facies St_i within in-channel dune fields.

d) Downstream accreted macroforms (DA)

Downstream accreted macroforms in the Bamboesberg Member include both longitudinal and linguoid bars (Figs.3.25, 3.30). These bar macroforms have either flat or slightly concave basal contacts and convexo-planar upper surfaces. They are traceable in a downcurrent direction for between 50-120m and are internally structured by facies Sh, St and Sp. Facies Sp is far less abundant than in transverse bars, and provide palaeocurrent directions similar to those obtained from in channel dunes.

The upstream side of longitudinal bars tend to be coarser than the minor channel fills. Where bar tops are preserved unaltered they may be capped by asymmetric current ripples. The scarcity of such ripple topped surfaces in the Bamboesberg Member is probably due to their low preservation potential, especially when bar tops become channel bottoms during peak discharge. The scarcity of bar top structures was explained by Turner (1983) in terms of de-activation of the slip-face followed by non-deposition. Rippled surfaces may be continuous for some 20m or more across the width of the bar tops, thus providing an indication of the width of longitudinal bars within the system during periods of low discharge.

3.3.4.2 Interchannel fines systems (IF)

The sequence of fines which tend to overly the tabular sheet sandstone associations are also broadly tabular in their geometry. Due to the fining upward nature, the presence of carbonized leaves and silicified wood, as well as immature palaeosol development, these units are interpreted as braidplain fines (element FFP of Miall, 1996). In general, the interchannel fines preserved in the Bamboesberg Member represent vertically accreted (VA) sequences from suspended load settling in standing bodies of water. Desiccation cracks are not common in the Bamboesberg Member and where preserved, occur as thin, shallow cracks, exclusively in mudstones (Fig.3.31).

a) Braidplain fines (Bf)

The channel sandstone assemblage grades upwards into finer grained, blocky lenticular sandstones and siltstones. These sequences are usually not very thick (<10m), with a maximum thickness recorded in the first fining upward sequence of the Bamboesberg Member of 22m. In most sequences the braidplain fines are massive or horizontally laminated (Fig.3.21), with a small percentage of ripple cross-lamination (Fig.3.22).

Megaplant fossils occur in various taphonomic states within the braidplain fines facies association and apart from the abandoned channel fills, braidplain fines tend to preserve the best fossil plant material. *In situ* silicified wood also occurs within the braidplain fines elements (Fig.3.32), being most prevalent in the upper reaches of the Bamboesberg Member.

Interchannel braidplain fines form the upper component of the typical fining upward sequences preserved in the Bamboesberg Member. The lower contact with the sandstones may be sharp or gradational. Thin (1-20cm), iron and manganese rich layers with preserved clay lined box-work lattices are abundant in the lower part of the Bamboesberg Member and are interpreted as weakly developed hydromorphic palaeosols. Periodic exposure of parts of the braidplain therefore allowed for the development of weak palaeosols, which were frequently drowned.

Cairncross *et al.* (1995) document the occurrence of crevasse splay deposits in the Bamboesberg Member and distinguish them from sheetflood deposits on the basis of their limited lateral continuity. A single example of such a deposit is preserved near the top of Boesmanshoek Pass, where a 1m thick deposit of facies Sp is sandwiched between layers of carbonaceous mudstone (Fig.3.29). The direction of transport (040°) shows it to be oblique to the main direction (350°) for the associated channel elements at this locality and it therefore most likely represents a single episode splay deposit onto the elevated braidplain.

The upper contact of the braidplain fines and coal seams tend to be irregular, due to erosion by the overlying channel sequences. In places the channel sandstone complexes (CHS) completely cut down into each other to form stacked sheets, such that the braidplain fines are completely removed from the sequence.

b) Lacustrine deposits

Lacustrine deposits are differentiated from braidplain fines on a combination of their stratigraphic position, lateral continuity, the stratification of the sequence, and on the taphonomy of their palaeontological signatures (Picard and High, 1973b). Large scale lacustrine deposits are documented only from the farm Norwood in the Bamboeshoek Valley, whereas minor lacustrine and backswamp deposits are recorded throughout the spatial and temporal extent of the Member.

On the farm Norwood in the Bamboeshoek Valley, the third and fourth channel sandstone complexes of the Bamboesberg Member pinch out at the northern end of the valley and their place is taken by a laterally extensive body of blue/grey fines (Fig.3.33). Exposures of this unit occur on both sides of the Bamboeshoek Valley and form a laterally continuous layer for some 2km or more. The unit ranges in thickness between 2-15m (Fig.3.33). Lithologically this deposit is dominated by mudstones, which have subsequently been silicified. The deposit is predominantly structured by facies Fh and Fr (Fig.3.22), with lesser Fe_t and Fe_h and shows little to no bioturbation and no faunal remains.

Although the exact point of intersection of the channel and lacustrine deposits could not be mapped out, the proximal reaches of the mudrock sequence contain a number of quartzite pebbles up to 8cm in length (Fig.3.20), whereas quartzite pebbles are unknown further away from the channels. For this reason, facies Fe_t and Fe_h are interpreted as representing the channel entry points to this standing body of water. Switching of sediment distribution patterns lead to the deposition of small coarsening upward units (Fig.3.19, 3.20) by progradation of channel sands into a standing body of water. Minor fluctuations in the aerial extent of the system are shown by rare desiccation cracks in the silicified mudstones (Fig.3.31).

Abundant, well preserved monogeneric accumulations of *Heidiphylum* and *Dicroidium*, as well as mixed plant associations of *Dicroidium* and *Heidiphylum* (Fig.3.34) are preserved on the individual bedding planes near the channel entry points. Such an association of *Dicroidium* and *Heidiphylum* as sole dominants is not unusual in the Bamboesberg Member and the situation of monogeneric *Heidiphylum* and mixed *Heidiphylum/Dicroidium* occurring as interspersed layers is very similar to that described by Cairncross *et al.* (1995) at Cyphergat 111. Megaplant fossils become dominated by miscellaneous stem axes away from the entry points. The plant assemblages probably represent parautochthonous deposition, with fairly short distances of transport as shown by the relatively unmixed nature of the sample and the good preservation of megaplant leaf material. These particular deposits were probably surrounded by a low-diversity coniferous thicket of *Heidiphylum* as this is the principal community represented in the taphocoenoses. Due to the disassociated nature of the fronds and the lack of associated fruiting structures, a more distant allochtony for *Dicroidium* is proposed.

This deposit is very similar to the Peninsula exposures described by Cairncross *et al.* (1995), although these authors interpreted the deposits as representing deposition during flooding of the distal floodplain. The lateral extent of the deposit; the predominance of mudstone, with intra- and extra-formational clasts; the presence of coarse feeder channels at the same stratigraphic horizon; and the fact that well preserved plant fossils are preserved only on the inlet side, whereas stem material predominates towards the outlet side tend to favour a lacustrine interpretation.

A good example of a more restricted lacustrine setting is preserved on the farm Klipkraal (Sterkstroom district), on the right hand side of the R397 between the town of Sterkstroom and the base of Bushmanshoek Pass. At this locality the deposit takes the form of a ±5m thick unit of interlayered mudstone and siltstone underlying a prominent sandstone ledge. The unit is internally structured exclusively by facies Fh and Fm. The fine rhythmical lamination suggests suspension settling in open water bodies. From the sedimentological evidence alone it is difficult to determine the depositional environment with any certainty, other than that it must represent a very low energy deposit, such as a lake, marsh or large abandoned channel. Its palaeontological signature however mirrors that of the previous setting and suggests a small lacustrine setting.

The plant assemblage at this locality has not been studied to the species level, but at the generic level is strongly dominated by *Dicroidium* and *Heidiphylum*. This assemblage lacks diversity and appears to represent only two plant communities growing on a floodplain surrounding an open body of water. The two taxa represent a *Heidiphylum* thicket and a low diversity *Dicroidium* woodland (Cairncross *et al.*, 1995). At this locality the presence of monogeneric layers of both *Heidiphylum* and *Dicroidium* may imply that normal leaf fall was not at the same time of the season for the two genera, however similar assemblages may be created due to the proximity of the taphocoenoses to the water body.

Well drained swamps or lakes have near-surface oxidising conditions with little or no preservation of organic matter whilst poorly drained swamps or lakes are of a reducing nature which tend to preserve plant material (Coleman, 1966). The abundance of plant material associated with the lacustrine deposits of the Bamboesberg Member tend therefore to favour restricted circulation and a reducing nature for the lake waters.

3.3.5 Petrography

As for the Burgersdorp Formation, petrographic analysis of the sandstones of the Bamboesberg Member was undertaken in order to determine original grainsize, gross mineral composition and textural maturity. Samples from similar facies type were sectioned for each of the main sandstone horizons, to test for stratigraphic changes, such as those proposed by Rust (1959, 1962). Textural analyses of the sandstones were mainly concerned with detrital grainsize as quartz overgrowths on detrital grains prohibits accurate grainsize analyses in hand specimen. Microscope analysis was therefore essential for the original grainsize of Bamboesberg sandstones to be determined.

3.3.5.1 Petrographic descriptions

The finer grained sandstones of the Bamboesberg Member are generally minerally and texturally submature, with moderate to poor sorting and sub-angular to well rounded grains. These finer sandstones have a fairly high percentage of clay matrix. The coarser sandstones tend to be mineralogically and texturally more mature, with high percentages of quartz, rounded to well rounded grains and far less matrix. The coarser sandstones tend to be cemented by rim cement, however they are generally more friable than the finer grained units.

a) Framework Grains

The major framework grains in the sandstones of the Bamboesberg Member are the light minerals, quartz and feldspar as well as numerous rock fragments.

i) Quartz

Quartz (Fig.3.35) is the principle component of the channel sandstones, as well as being fairly abundant in the braidplain rocks. Individual grains are generally subrounded to subangular, although well rounded grains are also present. Most of the grains show unit extinction, with only ±10% exhibiting undulatory extinction, showing that they have undergone strain to greater or lesser degrees. Many grains show fine tracts of inclusions and more rarely, small acicular rutile and zircon inclusions are present within the quartz grains (Fig.3.36). Long, point and floating contacts (Fig.3.35) are most commonly developed between detrital grains, although sutured and concavo-convex (Fig.3.36) grain boundaries also occur.

Both the fine and coarse grained sandstones of the Bamboesberg Member are modified by secondary (diagenetic) overgrowths of quartz (Fig.3.37), however the coarser sandstones display this feature to a far higher degree. The boundary between rim overgrowth and detrital grain is in many cases defined by a line of inclusions. Overgrowths are otherwise in optical continuity with the detrital grains, even when the detrital grain shows undulatory extinction. Overgrowths may be irregular (Fig.3.37) or euhedral (Fig.3.37b) in nature and may increase the size of the original grain by up to 20%, as well as altering the sandstones textural characteristics. Overgrowth contacts are dominantly concavo-convex or planar.

The low abundance of overgrowths in the fine to medium grained sandstones, which usually have high matrix contents, may be due to the lower porosity of such sandstones or due to the decreased number of grain contacts, which would reduce the amount of quartz made available by pressure dissolution.

ii) Feldspar

Fresh, partially and totally weathered feldspar grains are present in varying quantities within the sandstones of the Bamboesberg Member. Sodium rich plagioclase (Fig.3.38) is the most abundant feldspar in the basal part of the Bamboesberg Member and individual grains show albite, carlsbad and less frequently pericline twinning. They are typically euhedral when preserved as fresh grains. Potassium feldspar, is less frequent in the basal horizons, becoming more abundant in the upper reaches of the Bamboesberg Member, especially in the coarser fraction. Orthoclase (Fig.3.39) is uncommon and fresh, unweathered euhedal (Fig.3.40a) and well rounded microcline (Fig.3.40b) is the more common grain type. Weathered orthoclase grains (Fig.3.39) are often difficult to distinguish from the matrix content and this fact alone probably biases the true representation of feldspar within the Bamboesberg Member.

iii) Rock fragments

Rock fragments are not common in the finer grained sandstones of the Bamboesberg Member, but are fairly common in the coarser grained horizons. Rock fragments are most commonly polycrystalline quartz of sedimentary (Fig.3.41) igneous (Fig.3.42) and metamorphic origin (Fig.3.43), although granite fragments also occur. The most common sedimentary rock fragments are pebble sized extraformational clasts of quartz arenite composition (Fig.3.44) that are important provenance indicators. The lithic grains are usually larger in size than the average for monocrystalline grains in a particular sandstone unit.

iv) Mica

Preserved detrital mica is not an abundant component of the sandstones, but when present, muscovite (Fig.3.45) is the dominant form with biotite being extremely rare. Muscovite occurs as lath shaped grains, sometimes showing slight bending due to compaction. Biotite (Fig.3.46) occurs as small, angular grains and may show zoning due to variations in iron content.

b) Heavy minerals

Heavy minerals usually occur as accessory minerals in the Bamboesberg Member, in concentrations less than 1%, unless preferentially concentrated by fluvial processes. Detailed heavy mineral analyses and separations were not undertaken for this study and all identifications were undertaken solely by means of normal petrographic procedures. Christie (1981) lists the four non-opaque heavy minerals present as: colourless and pale pink/red garnet; colourless zircon; yellow brown rutile; and colourless and pale green tourmaline. Of these zircons, tourmalines and garnets were identified during this study.

Zircons are the most abundant non-opaque heavy mineral in the Bamboesberg Member and occur as well rounded (Fig.3.47a,b) and subhedral to euhedral grains.

Tourmalines are rare, but where present occur mainly as euhedral grains (Fig.3.48). Garnets (Fig 3.16) are fairly common within the coarse grained sandstones of the Bamboesberg Member, often occurring in scour hollows in front of longitudinal bars. Although detailed geochemistry was not undertaken on the garnets from the Member, Reynolds (1980) assigned the garnets in the Molteno Formation to the almandine-pyrope class, some with a small grossularite component.

Opaque heavy minerals are more abundant than non-opaques, with magnetite and ilmenite predominating, along with rare leucoxene (Christie, 1981). In the lower part of the Bamboesberg Member, oxides often form discrete laminae (Fig.3.49) associated with facies Sh.

c) Matrix

The matrix (Fig.3.50) of the sandstones of the Bamboesberg Member is composed of very fine grained quartz, decomposed feldspar and clay. It forms an important component of the overall assemblage, with detrital and authigenic clay mineral abundance up to 25%. X-ray diffraction (XRD) and microprobe analyses were not undertaken on the clay fraction, however the work of Turner (1969) showed the clay minerals present to be mainly illite and montmorillonite.

3.3.5.2 Sandstone classification

Previous authors (Rust, 1959, 1962; Turner, 1972b, 1975a; Christie, 1981; MacDonald, 1993) have in the past experienced problems with the classification of the sandstones of the Bamboesberg Member due to the large percentage of matrix and the variable feldspar contents. This problem is compounded by the *in situ* breakdown of feldspar to clay (Fig.3.50) and is discussed for immature sandstones by Dott (1964).

Rust (1959, 1962) classified the sandstones of the Bamboesberg Member as lithic sandstones (lithic arenites) to lithic sub-greywackes. Turner (1972b) gives a figure of 25.5% clay matrix for the sandstones of the Molteno Formation, making them greywackes (quartz and feldspathic wackes) according to the classification of Pettijohn *et al.* (1975, 1987). Christie (1981) regarded the sandstones of the Bamboesberg as ranging from feldspathic to lithic wackes, a classification adhered to by MacDonald (1993). Cairncross *et al.* (1995) classify the sandstones of the Bamboesberg Member as arkoses.

Figure 3.51 documents the framework grain plots determined from this study, and shows that the sandstones of the Bamboesberg Member range from sublitharenites, litharenites, arkosic arenites, to arkoses and subarkoses. Lithic, feldspathic and quartzwackes also occur. The coarser fraction are generally grain dominated, whereas in the finer sandstones, clay matrix may be an important component. The majority of wackes are secondary in origin and their predominance in some workers' classifications (Christie, 1981) is believed to have been brought about by the inclusion of altered feldspars as matrix rather than framework grains. The inclusion of all totally altered feldspar grains that preserve grain outlines, would shift the majority of Bamboesberg sandstones into the arkosic arenite sandstone field.

3.3.6 Palaeocurrent analysis, provenance and tectonic setting

3.3.6.1 Palaeocurrent analysis

Combined palaeocurrent measurements for the Bamboesberg Member are presented in Figure 3.52. The lower part of the Bamboesberg Member contains few directional indicators, although numerous trend indicators are present, particularly parting lineation associated with facies Sh. These measurement are however presented as directions due to the unimodal nature or the palaeocurrent direction as obtained from all other sources of data. Trough axes and parting lineation data is supplemented by pebble imbrication and long axis orientations, as well as long axis orientations of large stem axes and logs. In the south of the basin, each sandstone horizon was treated separately such that any stratigraphic variability would be evident. No marked inter-unit variation was however found to exist, and the data has therefore been lumped together to show the general palaeocurrent directions for the Bamboesberg Member as a whole.

This palaeocurrent analysis shows that the Bamboesberg Member was deposited by unimodal palaeocurrents flowing mainly to the north-northeast. These directions accord well with the north-easterly direction postulated by Turner (1975a) for the southern part of the basin, as well as the subordinate northeast flow direction of Christie (1981). They also accord fairly well with the figure of 350° given by Rust (1959, 1962) for Bushmanshoek Pass. They are however in contrast to the overall northwest basinal trend (Turner, 1977) and the northwest (329°) direction given by Christie (1981) for the Bamboesberg in the Indwe and Cala areas.

Turner (1975a) postulated a two component flow system governed by source areas to the south and south east. It appears therefore that this control was already present in Bamboesberg times as evidenced by the northeasterly flow ascertained in the west of the basin and the northwest flow evidenced in the east (Christie, 1981). In addition the petrological studies suggest that during the deposition of the Bamboesberg, two major complimentary systems were carrying material from varied source provenances situated to the southwest, south and southeast.

3.3.6.2 Provenance and tectonic setting

The sandstones of the Bamboesberg Member contain scattered extraformational clasts (Figs.3.7, 3.14), which are the most useful indicator of source area provenance. These clasts are predominantly quartz arenites (Fig.3.44), believed to have been derived either from the Witteberg or Table Mountain Groups of the Cape Supergroup (Rust, 1959, 1962; Turner, 1983). Rare pebbles of brown, litharenite, with inclusions of pyrite (altered to haematite) also occur. These are thought to be reworked from the Lower Beaufort Group, where such sandstones are common.

Study of the different microscopic rock fragments is the second most important indicator of provenance for the Bamboesberg Member. The presence of rock fragments with elongate, sutured quartz grai[illegible] Fig.3.43) that show a bimodal size distribution strongly suggest a metamorphic provenance for their derivation. Rock fragments composed of between two and six individual interlocking quartz grains are strongly suggestive of a granitic source area (Blatt *et al.*, 1972). Granite is also present as rock fragments and is indicative of an acid plutonic provenance.

A number of other lines of evidence as to the provenance for the Bamboesberg Member may be obtained from this petrographic study. Quartz in the Bamboesberg may display undulose extinction and strain, not in itself diagnostic, but suggestive of a plutonic igneous or metamorphic source (Blatt & Christie, 1963; Lewis & McConchie, 1994). Acicular rutile inclusions are present in some quartz grains and these are thought to be indicative of quartz of granitic derivation (Tucker, 1991). The sub-rounded to sub-angular shape to the quartz grains indicates that the predominant source area was primary, and the well rounded grains providing evidence of a secondary cycle of reworking, as also indicated by the presence of well rounded quartzite pebbles. The high percentage of sodium plagioclase (Fig.3.38) is common in sediments derived from an island arc source terrane (Lewis & McConchie, 1994). Microcline, is often used as a strongly suggestive indicator of pegmatites in the source area, especially when it displays perthitic twinning (Fig3.40a) (Lewis & McConchie, 1994). The absence of the heavy mineral assemblage of pegmatites, such as cassiterite, beryl, topaz, monazite and fluorite, in the sandstones of the Bamboesberg Member would tend to discount large pegmatites as a primary provenance. Rust (1959, 1962) suggests that the garnets in the Molteno come from reworking of the Dwyka Group. The occurrence of rare detrital biotite is not diagnostic, but is strongly suggestive of an acid plutonic to low grade metamorphic source terrane. The detrital mica content is particularly low, due mainly to its alteration to clay. Detrital mica is however more commonly derived from schists, gneisses and plutonic igneous rocks, although muscovite may be a product of a sedimentary source area (Zuffa, 1985).

The relative percentages of the non-opaque heavy minerals are used by Pettijohn (1975) and Lewis and McConchie (1994) as provenance indicators. The combination of rutile, tourmaline and leucoxene is used by Tucker (1991) to imply a reworked sedimentary source. The combination of rutile, pink tourmaline, sphene and magnetite, together with the presence of potassium feldspar, sodic plagioclase, biotite and muscovite is used to define an acid igneous source by Pettijohn (1975).

The ostensible paucity of garnet in the Formation was ascribed by DeVilliers and Wardaugh (In Ryan, 1963) to the cutting off of a crystalline area to the south by the rising CFB. This study has shown however that in the Bamboesberg Member garnets are still fairly abundant. The presence of garnets in the upper part of the Bamboesberg Member is indicative of a high grade metamorphic source. Garnets are also known from pegmatite deposits, however the associated heavy minerals, especially the lack of blue tourmaline, discount pegmatites as the source of the garnets in the Bamboesberg Member.

Petrographic evidence of the sandstones of the Bamboesberg Member therefore suggests a mixed sedimentary, acid-plutonic and associated metamorphic provenance, with contributions from the underlying Formations of the Karoo Supergroup. Figure 3.52b shows that the sandstones of the Bamboesberg Member plot within the quartzose recycled orogen field and into the craton interior field of Dickinson *et al* (1985). This position in the quartzose recycled orogen field reflects the reworking of Cape Supergroup rocks. The high percentage of sodic plagioclase may reflect either sedimentary reworking of sodic plagioclase rich sandstones of the Lower Beaufort, or that remnants of an island arc terrane were still available to supply sediment during Bamboesberg Member times. The heterogeneity of the sandstone composition suggests a varied source terrain that changed through time, with a high grade metamorphic terrane supplying material during the deposition of the uppermost part of the Member.

3.4 Indwe Sandstone Member

The Indwe Sandstone Member (Turner, 1975a; SACS, 1980) overlies the Bamboesberg Member in the south of the basin and the Burgersdorp Formation in the north of the basin (Fig.1.1). It is an important lithostratigraphic unit in that it is present throughout the basin and forms an easily identifiable marker horizon. For this reason it was taken as the uppermost unit for the stratigraphic range of this study.

The name Indwe Sandstone was first used in the literature by Du Toit (1905) for exposures around the town of Indwe in the Eastern Cape, which have subsequently been designated the type section (Turner, 1975a) and type area (MacDonald, *in prep.*). Robinson *et al.* (1969) preferred the usage of the term Indwe Member, however SACS (1980) formally accepted the Indwe Sandstone Member as suggested by DuToit (1905a). Christie (1981) felt that the type section as designated by Turner (1975a) was not representative of the Member as a whole, as only the basal 28m is preserved and instead used four reference sections to show the varied nature of the Member. MacDonald (*in prep.*) followed Christie (1981) in that he considered that the Member was not preserved to its full extent at Indwe, and designated Cala Pass, some 40km east of the town of Indwe, as the holostratotype. MacDonald (*in prep.*) also designates two borehole cores as reference stratotypes. The first of these is on the farm Sewefontein 157 in the Molteno district and the second on the farm Pesenkenplaats 212 in the Indwe district. Both cores are housed in the core sheds of the Council for Geoscience at Silverton (Pretoria).

3.4.1 General geological description

The Indwe Member outcrops from south of Sterkstroom in the Eastern Cape, to Bethlehem in the northern Free State, and from east of Indwe, to west of Aliwal North (Fig.3.53). The Indwe Sandstone Member has previously been proposed to extend all the way through to Zimbabwe (Turner *pers.comm.*) however the author feels that these deposits were formed in distinct separate basins and for this thesis, the usage of the term is restricted to occurrences within the main Karoo Basin of South Africa. It is however a Member of appreciable lateral extent and is therefore of regional significance as a lithostratigraphic marker horizon. It is fairly easily recognised in outcrop due to: the coarse nature of the channel sandstones; the presence of quartzite pebbles along the lower erosion surfaces, especially in the south of the basin; its characteristic weathering pattern; and by the glittery appearance imparted by the presence of secondary quartz overgrowths. Because of its distinctive nature, most work previously concerned with the Molteno Formation has focused on this Member

In the south of the basin, the base of the Indwe Sandstone Member often coincides with an accumulation of mixed extra- and intraformational debris, informally termed the "Kolo Pebble Bed" (Turner, 1975a). This "Bed" is a matrix supported conglomerate that varies in thickness and continuity on a scale of tens of metres. It is not always restricted to the basal contact and often occurs some 1-2m into a given sequence. Where longitudinal or transverse bar elements mark the base of the sequence, the "Kolo" is not present. For these reasons, although the term "Kolo" is used in this thesis, workers should take care when using the "Kolo Pebble Bed" to define the base of the Indwe Sandstone Member.

Although the basal conglomeratic units of the Indwe Sandstone Member are lenticular in nature, they occur on a regional extent and the sequence is informally known as the "Kolo Pebble Bed". This unit consists of oval to ellipsoidal pebbles, cobbles and boulders set in a poorly sorted, coarse to very coarse grained matrix. In the study area this bed is represented by a composite zone up to 2.0m thick. A maximum clast size of 68cm was recorded in the south of the basin, which approximates well to the maximum of 75cm recorded by Turner (1975a). Pebble size decreases rapidly to the north till at Senekal, the maximum clast size is only 1cm. In the south and southwest more than ninety percent of the pebbles in the Kolo and Indwe are white to pale grey quartzite, with the rest consisting of hornfels, slate, vein quartz, jasper, granite and brown quartzite with large inclusions of cubic pyrite. Rust (1959, 1962) reports pegmatitic material from the Molteno area, but such pebbles were not observed during this study. To the east and northeast vein quartz is most abundant, followed by pink and grey quartzite and jasper. This is particularly so in the vicinity of Senekal and Rouxville in the Free State.

In the southern margins of the basin, where the Indwe Sandstone Member directly overlies the uppermost sandstones of the Bamboesberg Member, the contact is conformable and usually flat and sharp, although it may be marked by an erosional surface of up to 1.5m, especially where the Indwe overlies carbonaceous mudstone or coal of the upper Bamboesberg Member. Both Turner (1975a) and Christie (1981) felt that the Indwe eroded up to 6m of underlying coal, however a lot of the discrepancies in coal thickness in the upper Bamboesberg may be accounted for by original topography and non-deposition and do not necessarily represent loss by erosion.

In the north of the basin, the basal accumulation of clasts is not as marked, being developed more commonly only as a band of coarse grit, with rare clasts up to 0.9cm. A numerous localities, the sandstones of the Member in the north of the basin show evidence of soft sediment deformation (Fig.3.54). This soft sediment deformation is localised to a single bed and does not cross cut bounding surfaces. For this reason they are interpreted as being due to syndepositional sedimentary loading and dewatering, rather than by tectonic shock.

Lithologically the Member is predominantly composed of moderate orange pink (5YR 8/4), light brown (5YR 6/6), moderate yellow brown (10YR 5/4) to moderate reddish orange (10R 6/6) coarse to very coarse grained sandstones, with accumulations of extraformational clasts of blue/grey quartzites and intraformational clasts of mudstone and siltstone. One reworked clast of silicified wood was also recorded during this study. The tops of individual sandstone beds often preserve limonite rich ferruginous concretions.

In the north of the basin what has previously been mapped as the Indwe Member often consists of two independent cycles, both with accumulations of intra- and extraformational clasts at the base. The actual stratigraphic affinity of the upper sandstone is however unclear at present, and for the purpose of this study, only the basal fining upward sequence was documented as the Indwe, with the upper sandstone assigned to the "Transitional" Member. Further fieldwork is required to determine the actual stratigraphic affinity of this upper sandstone.

3.4.2 Thickness

The Indwe Sandstone Member thins rapidly from south to north, following the regional pattern of the Molteno Formation, in that the major thinning occurs in the region of Aliwal North. MacDonald (*in prep.*) gives an average thickness for the Member of 25m. In general however the Member is thickest in the south and southeast and thins gradually west and east, and more rapidly north to south. In the south of the basin, local variations in thickness occur, with the Member ranging from between 10-60m around the type locality (Christie, 1981). In the north of the basin, recorded thicknesses range from between 2-9m in the area surrounding the town of Senekal. Turner (1975a) gives thickness figures of between 14-36m in the north of the basin. This relatively large fluctuation of thicknesses in the north of the basin is presumably caused by the occurrence of the split sandstones.

3.4.3 Sedimentology

All gradations between mudstone and conglomerate occur within the Indwe Sandstone Member, however coarse grained sandstone is the predominant lithology.

3.4.3.1 Lithofacies descriptions

Facies descriptions are provided for the Indwe Sandstone Member only where they are significantly different from the underlying Bamboesberg Member, and therefore have significance for the palaeoenvironmental and basinal reconstructions presented in Chapter Four.

A) Gravel Facies (G)

Although certain authors dislike the use of this facies because it refers to modern sediment, rather than a rock type, most authors describing coarse to very coarse grained sandstones, with included grainsizes above 2mm, still tend to include it (Miall, 1996) and as such use is made of the designation here.

a) Heterolithic scour fill (Ge$_h$)

Mixed intra- and extra-formational, clast and matrix supported conglomerate (Fig.3.55) commonly occur at the base of the Indwe Sandstone Member. Set thicknesses range from 10-100cm, but are usually in the 30-60cm range. This facies may be unstratified and ungraded, or show faint stratification and clear grading, with the coarsest clast sizes occurring along the basal erosion surface to a set. Extra-formational clast types range from white to blue quartz arenites and brown lithic arenites with pyrite inclusions which are totally altered to haematite. Clasts size ranges from 1-65cm. Intra-formational clasts consist mainly of siltstone and mudstone pebbles and a fair amount of oxidised wood. Discoidal shaped clasts show a well developed fabric, with their long axes dipping upstream and orientated parallel to the palaeoflow, whereas rollers (rod shaped) clasts have their long axes orientated perpendicular to flow. A single rounded pebble of silicified fossil wood of the genus *Auracarioxylon* (Bamford *pers.comm.*) was also discovered within the pebble conglomerate at the base of the Indwe Sandstone Member. Fossil wood of this type is common in the underlying Bamboesberg Member and this clast is most likely reworked from this Member. The matrix consists predominantly of coarse quartz grains and lesser feldspar. Quartz grains tend to be better rounded than the feldspars, which are often euhedral in nature. Large grains of feldspar sometimes form lenses associated with small pebbles.

Facies Ge$_h$ occurs mainly at the base of sandstone sequences as matrix supported lag conglomerates, although it does not always directly form the base of a particular unit and may occur sporadically distributed throughout a sandstone package.

These deposits are thought to represent lag accumulations following periods of peak flow, during which time the system could move large clasts as bedload. Harms and Fahnestock (1965) note that pebbles with long axes greater than 2.5cm and a specific gravity greater than two, could be transported only in the upper flow regime. The unstratified and ungraded nature of some of the sets probably represents rapid dumping of coarse suspended load following peak flood. No inversely graded sets were identified, and debris flows are not though to be active in the system.

b) Trough cross-stratified (Gt)

Facies Gt (Fig.3.56) is associated with, and sometimes laterally continuous to, facies Ge$_h$, with isolated pebbles and pebbly bands on individual set laminae. Trough widths are marginally greater than for facies St in the upper parts of the Bamboesberg Member. Individual troughs may have widths of up to 8m and can be up to 2.0m in height, although the norm is between 30-70cm. Foresets dip between 10-15°. These units may cut into one another both vertically and laterally, with the erosional base overlain by the coarsest grain fraction. Facies Gt represent the internal structure of coarse bedload, sinous crested dune migration.

c) Planar cross-stratified (Gp)

Facies Gp is rare in the Indwe Sandstone Member in the south of the basin, being far more abundant in the north (Fig.3.57). This facies occurs as a coarse pebbly sandstone, rather than a true conglomerate. Facies Gp usually occurs as solitary sets within facies St or Sh, but may occur as grouped sets. Textural variation within sets may be quite severe. They occur randomly distributed throughout the sandstone sequence, but are more prevalent in the upper reaches of a particular sandstone unit and in the northern part of the basin. Palaeocurrent directions may be parallel to those obtained from facies Gt and St, but more commonly are at an oblique angle to it.

Boguchwall and Southhard (1989) documented the formation of Gp and Sp under mean flow exceeding 1.0m/s (for standardised 10°C water temperature). Rust & Gibling (1990) record the formation of facies Gp by the migration of bar margins of minor bedforms into locally deeper channels. Facies Gp in the Indwe Sandstone Member therefore most probably represents deposition of gravelly transverse and longitudinal barforms in the quieter water settings of individual channel tracts. The large range of textural variation is thought to be caused by fluctuating hydraulic conditions, gravel-clast bypassing (Miall, 1996) and grainsize sorting resulting from the advancement of grains down the avalanche face of individual bars.

B) Sandstone facies (S)

The sandstone facies in the Indwe Sandstone Member are similar in nature to those in the underlying Bamboesberg Member, and therefore individual figures of the facies types are not presented. The facies types are however described as they differ from those in the Bamboesberg Member in certain respects.

a) *Trough cross-stratified* (St)

This is the dominant sandstone facies within the Indwe Sandstone Member and differs from the underlying Bamboesberg only in the larger grainsize and scale of the sets and stacked co-sets. Grainsize ranges from coarse to very coarse sand and individual troughs average 1.5m in width, but may be up to 6.0m.

b) *Planar cross-stratified*

Facies Sp is rare in the Indwe Member in the south of the basin, although it is common in the north of the basin where it occurs as thin sets (<10cm) interspersed with facies St and Sh, as well as large scale sets (10-100cm) and stacked co-sets (up to 3.0m).

Facies Sp represents downstream accretion of sand in longitudinal bars and straight crested sandwaves and [illegible] transverse migration of bars and sandflats in the distal reaches of the system.

C) Fines facies (F)

As for the sandstone facies, individual figures of the fines facies are not presented. The fine fraction consists predominantly of massive and horizontally laminated siltstones. These are broadly interpreted as braidplain and quite water deposits and form a very minor percentage of the Indwe Sandstone Member. In general, apart from minor characteristics, they do not differ significantly from the fines in the underlying Bamboesberg Member.

a) Massive (Fm)

Facies Fm includes structureless to faintly laminated fines which may show faint colour banding. Facies Fm may form thick (2-4m), laterally extensive deposits or occur as thin (<20mm) deposits draped onto the tops of other facies. This facies is often chertified, forming the chert gannister of Rust (1959, 1962) and the porcellanite beds of Turner (1975a). In the Indwe Sandstone Member this facies is often richly fossiliferous, preserving plant and insect material (Anderson & Anderson, 1983).

Facies genesis is thought to be due to the settling of suspended load fines from low energy currents in the lower part of the lower flow regime. This probably occurred in abandoned channel reaches and on the braidplains within and surrounding the main flow locus.

b) Ripple laminated (Fr)

Ripple laminated fines are rare in the Indwe and form sets up to 15cm thick, which may be laterally continuous for up to 100m. This facies may grade upward into facies Fm or Fh. Straight, asymmetric, sinuous crested and linguoid ripples are typically formed on the bed tops of such sets. Amplitudes range from 0.5-4.0cm. Facies genesis is thought to be as for the underlying Bamboesberg Member.

c) Horizontally laminated (Fh)

Facies Fh consists of horizontally to irregularly planar laminated fines forming beds up to 30cm thick. Organic rich laminae and whole fossil plant compressions occur throughout and invertebrate fossils may be locally abundant on bedding plains (Cairncross *et al.*, 1995). Facies Fh may have intercalations of fine to medium grained sandstone and at places.

d) Coal and Carbonaceous Mudstone (C)

Coal is rarely developed in the Indwe Sandstone Member, however a coal seam does occur topping the sequence in places. Turner (1975a) recognises two coals within the Indwe Sandstone Member, a lower Cala Pass and upper Guba Coal, whereas Christie (1981) and MacDonald (1993) do not recognise any coal seams within the Indwe Sandstone Member, but rather place the Cala Pass seam above the Indwe, at the top of their Mayaputi Shale Member. The coal in the Indwe Member is typically dull (inertinite/fusinite), with alternating bands of carbonaceous siltstone and mudstone.

3.4.4 Architectural element associations

The Indwe Sandstone Member forms a gross fining upward sequence between 10-35m thick in the south of the main Karoo Basin. Where fully preserved the sequence grades up from a basal accumulation of facies Ge_n through to facies Fm, Fh and Fr. As is the case for the underlying Bamboesberg Member, a channel and fines facies association were delineated, based on their overall geometries, architectural elements and component facies. Of these two associations, only the channel facies association was documented for the Indwe Sandstone Member during this study.

The tabular sandstones of the Indwe Sandstone Member take the form of sheet sandstone bodies ranging in thickness from 6-15m, that are laterally continuous and lithologically traceable over hundreds of kilometres. The basal contact may be sharp and flat, or strongly erosional and is often marked by an accumulation of facies Ge_h up to 2.0m thick, informally known as the "Kolo Pebble Bed" (Fig.3.55). As for the Bamboesberg Member, these thick sheet sandstones are interpreted as bedload dominated fluvial channel complexes.

3.4.4.1 Channel fill systems (CHS)

The nature of the channel fill systems in the Indwe Sandstone Member is well shown in a roadcut on the R394 between Queenstown and Sterkstroom (Fig.3.58). This channel fill system is internally structured by four main architectural elements including minor (CH) and abandoned channel fills (ACH), downstream accreted macroforms (DA) predominantly longitudinal bars and laterally accreted (LA) macroforms.

Individual channel margin structures are rare, but where preserved show deep erosion into the underlying facies (Fig.3.59), particularly where the underlying lithology is mudstone or coal. Where the base of the Indwe rests on sandstones of the upper Bamboesberg, the contact is sharp, flat, or slightly erosional (Fig.3.60). Individual major channel fills form large scale structures up to 90m wide and 9m deep, giving a width/depth ratio of 10. A similar figure of 80m by 9m was documented by Christie (1981) for a channel complex to the northwest of the town of Indwe, giving a width/depth ratio of 8.89. Compared to the width/depth ratios of between 20-26 for the underlying Bamboesberg Member, it seems that the main channel complexes in the Indwe Sandstone Member, were deeper and more incised.

a) Minor channel fills (CH)

Minor channel fill systems (Fig.3.61) in the Indwe Sandstone Member are most abundantly associated with the base of individual channel complexes, although they may also occur throughout such fills. These elements are usually internally structured by facies St_1 and Sm, and may have basal accumulations of facies Ge_h or Se_s.

Minor channels range in width from 3.0-9.0m and are between 0.8-2.5m deep, giving low width/depth ratios of between 3.75 and 11.25. The average width/depth ratios for these structures is 4.5. The elements probably represent channel switching during peak flow and rapid erosion and subsequent deposition of sediment by turbulent currents in the upper flow regime.

b) Abandoned channel fill systems (ACH)

Tracts of channel abandonment and fill may occur throughout the channel complex sequence. A good example of such fill is evidenced in Figure 3.58. Here the sequence is composed of a basal facies St_s overlain by facies Fr and Fl. The basal St_s most probably represents the channel floor prior to channel switching and abandonment and the sequence of Fr-Fl represents the fill subsequent to abandonment.

c) Laterally accreted macroforms (LA)

Laterally accreted macroforms include, transverse bars and sandflats and are the predominant architectural element in the Indwe Sandstone Member in the north of the basin (Fig.3.62). Transverse bars are predominantly internally structured by facies Gp or Sp and may consist of single or composite sets of Sp. They range in thickness between 10cm-2m and are remarkable similar in form to transverse bars described for the Platte River by Crowley (1983). Individual sand flat elements range in thickness from 50-300cm and are internally structured predominantly by facies St and SP.

d) Downstream accreted macroforms (DA)

Downstream accreted macroforms are the dominant architectural element in the Indwe Sandstone Member in the south of the basin, and include simple longitudinal and linguoid bars (Fig.3.58). Longitudinal bars (Fig.3.63) may be up to 2.0m thick and laterally persistent in a downstream direction for over a 100m. These elements are generally coarser at their upstream margin and may grade downstream into facies St$_l$. Due to the downcurrent migration of such bar forms, the sequence preserved at the downstream margin often reflects minor channel fill overlain by coarser bar sandstones. Accumulations of heavy minerals, especially garnet may be associated with facies St$_l$ at the downstream margin. The tops of these barforms may preserve thin mudstone veneers, or tracts of abandoned channel fill (Fig.3.64).

3.4.5 Petrography

The most obvious distinction between the sandstones of the lower Bamboesberg and Indwe Members is grainsize and the very distinctive secondary overgrowths of quartz. It must be noted that the uppermost sandstones of the Bamboesberg Member in the south of the basin may also have secondary overgrowths, but are not as coarse as the sandstones of the Indwe Sandstone Member.

3.4.5.1 Petrographic descriptions

a) Framework Grains

i) Quartz

Quartz is the predominant light mineral in the Indwe Sandstone Member, accounting for up to 90% of the framework grains. The majority of quartz grains are sub-rounded to sub-angular, with some very well rounded grains as well. Individual quartz grains often preserve lines of inclusions and heavy minerals (Fig.3.05). Many of the sandstones of the Indwe Sandstone Member have syntaxial secondary overgrowths distinguishable from the detrital grain by a rim of dark inclusions. Monomineralic quartz is sometimes present as part of the interstitial cement.

ii) Feldspar

Fresh and totally weathered feldspars are recognisable in hand specimen and various stages of decomposition are visible petrographically. Higher percentages and larger grains of feldspar are associated with the coarser facies and the largest recorded grains, from the south of the basin, measure 3.0cm. As for the uppermost part of the Bamboesberg Member, sodium plagioclase and microcline are the predominant feldspar types, however potassium feldspars are far more abundant in the Indwe than in the underlying Bamboesberg Member. Microcline is the most abundant feldspar, with subordinate amounts of perthitic microcline and orthoclase. Plagioclase is typically euhedral and is predominantly albitic in nature.

iii) Rock fragments

The percentage of lithic fragments in the Indwe Sandstone Member varies from south to north and is also dependent on facies types and grainsize. In general there is a higher percentage of lithic fragments in the coarser sandstones (facies Gp &

Gt) in the south of the basin. The amount of rock fragments preserved generally decreases towards the north of the basin. Lithic fragments are usually larger than monocrystaline grains and are predominantly polycrystaline quartz (Qp) of low grade metamorphic, sedimentary and igneous origin. The metamorphic fraction of the Qp is characterised by stretched or elongate crystals, with sutured intercrystalline boundaries, and which exhibit undulose extinction.

iv) Mica

Mica is not abundant in the sandstones of the Indwe and is usually less than 1% of the total grains. When present, muscovite is the dominant form, and occurs as small detrital flakes.

b) Heavy minerals

The heavy mineral suite is not distinctly different from the underlying Bamboesberg Member and contains in order of abundance, zircon, rutile, tourmaline and garnet. Garnet is not as abundant as in the Bamboesberg Member, a trend first recorded by Theron (1969), but disputed by Turner (1975a). Opaque heavy minerals may comprise as much as 20% of the assemblage, being mainly ilmenite and magnetite.

c) Matrix

The matrix component of the sandstones of the Indwe ranges from 5-18%, although it is usually lower than 10% The matrix is composed predominantly of silt sized quartz grains, partially to totally decomposed feldspars, and clay.

3.4.5.2 Sandstone classification

According to Turner (1983), the sandstones of the Indwe Sandstone Member are predominantly feldspathic lithic arenites, characterised by rapid textural changes. MacDonald (1993) states the lower part of the Indwe Sandstone Member is composed of very coarse litharenites and the upper part of feldspathic wackes.

From Figure 3.66 it is evident that the sandstones of the Indwe Member are quartz rich and fall in the lithic arenite, feldspathic arenite and quartz arenite fields of Pettijohn (1975). In the south of the basin the sandstones of the Indwe Member are more feldspar rich being sub-arkosic in nature, although with a significant percentage of the feldspar converted to clay minerals. In the north of the basin the sandstones preserve less feldspar and may be composed of up to ninety percent quartz. This is probably a reflection of prolonged reworking.

3.4.6. Palaeocurrent analysis, provenance and tectonic setting

3.4.6.1 Palaeocurrent analysis

Current direction indicators used for the palaeocurrent analysis of the Indwe are mainly trough cross-stratification, as well as pebble imbrication. Parting lineation, rills and plant stem orientation trends aided in the final interpretation. Planar cross-stratification was also used for palaeocurrent directions but the data was treated separately due to the large variation in the palaeocurrent means obtained from this structure. Elongate and flat extraformational clasts show a well developed fabric with their *a* long axis parallel to flow and dipping downstream. Rollers tend to be aligned with their *a* axis perpendicular to flow. Palaeocurrents based on clast imbrication show relatively little directional variance (Appendix 7).

Figure 3.67 shows that flow directions for the Indwe Sandstone Member are predominantly north-northeast, north and north-northwest, with a vector magnitude of 88.63 and a vector mean of 344.08° for the basin as a whole. This figure is almost identical to the mean of 344° given by Christie (1981) for Cala Pass and 337° for the type locality of the Indwe Sandstone Member above the town of Indwe in the Eastern Cape.

3.4.6.2 Provenance and tectonic setting

Numerous authors have in the past tried to define the provenance for the rocks of the Indwe Sandstone Member of the Molteno Formation. Ryan (1963) proposed a granitic source to the south-east to provide the feldspathic components of the Member. Johnson (1976) proposed that the folding, uplift and erosion of Witteberg and/or Table Mountain Group sandstones contributed significantly to the quartz content of the upper Beaufort as well as the Molteno and Elliot Formations. Turner (1980, 1983) postulated the existence of a southerly Molteno source comprising Cape Supergroup quartzites in addition to a southeasterly granitic source. Johnson (1991) concluded that the first evidence of a quartzose recycled origin occurred in the Molteno Formation. This study confirms that input from the Table Mountain and Witteberg Groups (quartzose recycled orogen) is first directly evidenced in the Bamboesberg Member (although it was possibly a significant source to the upper Burgersdorp Formation as well), and is dominant in the Indwe Member of the Molteno Formation.

The most direct evidence of the provenance of the Indwe Sandstone Member comes from the extraformational clasts preserved in the basal Ge_h facies. The light mineral and framework grain composition, coupled to the heavy mineral assemblage present shows that these clasts are predominantly metamorphosed quartz arenites from the Cape Supergroup (Table Mountain or Witteberg Groups), as for the underlying Bamboesberg Member. The presence of pebbles of hornfels and slate suggests a low to medium grade metamorphic terrane. The occurrence of fairly abundant polycrystaline grains with more than five individual crystals is probably indicative of a low grade metamorphic source, as Qp of igneous origin seldom contain more than five individual grains (Blatt *et al.*, 1972).

The presence of vein quartz, and rare granite and pegmatite clasts evidence plutonic acid igneous rocks in the source. The presence of microcline with a perthitic texture is strongly suggestive of pegmatites and plutonic rocks, and its presence together with orthoclase and non-perthitic microcline is strongly indicative of a granitic component to the source area. Turner (1975a) notes that the predominance of albitic twinning in the plagioclase component is a characteristic of plutonic rocks and that the acicular inclusions of rutile in the quartz grains are indicative of a granite source. Plagioclase from a metamorphic source usually contain numerous inclusions (Pittman, 1970). The presence of almandine garnets is suggestive of derivation from a pegmatoidal source (Turner, 1975).

Brown quartzite with altered cubic pyrite inclusions are most probably derived from the Lower Beaufort Group. The presence of a single, well rounded clast of silicified wood of the *Auricarioxylon* type, such as is known in the Bamboesberg Member, suggests uplift and reworking of the more proximal reaches of the upper Bamboesberg Member as well.

The primary source area for the Indwe Sandstone Member lay to the southwest, south and southeast of the present outcrop area, as witnessed by the predominantly northeasterly, northerly and northwesterly palaeocurrent directions. As for the Bamboesberg Member, the provenance area for the Indwe must have included a number of different source rock types as shown by the numerous pebbles of different lithotypes. Figure 3.68 shows that the sandstones of the Indwe Member plot within the upper reaches of the quartzose recycled orogen field and craton interior fields of Dickinson *et al* (1983). Based on the above evidence, the provenance for the Indwe Sandstone Member is therefore believed to be a mixed low to high grade metamorphic and acid plutonic source. The granite component is belived to have been supplied from the eastern margin of the Falkland Plateau (Turner, 1975a; Veevers *et al.*, 1994), and the metamorphic material from within the southern CFB. Small feldspar rich lenses at the base of channel elements in the north of the basin, may be indicative of a local plutonic source.

3.5 Palaeontology of the Bamboesberg and Indwe Sandstone Members

3.5.1 Palaeoflora

The palaeoflora of the Molteno Formation is well known from the extensive works of Anderson (1974, 1976a,b, 1978) and Anderson and Anderson (1979, 1983, 1984, 1989, 1995, *in prep.*) and is probably the most comprehensively sampled and richest known Triassic flora in the world. This study offers little new by the way of taxonomic assessment, except for the wood from the Formation, which was previously not well documented, being mostly lumped in the catch all genus *Dadoxylon*.

Due to the similar nature of the palaeontological signatures of both the Bamboesberg and Indwe Sandstone Members, they are treated together, the only major change being in the number of specimens collected. All the identifications of material described below were undertaken by John and Heidi Anderson.

Although the fines facies of the Indwe Sandstone Member are very rich palaeontologically (Anderson & Anderson, 1995), the bulk of the fossils collected during this study were from the fines in the lower two sandstone horizons of the Bamboesberg Member. In these horizons, fossil megaplant remains are preserved in the braidplain, lacustrine, channel and abandoned channel elements, with the best preserved material usually found within the lacustrine and abandoned channel elements.

Fossil megaplant material occurs throughout the Bamboesberg and Indwe Members in a number of different preservational forms, and associated with a number of different facies types, predominantly Ge_h, Se_h, and all the fines facies (F). Most of the fossil plant material associated with the gravel (G) and sandstone (S) lithologies, occur primarily as impressions (Fig.3.69) and very less frequently as haematitic or coalified compressions (Fig.3.70). Fossils from facies Ge_h and Se_h

include comminuted and whole plant material and coalified and haematite altered wood. The internal structure of this wood is however altered or obliterated by swelling and post depositional changes. Abundant well preserved stem axes imprints (Figs.3.69, 3.71), *Equisetum* (horsetail, Equisetales) casts and coalified compressions of lycopod stems occur in the basal two sandstones of the Bamboesberg Member in the south of the basin. Silicified stem impressions are common in facies Gt in the Indwe Sandstone Member.

The best preserved material is found within the fines facies association, especially within facies Fh and C and most of the collected megaplant material is broadly assignable to either *Dicroidium* (seed fern, Petaspermales) (Fig.3.72) or *Heidiphylum* (conifer, Volziales) (Fig.3.73). A single specimen of the fern *Ginkgophytopsis spatulifolia* was also identified (H.Anderson *pers.comm.*). This trifurcating frond is to be assigned new generic status as *Kanneskopia* (Anderson & Anderson *pers.comm.*).

In descending order of abundance, the megaplant associations in the Bamboesberg are monogeneric low diversity associations of *Heidiphyllum* and *Dicroidium* (Fig.3.34), and *Equisetum*. Monospecific to low diversity associations of *Heidiphyllum* are thought to represent thicket accumulations peripheral to swamps, and at low water stage in river channels (Anderson & Anderson, 1984). Monogeneric *Dicroidium* associations are proposed to represent low diversity forests and woodland associations, growing along the river bank and other elevated ground. Monospecific associations of *Equisetum* represent thickets in shallow water, in both river channels and back swamp areas of the braidplain (Cairncross *et al.* 1995).

Stow (1871) first reported on large silicified tree trunks from the Molteno Formation in the vicinity of Dordrecht (Fig.3.22). These trunks were also documented by Haughton (1970), and were assigned to the genus *Dadoxylon*. The Dordrecht locality preserves over 20 *in situ* trunks and occurs stratigraphically in the uppermost Bamboesberg Member, close to the contact with the Indwe

Sandstone Member.

Few authors have undertaken research on the silicified wood from the Molteno Formation, and only one other genus, *Rhexoxylon* (Walton, 1923) is described. Wood from the Molteno Formation is therefore not well documented, with most specimens being assigned to the form genus *Dadoxylon* Eindlicher (1847).

Much confusion exists in the literature as to the usage of the terms *Dadoxylon* Endlicher (1847) and *Araucarioxylon* Kraus (1872), with both names having been used almost interchangeably (Stockey, 1982). According to the rule of priority, the name *Dadoxylon* should be applied to both araucaroid Coniferales and Cordaitales wood (Erasmus, 1976), however certain authors use *Dadoxylon* for Palaeozoic wood and *Araucarioxylon* for auraucarian conifers of Mesozoic and younger age (Erasmus,1976; Stockey, 1982).

The wood in the Bamboesberg Member (Table 3.1) is assigned to the conifer *Araucarioxylon* (Bamford *pers.comm*). Most of this wood has been badly altered by heat and not much cell detail is visible as cells are modified and distorted to various degrees. Some cellular detail is preserved in BP/16/455b, including paired cell wall structures (Fig.3.74) and simple pits (Fig.3.75). The average width if the preserved growth rings ranges from between 0.6-1.25mm (BP/16/397) to 3mm (BP/16/396). These are fairly narrow for this type of wood and imply a fairly slow growth rate (Bamford *pers.comm.*).

The genus *Araucarioxylon* is known throughout Gondwana from the Triassic through to the Tertiary (Stockey, 1990), and therefore the presence of this type of wood in the Molteno Formation has little age or correlative value. Its main value stems from the information it provides regarding palaeoclimates (Taylor & Taylor, 1993), and comparison with the podocarp wood from the Burgersdorp Formation gives it a limited biostratigraphic value within the upper Karoo.

Anderson & Anderson (1984) note that one of the most striking features of the flora of the Bamboesberg Member is its relatively low numbers and diversity in relation to the overlying Indwe Sandstone Member. This fact may be accounted for by any number of reasons including a real lower diversity flora, a lower preservation potential for plant material, especially in the lowermost parts of the Member and a lack of adequate collecting. Collecting undertaken to date however seems to corroborate a low diversity flora.

Palynomorphs are also documented from the Bamboesberg and Indwe Sandstone Members (Plumstead, 1969; Stapleton, 1978; Falcon, 1986) (J.Anderson,; Macrae *pers.comm.*). Numerous samples were collected in the field and sampled from boreholes for palynomorph extraction. Care was taken to avoid oxidised near surface sediments and facies influenced by dolerite intrusions, but to date, no significant palaynomorphs have been discovered by the author. Early research on the palynology of the Formation by Girault-Tasia (in Stockley, 1947) indicated a dominance of pteridophytic trilete spores with sculpturing, zonates, monoletes and non-striate bisaccates (in Ellenberger *et al.*, 1964). This is broadly indicative of a *Allisporites/Falcisporites* assemblage as proposed by Falcon (1986).

3.5.2 Trace fossils

Trace fossils are rare in the sediments of the Molteno Formation and prior to Turner (1975a) trace fossils were not recorded for the Formation. Turner (1975a) describes only a single locality and trace type for the entire Formation. Turner (1975) felt this trace was of a surface crawling or browsing type and assigned it to the ichnogenus *Canalichnus moltenensis*, noting that it occured only in the upper Molteno. Trace fossils have not therefore been previously documented for the Bamboesberg Member. Although Raath *et al.* (1991) placed their dinosaur trackways within the Bamboesberg Member by inference, stratigraphic re-assessment of this site revealed that they occur in the uppermost part of the Formation ("Transitional" Member), some 30m below the Elliot Formation.

Although rare in the Bamboesberg Member, trace fossils do occur and are here described for the first time. Traces are mostly of three types and occur exclusively in the finer grained, lower two sandstone horizons of the Bamboesberg Member in the south of the basin. The first type consists of simple clay filled tubes which have a maximum diameter of only 4mm (Fig.3.76), with the diameter of the opening at surface normally between 2-4mm. They are orientated both obliquely and sub-vertically and may have a slight helical nature.

The second type consists of siltstone filled tubes which have a maximum diameter of only 8mm, with the diameter of the opening at surface between 5-6mm. These traces take the form of simple tapering tubes up to 10cm in length. The oblique nature of the trace to the host and the simple mudstone or siltstone infills, allow this trace to be assigned to the ichnogenus *Skolithos*.

The third type (Fig.3.77) occurs on bed tops and may take the form of a cast fill. The infill of the burrow is of the same material as the host lithology. This trace type is ovoid in section, being a maximum of 12mm wide and 8mm high. The trace shown in Figure 3.73 is 90mm in length and shows a distinct kink. This trace is thought to represent a backfilled horizontal feeding burrow (Seilacher, 1964).

To date trace fossils are not known in the Indwe Sandstone Member, probably due to the coarse nature of the sandstones.

3.6 Stratigraphy

3.6.1 Lithostratigraphy

The description of the lithostratigraphy of the Bamboesberg and Indwe Members is here geographically subdivided into the south, southwest, southeast, northwest and north of the basin. The generalised stratigraphy of the sequence is discussed, and the different geographical regions are correlated. The individual channel sandstone complexes are numbered BB1-5 in reference to their stratigraphic position, with BB1 being at the base, and BB5 at the top of the Bamboesberg Member.

A) Geographic Areas

i) South of the basin

The Bamboesberg and Indwe Sandstone Members of the Molteno Formation are well exposed in the Bamboesberg Mountains in the south of the basin and the southern exposures of the Bamboesberg Member in particular are typified by the sequence as preserved in Bushmanshoek Pass (Fig.3.78), and on the farm Aviiion (Bamboeshoek Valley) (Fig.3.79). These sections are supplemented by a single borehole core (SF1/85) drilled to the west of the town of Molteno (Fig.3.80). In this region, the Bamboesberg Member disconformably overlies the Upper Burgersdorp Formation, and is in turn disconformably overlain by the Indwe Sandstone Member, as indicated by the erosive nature of both contacts.

In Bushmanshoek Pass and the Bamboeshoek Valley, the sequence forms part of a large anticlinal structure first documented by Rust (1959, 1962). The strata dip between 1-4° northwards and the Bamboesberg and Indwe Sandstone Members are relatively undeformed, except for a few minor faults and dolerite dykes (Fig.3.78). In the Bamboesberg Mountains (Figs.3.78,3.79 & 3.80), the general sequence consists of five successive cycles, capped by the Indwe Sandstone Member (Fig.3.81). The base of each cycle is composed of a laterally extensive, tabular sheet sandstone, and is usually overlain by a sequence of fine sandstone, siltstone and rare mudstone or coal (Fig.3.80).

The basal channel fill complex (CHS) sandstone of the Bamboesberg Member (BB1) in the Bamboeshoek Valley (Fig.3.82) is between 3-9m thick, and is composed of numerous longitudinal bar elements (DA) and minor channel fills (Ch). The base of this sandstone is erosional into the underlying siltstones, and where channel bases are exposed, is often overlain by facies Se$_{i}$ and rarely Se$_{ii}$. Facies St dominates the channel fill complex of BB1. Impressions (Fig.3.69, 3.71) and coalified compressions (Fig.3.70) of plant stems are preserved throughout the fill. Towards the top of the unit, rare trace fossils are preserved (Fig.3.76).

The top of the first sandstone is gradational into finer grained sandstone and siltstone. The preserved fines sequence consists of between 10-30m of intercalated sandstones and siltstones which may be light olive grey (5Y 6/1) to dark greenish grey (5GY 4/1), or dark reddish brown (10R 3/4) to dusky red (5R 3/4). Directly above the top of the consolidated channel sandstone, iron boxwork lattices intercalated with zoned iron rich siltstones occur at places. These are interpreted as weakly developed hydromorphic palaeosols. Between the basal and second unit, a thin (<1m), laterally impersistant sandstone (BB1/2) is sometimes present (Fig.3.79). Directly below this sandstone, some 2.0m of dark reddish brown mudstone is exposed. Above this sandstone the dark greenish grey fines preserves large amounts of fragmentary fossil plant material.

The second sandstone of the Bamboesberg Member (BB2) is very similar in character to BB1, being dominated by facies Sh (Fig.3.25), in minor channel and bar elements. On the farm Avilion, numerous *equisetum* fossils are preserved at the base of this sandstone, including two impressions in growth position. The basal channel fill complex of BB2 is up to 8.0m thick, and has a gradational top contact into massive or trough cross-stratified fine sandstone and ripple cross-stratified siltstone. This unit preserves the stratigraphically highest evidence of bioturbation observed in the Bamboesberg Member.

The base of the third sandstone horizon (BB3) shows a change in the character of the Bamboesberg Member, and is marked by an erosional surface, above which a thick accumulation of facies So_l occurs (Fig.3.9). Facies Sh that predominated in BB1 and BB2 is present in the lower part of the channel fill complex of BB3 but is replaced by facies St_l higher up. Their is also a marked coarsening in the grainsize of the sandstones of this unit. BB3 is also gradational into overlying finer grained sandstone, but the fine component is not as thick as in the lower two cycles. The stratigraphically lowest coal may be present at the top of the sequence (Fig.3.78, 3.80). This lower seam is rarely encountered and would more correctly be described as a carbonaceous mudstone.

The fourth sandstone of the Member (BB4) in places has a strongly erosive base, and may cut down into BB3, such that the two form a coalesced stacked unit (Fig.3.79). In general the sandstones are coarser than those of BB1-3 and extraformational clasts are fairly abundant, occurring as accumulations at the base of minor channel fills, and dispersed throughout DA bar elements. The channel fill complex is composed of simple longitudinal bars (DA) and minor channel fills (CH) (Figs.3.26a,b), which are internally structured by facies St_l (Fig.3.11), St_c, Sm and Sh. In Bushmanshoek Pass, BB4 has a high concentration of heavy minerals (Fig.3.16) (predominantly garnets) associated with the downstream ends of longitudinal bars.

The upper part of the sequence may preserve the second of the coal seams found in the Bamboesberg Member (Fig.3.78), however at other localities this may be missing due to erosion (Fig.3.80). On the farm Avilion, coal is not developed and instead a 30-60cm thick ochre coloured layer of oxidised plant fossils is present.

The fifth and last sandstone (BB5) in the sequence is the coarsest, and in places has accumulations of extraformational clasts at the base of minor channel elements and longitudinal bars (Fig.3.14), as well as distributed throughout. This unit is almost exclusively internally structured by facies St_l and Sm. Above the main channel belt, a fairly extensive (up to 30m thick) unit of fines, carbonaceous mudstone and coal may be developed (Fig.3.23a). Within this thick accumulation of fines, *in situ* silicified trunks of *Araucarioxylon* are preserved in places, particularly in Bushmanshoek Pass and at Dordrecht (Fig.3.32). The uppermost coal is the best preserved and is directly overlain by the Indwe Sandstone Member.

Three coal horizons therefore occur in the Bamboesberg Member in the south of the basin, although they may not all be preserved at any single locality. In this region, the preserved seams only occur within the upper three sandstone horizons (BB3-5), and coal is not preserved in the lower two sandstone horizons. The number, stratigraphic position and nomenclature of these coal seams in the Bamboesberg Member has long been the source of confusion.

DuToit (1903, 1905a) and Turner (1975a) recognised only one seam in the Bamboesberg Member, whereas Christie (1981; 1985) places two coals in the Bamboesberg and MacDonald (1993) three (Fig.3.83). Turner's (1975a) belief that only a single seam occurred in the Bamboesberg Member stemmed from his placement of the Indwe Sandstone Member too low in the succession. The correct placement of the Indwe Sandstone Member (Turner's Sandstone Y, Fig.3.83) would incorporate his Cala Pass and Guba seams into the Bamboesberg Member, thereby increasing the number of seams in the member to three. From Figure 3.83 it is also evident that Turner's (1975) Suurkop coal equates to the Indwe Seam of Christie (1981) and MacDonald (1993), and is actually the middle seam in the Bamboesberg Member. As noted by Turner (1975a) the term Indwe coal is not favoured due to the use of the same geographic name to describe two lithological units of different status within the same formation. Confusion may also be created due to the fact that the "Indwe" coal actually occurs within the Bamboesberg Member. For these reasons the term Suurkop Coal is rather used to refer to the middle coal in the Bamboesberg Member.

The lowermost coal seam in the Bamboeshoek Valley and Bushmanshoek Pass therefore equates to the Lower Seam of MacDonald (1993), the middle seam equates to the Suurkop coal (Indwe Seam of Christie (1981) and MacDonald (1993), and the upper seam, which lies immediately below the Indwe Sandstone Member, equates to the Guba Seam of Christie (1981) and MacDonald (1993). With the correct placement of the Indwe Sandstone this is also the same Guba coal as defined by Turner (1975a).

The base of the overlying Indwe Sandstone Member may preserve laterally impersistant minor channels with accumulations of Ge_h, and is erosive into the underlying fines of the Bamboesberg Member. The Indwe Sandstone Member is almost exclusively internally structured by facies St_l, which occurs within dune fields in the major channel fill complex. Above the main sandstone layer, a thin (up to 4m) sequence of fines may be preserved basinwide. This unit of fines is often chertified, and in other parts of the basin has been referred to as the chert gannister (Rust, 1959, 1962) and the Aliwal North Porcellanite (Turner, 1975a).

ii) Southwest of the basin

Further to the west, the Bamboesberg Member thins and at the type section overlooking Grootdoringhoek Pass (Fig 3.84, 3.85) it is some 80-85m thick, being formed by only four sandstone bodies (BB2-5) (Fig.3.85). In this sequence, only BB2 is internally dominated by facies Sh. BB4 and BB5 have deeply erosive bases and are internally structured predominantly by facies St_l with lesser Sh and sporadically developed accumulations of facies Se_h.

Although the exposures at the type locality are fairly typical of the Bamboesberg Member, the sequence is not developed to it's fullest extent and is not representative of the Member as a whole. For this reason Bushmanshoek Pass is proposed as a neostratotype (Appendix 5) to replace Turner's (1975a) original type. Bushmanshoek Pass is further preferred over other sections in the Bamboesberg Mountains because of its accessibility and the presence of road cut exposures which show the nature of the channel fill complexes and their internal architectural elements.

The most westerly exposures of the Bamboesberg Member occurs on the farm Hillside in the Steynsburg district (Fig.3.86). Here the stratigraphic succession (Fig.3.87) is some 60m thick and consists of only three sandstones (BB3-5) of the Bamboesberg Member, overlain by the basal part of the Indwe Sandstone Member. The lowermost channel complex sandstone has an erosive contact with the underlying Burgersdorp Formation, and is internally structured equally by facies Sh and St_l. The upper two sandstone complexes are predominantly structured by facies St_l. In this region BB4 and BB5 preserve a higher percentage of facies Sh than in the upper sandstones in the south of the basin. Large quartz arenite clasts are also less common than in the south of the basin and these factors may reflect a more distal, basin edge setting.

iii) Southeast of the basin

The lithostratigraphic fill of the Bamboesberg and Indwe Members in the southeast of the basin is formed by a composite succession of up to five stacked sandstone horizons (Fig.3.88). These are well represented by the section at Cala Pass (Fig.3.89) where the Bamboesberg Member is some 110-115m thick, and is formed by five successive fining upward channel fill complexes. The sandstones in the basal part of the section are predominantly medium grained, and are internally structured mainly by facies Sh, with lesser St_l. Individual channel fill complexes are composed of a number of stacked sets of minor channel fills (Ch), longitudinal bars (DA) and transverse bars and sandflats (LA). The upper two sandstones (BB4 & BB5) are more consistently coarse grained and are internally structured predominantly by facies St_l within in-channel dune fields. BB4 and BB5 are more deeply erosional into the underlying units, and at places BB5 may downcut into BB4 to form a thick stacked sequence. At other places in Cala Pass the top of the BB4 sequence preserves abandoned channel fills. In Cala Pass, the Bamboesberg Member is overlain by up to 6m of the erosively based Indwe Sandstone Member.

The section at Cala Pass is similar, although less thick than the sequence preserved in the Bamboesberg Mountains. It is however typical of the Bamboesberg Member as a whole and for this reason it is designated as a reference stratotype for the Member (Appendix 5). East of Cala Pass the Bamboesberg Member thins rapidly, being only 50m thick at the easternmost exposures, to the southeast of the town of Cala. At this locality the succession is formed by only three cycles (BB3-5), overlain by the Indwe Sandstone Member.

iv) Northwest of the basin

The northwest of the basin is characterised by the exposures in the vicinity of Aliwal North (Fig.3.90) and extends to the northernmost outcrop in the area around Vanstadensrus (Fig.3.91). To the south of Aliwal North, the entire Bamboesberg Member is exposed in new road cuttings on the N7 (Fig.1.2 & 3.60), where it is composed of three individual sandstones, overlain by the Indwe Sandstone Member. At this locality, the uppermost succession of fines is not preserved due to the erosive nature of the Indwe Sandstone Member (Fig.3.60).

On the farm Braamspruit to the southeast of the town of Aliwal North, only the upper two sandstone units (BB4 & BB5) (Fig.3.92) are preserved, and form a unit some 20-30m in thickness. Both these channel complex sandstones are dominated by downstream accreted (DA) and laterally accreted (LA) architectural elements. Downstream accreted longitudinal bars are not as common as in the south of the basin, and are internally structured by both Sh and St$_{l,s}$. Laterally accreted transverse bars are far more abundant in this region and are internally structured predominantly by facies Sp and Sh. The predominance of facies Sh and Sp is thought to represent a distal setting.

Two coal seams occur in the vicinity of Aliwal North and may be associated with the top of either BB4 or BB5. The lower of these was once mined and is well exposed on the farm Gryskop, southwest of Aliwal North. These coals are equated with the middle (Suurkop) and upper (Guba) seam in the south of the basin.

In the area to the south, southeast and southwest of Aliwal North, the Indwe Sandstone Member lacks the characteristic basal accumulation of large extraformational clasts, although sporadic pebbles up to 19cm in diameter may occur. Large (up to 5cm) clasts of fresh feldspar may also occur. The channel complex is composed of numerous minor channels and transverse bars, and is internally structured almost exclusively by facies Gt$_l$, St$_l$ and Sp.

To the east of Aliwal North, the Bamboesberg Member outcrops in low lying hills and in roadcuts on the R58 to Lady Grey. Here the entire Member is preserved as only two thin sandstones, some 12m thick. North of this latitude the Bamboesberg Member outcrops only infrequently on isolated uplifted koppies. Some ten kilometres past Rouxville, the Member occurs as a single sandstone interval some 5.0m thick. The Member cannot be traced further north than ±15km to the south of the town of Vanstadensrus. Here the sequence is formed by a single fining upward sequence which consists of pale blue (5PB 7/2) medium grained sandstone (BB5) overlain by coal and carbonaceous mudstone (Fig.3.91). This coal seam is equated with the uppermost (Guba) seam in the south of the basin. This sequence is capped by the Indwe Sandstone Member. North of this point, the Bamboesberg Member is not exposed at surface, and 15km to the north of Vanstadensrus, the Indwe Sandstone Member directly overlies the Burgersdorp Formation (*Cynognathus* Assemblage Zone).

v) North of the basin

In the north of the basin the Bamboesberg Member is not preserved and the Indwe Sandstone Member forms a unit between 2-15m thick, directly overlying the Burgersdorp Formation (*Cynognathus* Assemblage Zone, Subzone A) (Fig.3.93). As discussed earlier, where two coarse sandstones occur separated by a unit of siltstone containing abundant plant fossils, the term Indwe Sandstone Member is used only for the lower of the two sandstones. This sandstone unit is predominantly composed of stacked sets of transverse bars (Fig.3.62), and is internally structured predominantly by facies Gp and Sp. The foreset laminae of this facies are often deformed due to soft sediment liquefaction (Fig.3.54).

From the above descriptions, a number of features of the stratigraphy of the Bamboesberg Member are evident. The most important of these is that the Member as a whole coarsens up and that the member is thickest in the south of the basin, decreasing to the north, east and west. The fact that the Bamboesberg Member coarsens upwards was first recognised by Christie (1981) and inferred by Ryan

(1963) in that his "Indwe transition zone" was coarser than the lower half of the Bamboesberg Member. It was not however recognised by Turner (1975a), and this led to the incorrect placement of the Indwe Sandstone Member. This low placement of the Indwe Sandstone Member brought about a general lowering of the thicknesses given to the Bamboesberg Member, and confused the stratigraphic placement of the coals. A number of other spatial and temporal trends are evident, and these are discussed below.

3.6.2 Temporal and spatial trends and interbasinal correlation of the Bamboesberg and Indwe Sandstone Members

From the above descriptions of the stratigraphy of the Bamboesberg Molteno, it is evident that the nature of the sequence changes both spatially and temporally. The five major laterally continuous sandstone horizons of the Bamboesberg Member have now been traced throughout the outcrop area, and are correlated as shown in Figure 3.94.

In the south of the basin, the sandstones of BB1 and BB2 are consistently more fine-medium grained than the upper three units, which are predominantly medium to coarse, and very coarse-grained. Due to their coarser nature, the upper three units frequently have a glittery appearance caused by the secondary overgrowth of quartz. South to north, these upper three sandstones decrease in grainsize, so in the area around Aliwal North, they are of a similar grainsize to the basal sandstones in the south of the basin.

Facies Se_l is abundant at the base of the first two Bamboesberg sandstones in the south of the basin and these two sandstones contain abundant plant stems, as well as the only evidence of faunal bioturbation. The major percentage of the first two cycles consists of sandstone predominantly structured by facies Sh. These two cycles also preserve the thickest deposits of braidplain fines, but do not have coal seams capping the sequences. The middle sandstone (BB3) is internally structured sub-equally by Sh and St_{s-l} and the upper two sandstones are dominated by St_l. In the basal two sandstones of the Bamboesberg Member facies St generally occurs as solitary sets between 15-80cm thick, whereas large scale sets (> 1.5m thick and up to 6m wide) and cosets tend to be more prevalent in the upper sandstone horizons of the Member, as well as from the overlying Indwe Sandstone Member. In general facies Sp in the Bamboesberg Member is most abundant in the lower part of the Member in the south, and increases from south to north within any particular sandstone horizon.

Extraformational clasts are very rare in the lower two sandstone bodies of the Bamboesberg Member and only a single quartzite pebble (8cm) has been discovered from the basal sandstone in the south of the basin. The abundance and size of extraformational clasts decreases from south to north and increases as one moves stratigraphically higher in the Bamboesberg Member, reaching a peak in frequency at the base of the overlying Indwe Sandstone Member. This fact has important implication regarding the channel gradient, proximity to the source area and the basinward progradation of the system discussed in Chapter Four.

Petrological studies of the compositional trends of the sandstones of the Bamboesberg Member show that the member coarsens up and become less matrix rich. The percentage of feldspar in the sequence also increases stratigraphically from BB1-5, with a gradual change from plagioclase to microcline as the dominant feldspar present. Rock fragments are not common in the lower horizons of the Bamboesberg Member, but increase up the sequence, being more abundant in the coarser grained sandstones. This brings about compositional changes from feldspathic and lithic wackes in the basal sandstones, to arkoses, subarkoses and quartz arenites in the upper sandstones.

Turner (1975a) considered that the most northerly sandstones of the Bamboesberg Member equated to the basal sandstones in the south, which implied that the aerial extent of the Bamboesberg Member diminished through time, and the Molteno should have an overall fining upward trend. The overall coarsening upward trend however implies a prograding system and an increase in aerial extent through time.

Turner (1975a) further noted that the thickness changes, and hence the temporal variation in the Member was brought about by the "Indwe transgression", which he believed bevelled away over a 1000m of previously deposited strata.

The nature of the thinning of the Bamboesberg Member coupled to the observed spatial and temporal trends are however all consistent with the basinal progradation of a bedload dominated system through time (Allen *et al*, 1986). The nature of the thinning of the Bamboesberg Member and its increase in spatial extent are therefore believed to represent the original extent of the system depositing the Bamboesberg Member, and not due to subsequent erosion as believed by Turner (1975a).

3.6.3 Biostratigraphy

Various attempts have in the past been made to subdivide the Molteno Formation based on its palaeontological signature (Ellenberger *et al.* 1964; Ellenberger, *et al.*, 1967, Anderson & Anderson *in prep.*), however at present the Formation is not biostratigraphically subdivided.

Ellenberger *et al.* (1967) subdivided the entire Stormberg into a Lower (A) and Upper (B) sequence and defined seven biozones for each of them. This biozonation was based on lithological and palaeontological criteria, mainly on fossil megaplants and trackways. In this subdivision, four of the seven zones were assigned to the Molteno Formation and three to the lower part of the Elliot Formation. This zonation is however inconsistent with accepted stratigraphic and palaeontological practices and there is some doubt as to the authenticity of the stratigraphic position of the tracks and therapsid material in question (Turner 1972b). The only definite evidence of tetrapod activity in the Molteno comes from a number of trackways in the Maclear district (Raath *et al.*, 1991; Raath *pers.comm.*), and these footprints, and possibly those recorded in the Molteno by Ellenberger *et al.* (1964, 1967), come from the uppermost part of the Formation.

Turner (1972b) considered the principal elements of the palaeoflora to have too erratic a distribution to be useful for biozonation, even at a local scale. Anderson & Anderson (*in prep.*) however challenge this view and propose four assemblage zones based on the co-occurrence of megaplant and insect fossils. They further note that at present these biozones are not as well differentiated as the tetrapod biozones of the Beaufort Group and should probably be referred to as subzones or interval zones.

Of the four biozones proposed, only the lower one has any bearing on this study, and due to the fact that no insect fossils were discovered during this study, only the megafloral component may be addressed. Anderson & Anderson (*in prep.*) propose a basal *Kanneskoppia spatulifolia-Permithonidae* Assemblage Zone which equates to the entire lithostratigraphic range of the Bamboesberg Member. This biozone is characterised by the common occurrence of *Kanneskoppia spatulifolia* and the absence of any other species of this genus. The predominant palaeofloral association for the Bamboesberg Member documented during this study is monospecific *Heidiphyllum* and *Equisetum* thickets and low diversity *Dicroidium* woodlands, which accords well with the most significant associations documented for the Bamboesberg Member at Aasvoelberg (Cairncross *et al*, 1995; Anderson & Anderson *in prep.*). Although a single specimen of *Kanneskoppia spatulifolia* was discovered, this genus was by no means common in the area studied. The Bamboesberg Member may be further defined biostratigraphically by the dominant association of a rather limited assemblage compared to the vast number of species found in the overlying Indwe Sandstone Member.

Silicified wood assigned to the conifer *Araucarioxylon* occurs throughout the entire Molteno Formation and is therefore of little use for biozonation within the Formation. It is however significantly different from the wood of the upper Burgersdorp Formation and therefore has a broad scale biostratigraphic use for the upper part of the Karoo Supergroup.

It is also of interest to note the fish fossils, first reported by Ellenberger *et al.* (1964), seem to be more frequently found in the lower half of the Formation, apart from the Birds River locality. The Birds River Dolerite complex however disrupts stratigraphic relationships fairly considerably in this area, and the exact stratigraphic position of the fish site is uncertain. Stratigraphic positioning is in fact the major stumbling block to a comprehensive biostratigraphy for the Molteno Formation, as much of the early work suffered from a lack of stratigraphic control.

The biostratigraphic partitioning of the Molteno Formation is therefore still in its infancy, but the combined use of megaplants, insect, fish, conchostrachians, as well as tracks and traces, coupled to strict lithostratigraphic control, may in the future allow for a coherent biostratigraphic subdivision of the Formation to be constructed.

4 DISCUSSION

The previous chapters have dealt with the quantitative and descriptive aspects of the Burgersdorp and Molteno Formations, as determined from field and laboratory studies. These findings now provide the basis for reconstructing the processes responsible for the facies genesis of the Burgersdorp and Molteno Formations, as well as the prevailing palaeoclimates. More precise inter- and intrabasinal correlations are presented, which in turn allow for refined dating of the two Formations, and new insight into the diachronous nature of the Beaufort-"Stormberg" contact. Previous models for the basin development of the upper part of the Karoo Supergroup are evaluated in light of modern advances in retro-foreland basin modelling (Beaumont, 1981; Quinlan & Beaumont, 1984; Flemings & Jordan, 1989; Cateneanu *et al.*, 1997) and a new basinal model for the development of the main Karoo Basin during the Triassic is proposed.

4.1 Palaeoenvironmental Reconstruction

Palaeoenvironmental reconstructions previously proposed for the Burgersdorp and Molteno Formations have in most cases been based on only a single aspect, such as the sedimentology or palaeontology, and to date no holistic paleoenvironmental synthesis has been proposed. Palaeontological and sedimentological data should be used in conjunction in order to provide the most accurate reconstructions possible (Hughes, 1989).

In the following section the palaeoenvironmental settings for the Burgersdorp and Molteno Formations proposed by previous authors are discussed, and the nature of the sequences are assessed by analogy with modern depositional systems. In the past, facies genesis and palaeoenvironmental conditions have often been lumped together as palaeoenvironmental or depositional models. In the following section however, the palaeoenvironmental reconstructions are subdivided, firstly into facies genesis and depositional system type, and secondly into environmental aspects, including palaeoclimate.

4.1.1 Facies genesis

Recent years have seen a revolution in the documentation and understanding of modern depositional systems, and consequent major advances in the sophistication of actualistic depositional models (eg Walker & James 1992; Reading, 1996; Miall, 1996). Process-response models are now known for many modern fluvial environments and these models allow for a far greater understanding of the ancient record than was previously possible (Reading, 1996). Research on modern depositional environments has however revealed shortcomings in some of the classic vertical sequence models (Jackson, 1976, 1978a; Cant & Walker, 1976; Miall, 1977), and Miall (1978, 1996) has stressed the spatial complexities of individual fluvial environments.

The hydrodynamic conditions under which sedimentary rocks are deposited are reflected in their gross geometries, internal architectural elements, facies associations, and the presence or absence of biological activity (Miall, 1996). The presence of fossil remains, their abundance, mode of preservation and gross assemblages, provides supportive evidence for the interpretation of depositional environments (Colbert, 1963). The depositional system interpretations presented below are largely dependant on gross sandstone geometry, architectural element and facies analysis, complimented by the wealth of available palaeontological information.

4.1.1.1 Burgersdorp Formation

The sedimentary strata of the of the Burgersdorp Formation which preserve a *Cynognathus* Assemblage Zone fossil record, have previously been interpreted as being deposited by meandering, high sinuosity rivers, with fine grained sediment accumulating in an inland basin, receiving detritus from the south, southwest and southeast (Hiller, 1990; Groenewald, 1995; Kitching, 1995). The northern deposits (Driekoppen Formation) have been interpreted as those of a meandering river, representing the distal facies of a braided system (Groenewald, 1984) and as an extensive lacustrine setting (van Dijk *et al.*, 1978; Groenewald, *pers.comm.*).

Previous authors usually referred to either the Burgersdorp Formation or the *Cynognathus* Assemblage Zone as a whole and suffer strongly from a lack of temporal and spatial control. The subdivision of the Burgersdorp Formation into a lower, middle and upper part allows for each of these units to be individually assessed. The envisaged depositional styles for the various parts of the Burgersdorp Formation are presented in Figure 4.1.

a) Lower Burgersdorp Formation

The lower part of the Burgersdorp Formation in the north and west of the basin preserves numerous, thin channel sandstones, as well as a thick channel fill sandstone towards the top of the sequence (Fig.2.80). The thin channel sandstones deposits have a width/depth ratio of between 34-54 and are internally structured predominantly by calcarenites of facies Se_l and $Sh_{b\&l}$. The abundant, laterally extensive basal lag deposits (Se_l), consist of reworked calcareous and septarian nodules, well rounded clay pebbles, invertebrate burrow casts, coprolites and fossil fragments assignable to subzone A of the *Cynognathus* Assemblage Zone. The secondary rounding of the clay pebbles, coprolites and fossil bone in facies Se_l implies the reworking of earlier deposits, the rounding of floodplain material by sheetwash and/or the abrasion of skeletal material in channel. The presence of these lags in scoured pockets can be accounted for by winnowing and hydraulic sorting, with localized depression fill. The laterally continuous nature of the lag deposits however implies that there was a time of erosion or non-deposition on a regional scale prior to the deposition of the overlying sandstone fill.

A high percentage of facies Sh in a system is often used as evidence for non-perennial rather than perennial flow (Stear, 1983). The main descriptions of modern ephemeral flood sedimentation are those of McKee *et al.* (1967), Picard & High (1973), Frostick & Reid (1977) and Stear (1983, 1985). All these authors emphasize the dominance of upper flow regime flat bedding (Sh) in their facies sequence models. Miall (1977), Rust (1978), Turnbridge (1981) and Stear (1983, 1985) also all list a high percentage of facies Sh as a critical element of the facies model for ancient ephemeral streams. Similar high percentages of Sh are however also known from modern perennial rivers subject to strongly fluctuating discharge, either of a seasonal or local nature, including braided systems such as at Bijou Creek (McKee *et al.*, 1967).

The predominance of facies Sh and Se, coupled to the high width/depth ratios of the sandstone bodies, in the lower part of the Burgersdorp Formation in the north and west of the basin is therefore strongly suggestive of deposition in a shallow system with highly sporadic (ephemeral or pulsatory) upper flow regime discharge. Such a scenario is similar to that proposed by Hiller & Stavrakis (1984) for the lower Burgersdorp Formation in the south of the basin.

The fines in the lower part of the Burgersdorp Formation are of two main types. The first consist of thick accumulations of facies Fm and preserve a rich amphibian and archosaurimorph fauna. These deposits also preserve small haematite crystals, which have replaced cubic pyrite. The lack of pedogenic modification, the homogeneous nature of the fines and the abundance of well preserved amphibian and archosaur remains, suggests that these deposits represent lacustrine conditions, with periodic drying out due to groundwater table fluctuations. The second type of flood basin deposit exhibits colour mottling and preserves numerous large rhizocretions, root infills, desiccation cracks and barytes aggregates. These are thought to represent overbank flood accumulations subject to rapid drying and pedogenic modification (Type I palaeosols). The occurrence of patchy accumulations of barytes in the overbank deposits may be indicative of localised hydrothermal vents or springs (Duda & Rojl, 1986), or may be of a pedogenic nature.

The upper sandstone in the sequence (Fig.2.80) has a width to depth ratio between 15-20, is lenticular in nature and is internally structured by facies St, and Sh. Although point bar deposits are not well preserved, the lenticular nature and fining upward fill characterised by fine grained Sh and St, point to a high sinuosity channel system with fluctuating discharge.

b) Middle Burgersdorp Formation

For the most part the strata of the middle part of the Burgersdorp Formation are characterised by fining upward cycles of arenitic sandstone overlain by thick sequences of fines (Fig.2.30). Fines to sandstone ratios of ± 4:1, and channel width to depth ratios of between 18-20 are common. The channel complex deposits are internally composed of channel and point bar elements, and characteristically display a classic fining upward sequence. This sequence is formed by a basal scoured surface of low relief, fining up through facies Se_l, St_l, Sp, Sh and terminating with thick accumulations of facies Fl-Fm and Fr.

The recognition of: thick and thin, lenticular, bedload (Fig.2.23) and mixed load dominated channel fill elements (CH) (Fig.2.29); low angle lateral accretion surfaces (LAS) (Fig.2.31a,b) with facies St, Sh and Sr current indicators perpendicular to the dip direction of the LAS; point bars with interspersed mudstone couplets (Figs.2.29, 2.31c); the high suspended load/bedload ratio; and presence of thick suspended load floodplain deposits with interspersed sandstone splays (Figs.2.37, 2.38), is all highly indicative of a mixed load, high sinuosity meandering fluvial system with frequent periods of overbank flooding and levee breach (Allen, 1965a,b; Jackson, 1976; Lewin, 1978; Bridge, 1985). The high variance and low vector strengths of the palaeocurrent data is further evidence for deposition by a high sinuosity meandering system rather than a low sinuosity system.

The point bar sandstone/mudstone couplets are very similar to Jackson's (1978) Class 1 lithofacies, which he documents as having formed in a muddy system with fine grained sand bedload. Smith (1987) documents similar point bar deposits and shows that these are more common in the lower reaches of a system, especially those with either a very low fluvial energy, or that are tidally influenced. As there is no supporting evidence of tidal activity in the Burgersdorp Formation, these deposits are thought to represent the most distal reaches of a fluvial system of very low energy.

The nature of facies Se_l (Fig.2.3) differs from that of the lower Burgersdorp Formation in: that it is composed almost entirely of larger, ellipsoidal mudstone and siltstone clasts, plant impressions, and infrequent bone; and that the matrix is arenitic rather than calc-arenitic. The mixed percentage of facies Sh and St_l probably reflects seasonal fluctuations in discharge, and at times the river course may have been totally dry. There is however some debate as to whether the flow in meandering systems may be ephemeral. Cadle (*pers.comm.*) believes that perennial flow is necessary for the formation of meandering systems, whereas Stear (1983, 1985) documents that many stable meandering channels in semi-arid to sub-humid terrains experience only ephemeral flow, with flood events limited in their duration, normally to only a matter of hours. Periodic high rates of discharge due to rapid run-off in the catchment areas may have led to breaches of the levees and inundation of the surrounding floodplains. Because levees are not well developed for the channels of the middle Burgersdorp, overbank sedimentation during peak discharge was probably fairly common.

The thick laterally extensive tabular sandstone deposit in the middle Burgersdorp Formation has previously been variously referred to as the Middle Sandstone Marker (Johnson & Hiller, 1990) and the Andriesberg Member (Groenewald, 1996). This sandstone differs from the sandbody geometries of the rest of the middle Burgersdorp Formation in: its tabular geometry and lateral continuity; the prevalence of numerous internal scour surfaces; and the presence of minor channel and bar architectural elements, which are in most places internally structured by facies St and Sh_{bar}. The sandbody geometry and structure points to deposition in a bedload dominated, low sinuosity system, with higher fluvial energy than for the rest of the middle Burgersdorp, and may reflect either a tectonically controlled gradient change or a change in the sediment supply to the system (Paola *pers.comm.*). Sediment supply is also strongly controlled by climate, so climatic change may be an additional factor.

Above this thick tabular sandstone body (Fig.2.42) in the type section at Nonensi's Nek, the sequence reverts to a fines dominated low energy meandering system. This upper part of the middle Burgersdorp also preserves evidence of small floodplain (Fig.2.34.) and splay top channels (Fig.2.38). Towards the top of the sequence, the width to depth ratios of the major channels decrease to between 10-15, and are more commonly structured by facies St$_i$ than Sh. Both type II and III palaeosols occur within the middle part of the Burgersdorp Formation, sometimes as stacked units which evidence long periods of non-deposition on the floodplain. Palaeontologically there is also a change towards a greater amount of preserved plant material, and an increase in the number of recovered specimens of *Kannemeyeria.*

c) Upper Burgersdorp Formation

The upper part of the Burgersdorp Formation has a far higher percentage of sandstone then either the lower or middle sections. Coupled to the change in nature of the channel geometries (being significantly deeper with high cutbanks), and lack of interspersed mudstone couplets within the point bar elements (Figs.2.22a,b), the high sandstone percentage is indicative of a system capable of moving a high percentage of bedload. The abundance of facies St$_i$ and Sh, large mudstone intraclasts, and thick units of facies Sm, are evidence for formation of the deposits in a river system with considerable bank relief and channel depth. The gross fining upward sequence, sand body geometry, internal architecture and facies relationships of the channel sandstones in the upper Burgersdorp Formation however still resemble the classic high sinuosity, meandering stream model of Allen (1965, 1970).

The up section decrease in the frequency of palaeosol development, calcareous nodular layers and rhizocretions, coupled to the change in palaeosol geochemistry (to a carbonate poor, Fe_2O_3 and silica rich type) suggests higher levels of precipitation and more poorly drained soils. The lack of well developed stacked paleosols may imply either a fairly high water table, or frequent inundation of the floodplain, such that the time interval between flood events was not long enough for recognisable pedogenic development. The thick units of facies Fm may be attributed to rapid suspended load deposition on the floodplain, and biogenic modification. The thin coarsening upward sandstone splays are believed to be produced by small deltaic type build-out of sand into a standing body of water.

The presence of abundant stable vegetation is directly evidenced by: impressions of large fossil pteridosperm axes (Fig.2.75a,b); casts of the spenophyte *Calamites* (Fig.2.76); and silicified wood. The presence of laterally continuous fibrous rooted horizons within thin siltstone splays (Fig.2.40) shows that vegetation was present in the proximal parts of the floodbasin and vegetation probably played an important role in stabilising the position of channel as documented for modern settings by the likes of Smith (1976), McCarthy *et al.*, (1986) and Stannistreet *et al.* (1993).

Although these findings for the Burgersdorp Formation do not differ significantly from those already published, it is evident that the depositional history of the Burgersdorp Formation (Fig.4.1) is more complex than previously recognised. Newly documented environments and sub-environments, include low sinuosity channels (Fig.2.34), minor floodplain (Fig.2.34) and crevasse top channels (Fig.2.38), thick splay deposits (Fig.2.35) and palaeosols (Fig.2.19).

4.1.1.2 Molteno Formation

The Molteno Formation has previously been proposed to have been deposited by systems ranging from subaerial deltas (Haughton, 1924) and distal meander tracts (Smith *et al.*, 1993; Anderson & Anderson, *in prep.*), to braided and anastomosed river systems (LeRoux, 1993). The current consensus (Turner, 1975a, 1978; Christie, 1981; Cairncross *et al.*, 1995; Rust *pers.comm.*) seems to be for a braided river origin, with material deposited in the proximal reaches of a system draining an alluvial fan of the glacial outwash type. Previous models for the Molteno Formation suffer from a lack of stratigraphic and spatial control and no changes within the Bamboesberg Member have been documented.

Christie (1981) considered the large proportion of planar stratified sandstone (facies Sh) and the scarcity of "argillaceous" fines to be features which showed the Bamboesberg Member to resemble the Bijou Creek ephemeral model (McKee *et al.*, 1967). He furthermore noted that the geometry and internal structure of the sandstones were similar in appearance to the Brazeau-Paskapoo Sequences of Brazil (McLean & Jerzykiewicz, 1978).

MacDonald (1993) followed Christie (1981) in proposing that the Bamboesberg Member of the Molteno Formation was the product of sandy ephemeral streams, due predominantly to the large percentage of facies Sh. High percentages of Sh are however also known from braided streams with perennial, although fluctuating, flow (Langford & Bracken, 1987).

Based on a study of grainsize distributions, LeRoux (1993) proposed deposition by an anastomosing system for the Indwe Member in the north of the basin. No evidence of anastomosing (anabranching) was recorded in the Indwe Sandstone Member during the course of this study. Eriksson (1983, 1984, *pers.comm.*) feels that the deposition of the Indwe Sandstone Member in the northeast of the basin took place within a classic braided river setting, with perennial flow, but with low and high water phases. The high percentage of fines in the upper part of BB5 led Anderson & Anderson (*in prep.*) to suggest intervals of low sinuosity meandering river sedimentation towards the close of the Bamboesberg Member.

The nature of the fining upward sequences found in the Bamboesberg and Indwe Sandstone Members grossly resembles the facies sequence of both braided (Doeglas, 1962) and meandering systems (Allen, 1964a, 1965a; Coleman, 1969; Smith, 1970). The: thickness; gross geometry and internal architecture of the channel complex sandstones; numerous scour surfaces representing channel switching; facies types and relationships; grainsizes; rapid textural changes; high sandstone to fines ratio; and the high vector strengths and low variance of the palaeocurrents, all favour deposition in a low sinuosity braided system (Ore, 1964; Miall, 1974, 1976) as proposed by Rust (1959, 1962), Turner (1975a, 1983, 1984), Christie (1981, 1986) and Eriksson (1984).

Blair & McPherson (1994) have however documented that braided sedimentary deposits may accumulate on alluvial fans, in braided rivers and on braidplains. The recognition that the Molteno Formation is predominantly structured by braided deposits raises the question as to the type of depositional system (alluvial fan, braided river or braidplain) responsible for the pattern of sedimentation preserved within the Bamboesberg and Indwe Sandstone Members.

Alluvial fans are a form of fluvial depositional system distinguished on the basis of geomorphological characteristics rather than by a particular fluvial style (Bull, 1972, 1977). The term is broadly used by in the literature, with considerable disagreement and confusion as to the range and types of depositional system that should be termed alluvial fans (Stannistreet & McCarthy, 1993; Miall, 1996). Reading (1996) recognises gravity flow (semi-arid) and fluvial (humid) fans based on the processes operative on the fans. Following Blair & McPherson (1994) humid fans are here considered to be large braidplains.

Although the definition of fans is therefore the subject of much debate, in general fans are semi-conical features, with radial dispersal from a single point source. They have radii which are normally less than 10km, especially in arid climates. In contrast, braided rivers and braidplains (braid deltas and humid braided fans) show essentially parallel dispersal on sub-planar surfaces and extend from tens to hundreds of kilometres (McPherson & Blair, 1993; Blair & McPherson, 1994). The: lateral continuity of the channel sandstone complexes; their high width to depth ratios; unidirectional palaeocurrents; and lack of angular clasts, matrix supported sieve conglomerates and small inversely graded coarsening upward units indicative of debris flow deposits, all argue against proximal arid alluvial fan deposition (Blissenbach, 1954). This allows for a general braided fluvial environment to be constrained for the Bamboesberg and Indwe Members of the Molteno Formation as has been previously suggested by earlier workers (Turner, 1975a; Christie, 1981).

Braidplains differ from braided rivers in being unconfined by valleys, although the active tracts of braidplains may be temporarily confined within banks of their own alluvium (Blair & McPherson, 1994). Braidplains commonly arise from the downslope coalescence of fans or of braided rivers where they emerge from their confining valleys. The distinction between braided rivers and braidplains is important because most models for braided alluvium are based on braided rivers.

Because there is no evidence that the channel complexes of the Bamboesberg and Indwe Sandstone Members were constrained by bedrock, they are best referred to as braidplains (broadly including humid braided fans). Most of the literature documenting modern braided systems however deals with processes in braided rivers, and furthermore are concerned with gravel and sand dominated pro-glacial rivers (Boothroyd & Ashley, 1957; Boothroyd & Nummendal, 1978; Miall, 1978; Cant & Walker, 1978). Only the Brahmaputra and Kosi systems are adequately described (Coleman, 1969; Bristow, 1987; Welles & Dorr, 1987) to act as a models for sand dominated bedload deposition in a humid fan setting.

Although most models are therefore based on pro-glacial, braided rivers, it is still useful to compare actualistic studies of modern systems (both braided river and braidplain) to the deposits of the Bamboesberg and Indwe Sandstone Members, in order to understand the processes operating within the system.

a) Bamboesberg Member

A number of features of the Bamboesberg Member are indicative of deposition in a bedload dominated, low sinuosity braided fluvial system. These include: the elongate, sheet-like nature and large lateral extent of the channel sandstone complexes; their high width to depth ratios, at times approaching 70:1; their multistoried nature with abundant erosion surfaces marking downcutting and channel shifting; the dominance of longitudinal and transverse bar elements; the lack of lateral accretion surfaces; the medium-coarse grainsize of the sandstones; their rapid textural changes; the inclusion of both intra- and extraformational clasts;

the low variance and high vector strengths for the palaeocurrents; and the paucity of overbank deposition of fines (low fines/sandstone ratio). The uniformity of facies dominated by Sh and the consistent mean palaeoflow direction (north-northeast) are two characteristics that Rust & Gibling (1990) believe clearly identifies braidplain deposits as opposed to braided rivers.

The entire Bamboesberg Member does not however fit any of the pre-existing braided river, braidplain, or humid fan models for sandy, braided fluvial deposition, and no single model can account for the large range of stratigraphic variation of architectural style seen at the regional level.

Using the stratigraphic section at Bushmanshoek Pass (Fig.3.78) as a reference type for the Bamboesberg Member in the south of the basin, it may be seen that a number of changes occur stratigraphically within the Member. The lower two sandstones of the Bamboesberg Member preserve a high percentage of facies Sh with parting lineation on the upper surfaces. These are indicative of shallow water deposition, and as proposed by Christie (1981), may be the product of shallow, ephemeral braided streams, or the product of seasonal flow fluctuations as shown.

Vertically accreting Sh such as is found in the lower two sandstones of the Bamboesberg Member is however not common in braided river sequences except in the Bijou Creek and Medano Creek models (McKee *et al.*, 1967; Langford & Bracken, 1987). Facies Sh may however be abundant in the more distal reaches of braided systems where finer grainsizes are deposited, and the scarcity of facies Sh in the proximal reaches of the Bamboesberg Member is most probably a function of grainsize and not flow velocity.

The presence of significant amounts of braidplain fines in the lower Bamboesberg is atypical for bedload dominated fluvial systems and may also be indicative of a distal braided setting. This abundance of fines in the lower part of the Bamboesberg Member may also be provenance related, in as much as the source at this time may still have been reworked Dwyka, Ecca and lower Beaufort Group strata (Rust, 1959, 1962). In a few places plant fossils are preserved in a growing position within the finer grained sandstone in the lower part of the Bamboesberg Member. This is also typical of the more distal reaches of braided systems, where equisitaleans often colonise raised or abandoned levels as well as bar tops (Williams & Rust, 1969).

The lower two sandstones of the Bamboesberg Member therefore preserve features suggestive of shallow, high energy flow, with rapid switching and lateral migration of channels in a distal braidplain setting. This distal setting and rapid lateral channel shifting allowed for the formation of thick accumulation of fines in the abandoned channel tracts and on the braidplain overbank. With its larger amount of braidplain material, predominance of facies Sh and lesser proportions of St and Sm, the basal Bamboesberg has no direct modern analogue, but is suggestive of deposition in a system very similar to the distal reaches of the Kosi megafan (Welles & Dorr, 1987; Gohain & Parkash, 1990).

The upper three sandstones of the Bamboesberg Member preserve different internal architectural elements, have a coarser grainsize, and show a decrease in the percentage of faces Sh and fines, than those of BB1 or BB2. Facies St$_l$ becomes the dominant in channel facies and coal is found topping individual fining upward sequences. Facies Sm in the upper Bamboesberg occurs within transverse bars and sheets in the erosively based minor channels. These equate to the massive sheet facies and massive erosively based facies of Turner & Martin (1987). Such facies are common within permanent braided systems and are documented for the ancient in the Hawkesbury Sandstone by Rust & Jones (1987).

The predominance of facies St$_l$ in the upper part of the Member, as opposed to facies Sh in the lower Bamboesberg, suggests that the system was different to that for the lower part of the Member. This system seems to be most similar to that described by Cant & Walker (1978) for the South Saskatchewan River. The upper part of the Bamboesberg Member in the south of the basin however differs from the South Saskatchewan in the greater abundance of facies St, the scarcity of facies Sp and the fewer completely preserved fining upward channel fill sequences. This suggests that the active tract relocated by lateral channel switching. Such lateral switching (active tract avulsion) is most likely when the river is not confined to a valley (Blair & McPherson, 1994). In the upper Bamboesberg it seems then that channel switching brought about the rapid abandonment of the previously active tract, such that the waning channel fill sequence, characteristic of South Saskatchewan type deposition, is often not deposited. Instead, the abandoned tract may have become colonised by plants, receiving sediment only during high stage flow. Following high stage flow, the water body may have stood for some time, thereby allowing for the suspended load settling of laminated muds and silts, which form the abandoned channel fills documented in the upper Bamboesberg (Cairncross *et al.*, 1995; Fig.3.27).

The abundance of facies St$_l$ in the Bamboesberg Member allows for speculations to be made regarding the depth of flow. Facies St$_l$ is the internal structure to subaqueous dunes and Harms *et al.* (1975) state that the water depth at which these dunes form is ± twice the thickness of the individual set. Allen (1983, 1984) also demonstrated a relationship between dune height and flow depth in rivers, although Rust & Gibling (1990) point out that there is considerable scatter in this relationship. Applying the simple estimation of Harms *et al.* (1975) to the maximum set thickness of 80cm for the lower Bamboesberg, and 1.2m for the upper Bamboesberg would give a mean water depth in channel of 1.6m and 2.4m respectively. These figures are similar to those supplied by Turner (1983) of between 0.73-2.2m based on the sixth power law of clast sizes between 16.5-70cm in diameter. The depth figures are also consistent with both the thickness of sets and cosets of St$_l$, and the preserved thicknesses of fining upward channel fills. Abandoned channel fill thicknesses of up to 3.0m provide supportive evidence of channel depth and bank height.

The South Saskatchewan River has an average in-channel bankfull water depth of 3.0m with a maximum of 5.0m, values which are very similar to those proposed for the upper Bamboesberg Member. The slightly deeper channels in the South

Saskatchewan may be accounted for by valley confinement (Blair & McPherson, 1994), and although this may have been the case for the upper Bamboesberg, is not likely given the lateral extent of the channel complexes and the fact that such deposits are only very rarely preserved in the ancient (Rust & Gibling, 1990). This therefore raises the question of how channels some 2.4m deep were maintained, as such depths could not have extended simultaneously over the entire braidplain. The most likely explanation is that during the deposition of the upper Bamboesberg Member, braided tracts were temporarily confined by alluvial banks of finer material stabilized by vegetation. These where not however stable enough to maintain the active channel tract in one position indefinitely, and their erosion allowed for the channel to migrate transversely across the braidplain with time. Although of a smaller scale, a possible modern analogue for this style of sedimentation is the Lake Torrens Plain of South Australia, which has banks up to 4m high cut into essentially contemporaneous alluvium (Leckie, 1994).

The two principle phytotaphocoenoses noted for the Bamboesberg Member are monodominant to monospecific *Heidiphylum* thickets, thought to represent shrubby coniferous stands associated with areas of higher water table on the braidplain, or sandbars within the channel systems (Cairncross *et al.*, 1995) and *Heidiphylum/Dicroidium* association, which are believed to represent tracts of stable vegetation flanking the main channel. The presence of silicified logs in the upper Bamboesberg, up to 15m in length, demonstrates that trees of a moderate size were also present. The presence of coal in the upper Bamboesberg is evidence for the development of peat swamps on the braidplain. Peat probably grew on elevated terraces, abandoned channels, backwater swamps and lacustrine settings and probably added to bank and active tract stability.

The most extensive time of peat swamp formation is represented by the Guba coal seam which is up to 4.5m thick in places (Christie, 1981). Based on a compaction ratio of 11:1 (Ryer & Langer, 1980), the 1.2m thick coals seams in the upper Bamboesberg, are indicative of peat thicknesses of up to 13m, and the 4.5m thickness recorded by Christie (1981), of peat accumulation of up to 50m.

Taking an average for peat formation of 1mm/yr (McCabe, 1984) would give an estimate of peat swamp formation of between ±13 000 and 50 000 years for the Guba Seam. This implies long periods of high water tables, active subsidence and relative stability on the braidplain prior to the erosion and burial of the peat by the active river tract.

b) Indwe Sandstone Member

A number of features indicate that deposition of the Indwe Sandstone Member occurred during a time of increased discharge and channel depth than for the underlying Bamboesberg Member. These include: the greater lateral extent and tabular nature of the channel sandstone complexes; the lenticular nature of the minor channels within them; the coarser grained nature of the sandstones; the abundance of facies Ge_h and Se_h; the predominance of facies Gt_l and St_l; the presence of thick units of facies Gm and Sm; the lower width/depth ratios; and the low fines/sandstone ratio. These characters all suggest formation of the Indwe Sandstone Member in a braidplain system with considerable bank relief (Fig.3.59) and greater channel depth than for the underlying Bamboesberg Member (Fig.4.2).

The most southern outcrops of the Indwe Member show certain of the features of a distal alluvial fan setting including thin graded sheet flood deposits with pebble lags, and channel flood conglomerates with well developed horizontal cross-stratification. The erosional nature of the basal surface and the predominance of facies St_l may however best be explained by deposition in a moderately confined, proximal humid braidplain setting. The presence of sequences of facies Ge_h with well rounded clasts, overlain by Gt_l, St_l, Sm and Sh, is also similar to the sequences preserved in the proximal deposits of several braided rivers, including the Scott (Miall, 1977), Donjek (Rust, 1972) and Yukon (Rust, 1972) rivers. The Scott River however is characterised by a higher percentage of gravel than found in the Indwe.

In the north of the basin, the Indwe Sandstone Member has a high percentage of facies Sp, preserved within transverse and linguoid bar elements, and the sequence is similar in character to the Platte River model (Smith, 1970, 1971, 1972; Blodgett & Stanley, 1980).

Although the preserved sequences show similarities to certain of the braided river models, the lateral extent and sandbody architecture of the Indwe Sandstone Member differs shows that it was not confined within a valley, and modern analogues may be the proximal reaches of the Kosi Fan (Singh *et al.*, 1993) and the Brahmaputra River of northern India (Coleman, 1969; Bristow, 1987).

i) Evolution of the Bamboesberg and Indwe braidplain

Although Blair & McPherson (1994) believe that the lateral confinement of braided rivers by valley walls should result in facies assemblages different from those found on braidplains, the facies associations for the Bamboesberg and Indwe Sandstone Members, show remarkable similarities to a number of the braided river models. This may in part be due to the confinement of the main channel tract by banks of alluvium and peat marshes, and in part by the similarity in processes operating on the systems.

Placing the typical in channel sequences of the Bamboesberg and Indwe Members within the classic braided stream models (Miall, 1977, 1978), it becomes apparent that the lower part of the Bamboesberg Member is most similar to the Bijou (McKee *et al.*, 1967) and Medano Creek (Langford & Bracken, 1987) models, where Sh is the dominant facies, and flow is episodic and unconfined. The upper Bamboesberg is more similar to the South Saskatchewan (Cant & Walker, 1978) in nature being the product of in-channel dune and bar migration, within temporarily confined banks. The Indwe Sandstone Member does not fit perfectly into any of the proposed models for braided rivers, but seems to be intermediate between the Scott and Donjek River models in the south of the basin, and similar to the Platte River model in the north of the basin.

Miall (1978) considers that the Scott, Donjek and South Saskatchewan profile types represented a gradational proximal-distal sequence in ancient braided systems, with the boundaries between the three types determined on gravel content. The percentage of included gravel decreasing from greater than 90% for the Scott to between 10-90% for the Donjek and less than 10% for the South Saskatchewan type. In terms of the lateral relationships of these models, the gross petrological resemblance of the sandstones, and the similarity of the palaeontological signatures of the Bamboesberg and Indwe Members, it is not unreasonable to assume that the Bamboesberg deposits are a distal facies equivalent of the coarser grained Indwe Sandstone Member. In this scenario, the more proximal Indwe strata progressively overstepped their distal equivalents due to basinward progradation of the fan, in response to increased gradient and sediment supply in the southern reaches of the system.

The vertical transition between the lower and upper Bamboesberg Member and between the upper Bamboesberg and the Indwe Sandstone Members, shows the classical coarsening upward motif of prograding alluvial systems (Davis *et al*, 1983), and indicates deposition of transitional sub-environments within an integrated drainage system. The deposits of the lower two members of the Molteno Formation may therefore be envisaged as representing a continuum from deep gravelly braidplain channels to a shallow distal sand dominated braidplain.

ii) Conclusion

In terms of the fluvial models of Leopold & Wolman (1957) and Schumm (1972) the channel fill sequences of the Bamboesberg and Indwe Sandstone Members of the Molteno Formation fall into the low sinuosity, bedload dominated, braided systems, as concluded by Turner (1975a, 1983, 1984) and Christie (1981, 1986). The system was structured predominantly by active and abandoned channel tracts and in-channel bars of various morphologies, and the overall environment for the deposition of the Bamboesberg and Indwe Sandstone Members of the Molteno Formation may therefore be envisaged as a sand-bedload dominated braidplain system, which prograded into the basin from an uplifted source area. Palaeocurrent partitioning does not occur in the Bamboesberg and Indwe Sandstone Members and the lack of significant palaeocurrent changes between major channel complex sequences suggests that changes in slope, rather than major avulsions, were the cause of system progradation and the stacking of channel complexes. The evolution of the lower Molteno Formation braidplain through time (Fig.4.2) may therefore be seen as a response to increased slope and differential erosion and subsidence.

Pulsatory flow within the Bamboesberg Member is evidenced by numerous factors and may be attributed to episodic, possibly ephemeral flow in the lower part of the Member, and to pulsatory seasonal flow in the upper part. This may be attributed to variable precipitation and/or seasonal fluctuations in discharge.

The depositional system for the lower Bamboesberg is envisaged as a tract of coalescing braided rivers with little lateral stability, whereas the upper Bamboesberg and Indwe Members may be regarded as having a more permanent active tract, flanked by well vegetated banks, and overbank environments on which peat bogs and swamps were formed (Figure 4.2). Although the Bamboesberg and Indwe Sandstone Members share numerous process related features with modern braided river models, their lack of confinement by bedrock, and sheer size suggests that better modern analogues are the Lake Torrens Plains of South Australia, the Kosi Fan of northern India (Gole & Chitale, 1966; Gohain & Parkash, 1990; Singh *et al.*, 1993) or the Canterbury plains of New Zealand (Leckie, 1994).

4.1.2 Environmental aspects

Environmental aspects assessed include the groundwater pH-Eh, water table levels, and palaeoclimate. The groundwater pH-Eh is controlled primarily by the nature of the vegetation cover and the exchange of dissolved salts, and the water table level by the amount of precipitation and infiltration, as well as tectonics. Both of these aspects are further influenced by climate.

Climatology is the net result of a number of integrated parameters including: solar energy admission; atmospheric composition; landform configuration; sea-level; positions of the poles; oceanic and atmospheric circulation (Visser, 1991). Global trends are regionally mediated by factors such as local atmospheric conditions, large bodies of water and mountain ranges. The relative importance of, and interplay between, these factors is not yet fully understood, and a number of these inputs are unavailable to the student of ancient sequences. As such, palaeoclimatic and palaeoenvironmental reconstructions have to be based on the sedimentological and palaeontological record. Thin section petrography, combined with other sedimentological and palaeontological data (Gould, 1972), especially the study of palaeosols (Retallack, 1990), allows for various conclusions to be drawn regarding the palaeoenvironment prevalent during facies genesis of the Burgersdorp and lower Molteno Formations.

Numerous authors have previously used mineral stability relationships to infer palaeoclimates (Krynine, 1949; Folk, 1959, Todd, 1968; Basu, 1985; Lewis & McConchie, 1994). Krynine (1949) and Folk (1959) proposed that the mutual presence of fresh and weathered feldspar to be indicative of humid weathering conditions. James *et al.* (1981) have however shown that there is a broad overlap in the amount of alteration on detrital feldspars from wet and dry climates and that the amount of detrital feldspar in ancient sandstones is not a good indicator of palaeoclimatic conditions. James *et al.* (1981) also show that the alteration of detrital feldspars from humid climates is predominantly limonite and kaolinite, whereas in semi-arid and arid climates it is predominantly limonite and smectite. The use of feldspar ratios or decay in predicting palaeoclimates is further compounded by diagenetic overprinting. Bearing these limitations in mind, the overall composition of feldspar is used cautiously, and is combined with all other available data to predict palaeoclimate. The palaeoenvironmental aspects of the Burgersdorp Formation are based predominantly on palaeosols and palaeontological data, whereas that for the Molteno Formation is strongly based on palaeontological criteria, supplemented by lithological data.

Cadle *et al.* (1993) propose that the climatic evolution of the Karoo Basin may be correlated to the global trends of Frakes (1979), in that a cold, moist Early Permian was followed by steadily increasing temperature and aridity until the Jurassic. Global temperatures rose sharply during the Late Permian and Early Triassic and during the Middle Triassic the climate was warm and seasonal, with atmospheric circulation sluggish in the absence of polar ice caps (Frakes, 1979). With the exception of the Molteno Formation, for which Visser (1991) proposed abnormal cold and wet conditions, arid conditions have therefore been proposed to have prevailed during the Triassic deposition of the Karoo sedimentary strata succession. The enigma of a cold, wet Molteno, as proposed by Haughton (1924), Anderson & Anderson (1970, 1976, 1983), Turner (1983), Visser (1991) and MacDonald (1993) therefore needs to be re-examined.

4.1.2.1 Burgersdorp Formation

Most workers agree that the thick sequences of fines and sandstones within the Burgersdorp Formation were deposited under warm, arid to semi-arid conditions (Kitching, 1977, 1995; Visser, 1991; Groenewald, 1996). Visser (1991) states (p.428) "In the Karoo Basin the early Triassic (Anisian & Ladinian, 231-248Ma) climate was also warm and very similar to that of the Late Permian, except that it was perhaps more equable". It should be noted that the time period referred to here (Anisian-Ladinian) is actually Mid-Triassic, and that the ages given cover a range from the late Permian through to the Late Triassic.

During the deposition of the Burgersdorp Formation, the Karoo Basin was situated between latitudes 45-55°S (Visser, 1991). At this time, the magnetic south pole was located over the palaeo-Pacific Ocean, and the orientation of the palaeo-Pacific margin of south-western Gondwana changed from north-northwest to northwest. This would have brought about a partial obstruction of the flow of cold water towards the equator, which in turn would have restricted the width of the cold circum-polar zone.

Based on the red and purple colouration of the mudstone and sandstones, Groenewald (1996) proposed that climatic conditions were dry throughout the depositional history of the upper Burgersdorp in the southeastern part of the basin. Dubiel (1991) believes that red beds actually have no palaeoclimatic significance since they are known to occur in early to late stage diagenetic oxidising Eh-Ph conditions, in a wide spectrum of subaqueous and subaerial settings, both humid and arid. This stated however, colour is used by many authors as an environmental indicator (Krynine, 1949; McBride, 1974), due to the fact that the red colouration of many sequences is imparted by iron oxides (particularly haematite), which once formed tend to be relatively immobile and diagenetically stable. The abundance of haematite as the predominant iron mineral in the Burgersdorp Formation favours sedimentation under oxidising conditions for the majority of the floodplain fines. Localised green mottling may indicate local reducing conditions, as does the local formation of cubic pyrite (replaced by haematite). Under oxidising conditions, organic matter would simply be oxidised to CO_2 and water and this probably accounts for the lack of preserved plant remains within the fines of the Burgersdorp Formation. The red colouration of the fines and palaeosols in the Burgersdorp Formation, coupled to the presence of haematite as the main iron mineral, therefore tends to evidence oxidising conditions on the floodplain, which coupled to the palaeogeographic setting and depositional style, favour a warm palaeoclimate. High temperatures would also lead to accelerated rates of organic decay, which in turn create less acidic and reducing pore waters and a preferential environment for the preservation of bone.

Calcrete formation is documented almost throughout the Beaufort Group (McPherson & Germs, 1979; Smith, 1980, 1981, 1989, 1990b), and the Burgersdorp Formation is no exception. Calcareous concretions occur at most levels within the Formation and by comparison with Holocene pedogenic carbonates (Goudie, 1973; Reeves, 1970; Hubert, 1978; Netterberg, 1980) calcretes are generally accepted as being indicative of arid to semi-arid climates (with a mean annual temperature of 16-20°C) (Goudie, 1973) and a highly seasonal, periodically distributed rainfall (mean annual of 100-500mm) (Seminuik & Searle, 1985).

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