A Stratigraphic, Sedimentological and Palaeoenvironmental synthesis of the Beaufort-Molteno contact, in the Karoo Basin.

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A Stratigraphic, Sedimentological and Palaeoenvironmental synthesis of the Beaufort-Molteno contact in the Karoo Basin.

Volume I

By

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FRONTISPIECE

OUT OF AFRICA THERE IS ALWAYS SOMETHING NEW

Aristotle via Pliny the Elder

DECLARATION

Except where stated this thesis represents unaided original work by the candidate and has not been submitted in part or in whole at any other university. The research was undertaken in the departments of Geology and Palaeontology under the supervision of Professor B.S.Rubidge.

P.J.Hancox

Signed in Johannesburg, this .23rd.... day of .January.. 1998

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ABSTRACT

The Burgersdorp and lower Molteno Formations (Bamboesberg and Indwe Members) form a well exposed sequence of sedimentary strata in the main Karoo Basin. A knowledge of the fill of these two formations is critical to understanding the basinal development of the upper part of the Karoo retro-foreland. Presently both formations are poorly understood and this study addresses the problem by investigating the stratigraphic, sedimentological and palaeontological signatures of the two formations.

Lithologically, the Burgersdorp Formation is composed of varicoloured floodplain fines and fine-medium grained channel sandstone bodies. Palaeocurrent measurements indicate a system with unimodal flow to the north-northwest. The depositional environments for the Burgersdorp Formation are dominated by high sinuosity, mixed load meanderbelt facies associations deposited under semi-arid conditions. The provenance for the Burgersdorp Formation is a mixed acid plutonic, low grade metamorphic and sedimentary source, situated to the south and south-southeast.

The uppermost strata of the Burgersdorp Formation in the south of the basin yielded a new tetrapod fauna broadly assignable to the *Cynognathus* Assemblage Zone, but which also includes new capitosauroid amphibians and the first Stahleckeriids and Shansiodontiids in South Africa. The discovery of this new fauna, coupled to the spatial and temporal distribution of the temnospondyl amphibians from the biozone, allowed for a threefold biostratigraphic subdivision for the *Cynognathus* Assemblage Zone to be erected. Correlation of the *Cynognathus* Assemblage Zone with other well dated nonmarine terrestrial deposits of Gondwana, China and Russia, shows that the age of the biozone spans the Lower Triassic (Tr1; Scythian) - Middle Triassic (Tr2; Anisian) boundary.

The Bamboesberg and Indwe Members of the Molteno Formation form a thick coarsening upward, sandstone dominated sequence, with subordinate fines and coal. Palaeocurrent directions indicate unimodal flow to the north-nort

north-northwest. Depositional environments are mainly low sinuosity, bedload dominated humid braidplains on which peat swamps flourished. Provenance studies document a mixed plutonic and metamorphic source, with significant input from the Cape and lower Karoo Supergroups. The Bamboesberg and Indwe Members contain a well preserved palaeoflora, but no tetrapod fossils, and the palaeontological signature of the two members indicates a Carnian age for the lower part of the Molteno Formation.

The contact between the Burgersdorp and Molteno Formations is formed by a diachronous unconformity surface, which decreases in magnitude sourceward from ±33Ma to ±4.5Ma. The geometric form and fill of the main Karoo Basin during the Triassic is strongly controlled by the flexural response of the heterogeneous lithosphere, which underplates the basin, to orogenic loading caused by thrust activity in the Cape Fold Belt (CFB). The spatial and temporal distribution of the Burgersdorp and Molteno Formations may therefore be explained in terms of tectonically controlled sourceward and basinward shifts in the depositional system, overprinted by the prevailing palaeoclimate.

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INSTITUTIONAL ABBREVIATIONS USED IN THE TEXT

AMG	=	Albany Museum, Grahamstown, South Africa
AMNH	=	American Museum Natural History, New York, USA
BMNH	=	Natural History Museum, London, England
BPI	=	Bernard Price Institute for Palaeontological Research, Johannesburg, South Africa
CG	=	Council for Geosciences, Pretoria, South Africa
CUMZ	=	Cambridge University Museum of Zoology, England
ELM	=	East London Museum, East London, South Africa
GSP	=	Geological Survey, Pretoria[*1]
HMV	=	Hofmuseum, Vienna, Austria
IVPP	=	Institute of Vertebrate Palaeontology and Palaeoanthropology, Beijing, China
NMB	=	National Museum, Bloemfontein, South Africa
PEM	=	Port Elizabeth Museum, South Africa
SAM	=	South African Museum, Cape Town, South Africa
TM	=	Transvaal Museum, Pretoria, South Africa
UCMP	=	University of California Museum of Palaeontology, Berkley, USA
UT	=	Universität Tübingen Museum und Institut für Geologie und Paläontologie

*1 = Renamed the Council for Geosciences, Pretoria, South Africa (CG).

1 INTRODUCTION

1.1 Background

The main Karoo Basin of South Africa contains one of the most temporally and spatially extensive and well exposed sequences of Gondwanan rocks in the world. The preserved outcrops of this predominantly sedimentary sequence, have a spatial distribution of some 300 000km^2 (Smith, 1990a), more than half the land surface of South Africa. These strata accumulated in a large, intra-cratonic retro-arc foreland basin (Johnson, 1991) under environments ranging from glacial to aeolian, and record an almost continuous sedimentary succession from the Late Carboniferous (300Ma) to the Early Jurassic (190Ma) (Smith, 1995).

Bain (1845) was the first person to draw attention to this extensive sequence of rocks, subsequently naming these strata the Karoo "Series" (Bain, 1856). Jones (1867) introduced the nomenclature Beaufort "Beds" for sedimentary rocks within the lower part of the Karoo "Series" at Beaufort West and Dunn (1873, 1878) proposed the term Stormberg "Beds" for the uppermost part of the Karoo "Series". Dunn (1878) further subdivided the sequence into the "Coal Measures, Red Beds, Cave Sandstone and Volcanic Beds". The value of Dunn's work is, that with minor refinements of terminology, it is still the basis of what is accepted at present for the upper Karoo.

Rogers (1903) lithostratigraphically divided this sequence of rocks, which he termed the Karoo "System", into the Dwyka, Ecca, Beaufort and Stormberg Groups. Rogers (1905) and Broom (1906a) further subdivided the Beaufort Group into a Lower, Middle and Upper Series. This partitioning of the Beaufort Group was accepted until Johnson (1976) created a new lithostratigraphic subdivision for the Group, for the area covering East London to Pearston in the Eastern Cape. Johnson (1976) divided the Beaufort Group into a lower Adelaide Subgroup, which broadly corresponded to the Lower Beaufort Series of Rogers (1905) and Broom (1906a), and upper Tarkastad Subgroup which equated to their Middle and Upper Series.

Johnson (1976) further concluded that there was no justification for the retention of the term Stormberg Group. With minor alterations Johnson's (1976) subdivision of the Beaufort Group was accepted by the Karoo Working Group of the South African Council for Stratigraphy, who also abandoned the term Stormberg in favour of assigning formational status to each of the units that made up this group (SACS, 1980).

DuToit (1954) recognised two major stratigraphic breaks within the Karoo Supergroup, one at the top of the Dwyka Group and the other at the base of the "Stormberg" Group. These stratigraphic breaks are of critical importance for basinal development studies, as they are thought to represent the major hiatal surfaces and changes in sedimentary style within the main Karoo Basin.

Hobday (1978) noted the paucity of sedimentary studies in various parts of the succession and pointed out the need for detailed investigations of the contacts between the various subdivisions of the Karoo Supergroup, stating (p.1) "today the only issues involve details of correlations and contacts between the units and these problems are likely to remain". Many of the contacts between the Groups and Formations of the Supergroup have however been well documented for certain parts of the basin. Loock (1967) described the contact between the Dwyka and Ecca Groups, whilst Rubidge (1987, 1988, 1990), Jordaan (1981) and Wickens (1984, 1987) re-defined the Ecca-Beaufort contact in the southwestern Karoo on sedimentological and palaeontological grounds. One major contact that remains problematical is that between the uppermost, Burgersdorp Formation of the Beaufort Group and the basal Molteno Formation of what was previously termed the "Stormberg Group". Johnson (1976) concluded that there was no justification for the retention of the term "Stormberg Group" and the nomenclature was therefore abandoned by SACS (1980) in favour of assigning formational status to each of the units (Table 1.1).

The Molteno Formation therefore overlies the Burgersdorp Formation (Table 1.1) and the contact between the two sequences represents one of the two major stratigraphic breaks identified by DuToit (1954). A detailed knowledge of the stratigraphy and lithology of the Burgersdorp and Molteno Formations is crucial to the understanding the nature of the contact that separates them.

The rocks of the Karoo Supergroup also preserve a fossilized record of the numerous faunal and floral elements that inhabited the Karoo Basin. The fossils of the Beaufort Group in particular represent one of the best preserved ecological assemblages of pre-mammalian terrestrial vertebrates in the world (Keyser & Smith, 1977-1978). The importance of these fossils is two-fold, as they allow for evolutionary studies into important vertebrate lineages (Broom, 1932), as well as for the biostratigraphic subdivision and global correlation of the Beaufort Group.

The oldest record in print of fossils in the rocks of the Karoo Supergroup bears the date 1831 and takes the form of a letter written by C.H.Crisbrook, which was published in the South African Quarterly Journal under the title "Organic remains in the Karroo". The locality data and whereabouts of the referred to material is however unknown and the first documented discovery of fossil reptiles in Karoo strata is of a dicynodont found near Fort Beaufort by A.G.Bain in 1838 (Bain, 1845; Owen, 1856).

Because of their abundance in the rocks of the Karoo Supergroup and particularly, the Beaufort Group, fossil tetrapods have long been used for the biostratigraphic subdivision of the sequence. Wyley (1859) introduced the term "Reptilian Beds" for fossiliferous Karoo strata near Beaufort West and Seeley (1892) was the first to attempt to subdivide the rocks of the Karoo biostratigraphically. Broom (1906b,c,d 1907, 1909a) proposed a six-fold biozonation for the Beaufort Group (Table 1.2), which, with slight modification (Hotton & Kitching, 1963) was the work accepted by most authors for the next sixty years (Watson, 1913, 1914; Von Huene, 1925; DuToit, 1954).

With the intensive collecting in the Karoo Basin since Broom's (1906b) biozonation, numerous new discoveries of tetrapod fossils including amphibians, primitive reptiles, mammal like-reptiles, early mammals and dinosaurs have been made. This wealth of new material has allowed for major revisions to the early biostratigraphy (Kitching, 1970, 1972, 1977, 1984; Keyser & Smith, 1977-1978; Keyser, 1979; SACS, 1980; Rubidge *et al.*, 1996) such as to include the Elliot and Clarens Formations as well (Kitching & Raath, 1984). The current tenfold biostratigraphic sub-division of the Karoo Supergroup is presented in Table 1.2, along with the major historical revisions that have occurred. This refined biostratigraphy has facilitated the correlation of these strata with equivalent sequences elsewhere in the world, which in turn has allowed for more precise relative dating of the sequence.

The rocks of the Karoo Supergroup have therefore been the focus of much sedimentological and palaeontological research, yet despite the vast amounts of work undertaken in the past hundred and fifty years, many aspects of the stratigraphy, lithology, palaeontology and basinal fill of the sequence are still not adequately resolved. This is particularly true in respect of the Burgersdorp and Molteno Formations.

1.2 Burgersdorp Formation

1.2.1 Historical Overview

Most of the early research on the Burgersdorp Formation (Tarkastad Subgroup, Beaufort Group) was undertaken by Alex DuToit between the years 1904 and 1918, and it was DuToit (1905a) who introduced the name "Burghersdorp Beds" for the sequence of predominantly red and purple mudrocks and subordinate sandstones, which outcrop around the town of the same name in the northeastern Cape Province.

Subsequent to the division of the Beaufort Group into a Lower, Middle and Upper Series (Rogers, 1905; Broom, 1906a), the Burgersdorp Formation was equated to the Upper Beaufort (Rogers & DuToit, 1909). Watson (1914) produced the first map of the strata assignable to the Burgersdorp Formation in the northeastern Cape Province and Stockley (1947) documented strata assignable to the Formation from Lesotho. Rust (1959 1962) described the rocks of the uppermost part of the Formation in the area of Bushmanshoek Pass, stating that they were very similar in nature to the overlying Molteno strata. This observation led him to propose a paraconformity between the middle and upper parts of the Burgersdorp Formation.

Johnson (1966) considered the term "Burghersdorp" Formation unacceptable due to the fact that the exact spatial distribution of the Formation was uncertain and in that he felt DuToit (1905a) had not properly defined the lower contact. Johnson (1966) therefore introduced the name Queenstown Formation for the argillaceous strata above the Katberg Formation in the southeast of the main Karoo Basin. Theron (1970) and Van Eeden (1972) termed the Burgersdorp Formation the Upper Beaufort Formation and Upper Beaufort Stage respectively. Neither these, nor Johnson's (1966) nomenclature were however accepted by SACS (1980), who in standardising the description of the Formation retained the historical name "Burghersdorp" but adopted the modern spelling of Burgersdorp.

In his summary of the distribution of the Karoo vertebrate fauna, Kitching (1977) gives a brief overview of the rocks of the Burgersdorp Formation, as well as a summary of the general sedimentary environments and climate prevailing during the deposition of the Formation. He also includes numerous notes on the distribution of the fauna, their abundance and biostratigraphic importance.

In a paper detailing the sedimentation of the Katberg Sandstone and adjacent Formations in the southeastern Karoo Basin, Stavrakis (1980a) agreed with Rust (1959) that the upper Burgersdorp was similar to the lowermost Molteno Formation and that a major paraconformity existed within the Burgersdorp Formation.

Johnson and Hiller (1990) described the Formation in the south of the basin for the catalogue of South African Lithostratigraphic units, stating that north of the towns of Burgersdorp in the east and Umtata in the west, the Burgersdorp and Katberg Formations cannot be easily distinguished and the Tarkastad Subgroup is in effect a single Formation, for which they proposed the name Tarkastad Formation. These authors also submitted that a sandstone rich interval within the lower half of the Formation in the Tarkastad area constituted a potentially mappable member and hence a useful marker horizon. The Tarkastad Formation of Johnson and Hiller (1990) roughly corresponds to the Otterburn Formation in western Natal (Botha and Linström, 1978) and the Driekoppen Formation in the Free State (Groenewald, 1984, 1989, 1990, 1996).

The most recent work on the stratigraphy and sedimentology of the Burgersdorp Formation is that of Groenewald (1996) who described the sedimentology and lithostratigraphy of the lower parts of the Burgersdorp Formation. Following Keyser (*pers.comm.*) he proposed the nomenclature "Andriesberg Member" for a sandstone rich interval in the middle of the Formation.

Most previous work on the Burgersdorp Formation has been undertaken by palaeontologists and the vertebrate fossils from the Burgersdorp Formation are far better documented in the literature than is the lithology. The Formation is currently thought to contain representatives of two biozones (Rubidge, 1995), with a fauna assignable to the *Lystrosaurus* Assemblage Zone (Groenewald & Kitching, 1995) preserved in the lower third, and the entire *Cynognathus* Assemblage Zone (Kitching, 1995) within the upper two-thirds of the Formation.

Due to the number of names previously proposed for the *Cynognathus* Assemblage Zone, and in light of the new finds and subdivision proposed in this thesis, a brief review of the nomenclature pertaining to the biozone is necessary. The *Cynognathus* Zone was created by Broom (1906b) and corresponds to Seeley's (1892) Zone of specialised theriodonts. Broom's (1906b) nomenclature of this biozone remained in use for the next seventy years and was accepted by Kitching

(1970, 1972, 1977) during his revision of the biostratigraphy of the Beaufort Group (Table 1.2). Keyser and Smith (1977-78) introduced the nomenclature "*Kannemeyeria*" Assemblage Zone to replace the *Cynognathus* Zone of Broom (1906b) and Kitching (1970, 1972, 1977). This terminology was modified to the *Kannemeyeria-Diademodon* Assemblage Zone by Keyser (1979) and was formally accepted by SACS (1980) (Table 1.2). The dicynodont *Kannemeyeria* was preferred over *Cynognathus* as the zone fossil as the authors believed that *Cynognathus* was rare in the sediments and that it was impossible to accurately establish the range of this genus. They furthermore argued that *Kannemeyeria* specimens were larger, more abundant and more easily recognisable in the field. Using a dicynodont genus was also in line with the practice for the biozonation of the rest of the Beaufort Group at that time. They did however note that complete skulls of *Kannemeyeria* were not common.

Kitching (1984) re-assessed the biozonation of the Beaufort Group as accepted by SACS (1980) and proposed the name *Cynognathus-Diademodon* Assemblage Zone instead of the *Kannemeyeria-Diademodon* Assemblage Zone of SACS (1980). His re-instatement of *Cynognathus* as the zone index fossil was based on the fact that the genus occurs throughout the biozone and that it is abundant in collections worldwide. *Diademodon* was preferred over *Kannemeyeria* as an associated index fossil due to the fact that it was the most abundant genus in the zone (Kitching, 1977). To bring this biozone in line with internationally recognised nomenclature, Kitching (1995) re-assigned the assemblage zone to the historically important genus *Cynognathus*, creating the *Cynognathus* Assemblage Zone.

The *Cynognathus* Assemblage Zone (Kitching, 1995) as used in this thesis therefore corresponds to Seeley's (1892) Zone of specialized theriodonts, the *Cynognathus* Zone of Broom (1906b) and Kitching (1970, 1972, 1977), as well as the *Kannemeyeria* Assemblage Zone of Keyser & Smith (1977-78), the *Kannemeyeria-Diademodon* Assemblage Zone (Keyser, 1979; SACS, 1980) and the *Cynognathus-Diademodon* Assemblage Zone of Kitching (1984).

Early workers who collected in the *Cynognathus* Assemblage Zone included the likes of Thomas Bains, Alfred (Gogga) Brown and Daniel Kannemeyer. Published accounts of their discoveries are given in Seeley (1888, 1889, 1892, 1894, 1895 a,b) and Broom (1903, 1905a, 1906 a,b,c, 1909b, 1913a,b) and include the generic descriptions of the cynodonts *Cynognathus* and *Diademodon*. Brown in particular made an enormous contribution to the knowledge of the fauna and flora of the biozone and his collecting trips and localities are recorded in his twenty-one volume unpublished journal. He is credited with numerous discoveries including the amphibian *Batrachosuchus browni* (Broom, 1903); the captorhinid (parareptile) *Thelegnathus browni* (Broom, 1905a,b); the eosuchians *Erythrosuchus africanus* (Broom 1906b), *Palacrodon browni* (Broom, 1906a), *Howesia browni* (Broom, 1906c) and *Mesosuchus browni* (Watson, 1912a) as well as numerous fish fossils (Broom, 1909b). In his later life, Brown employed Albert William Higgins to collect for him, to whom is credited the discovery of the eosuchian *Euparkeria capensis* (Broom, 1913a,b; Ewer, 1965).

In 1889 Bain introduced Seeley to Brown and Kannmeyer. Kannemeyer, a medical doctor who lived in Burgersdorp is remembered in particular for the numerous skulls of *Kannemeyeria* (Weithofer, 1888) he collected from this area. From his trip to South Africa and the meeting with Kannemeyer and Brown, Seeley (1904, 1906, 1907, 1908a,b) described a number of *Cynognathus* Assemblage Zone forms.

During the period 1935-39 and 1947-49 Camp and Welles collected a number of complete specimens of *Kannemeyeria* from the *Cynognathus* Assemblage Zone near the towns of Burgersdorp and Rouxville. This collecting was undertaken due to the paucity of comparative material available for their monograph on the Triassic dicynodonts (Camp, 1956; Camp & Welles, 1956). Hotton (1974) described the small dicynodont *Kombuisia*, bringing the total number of dicynodont genera known from the biozone to two. Hancox & Rubidge (1994) described the discovery of a third dicynodont from the *Cynognathus* Assemblage Zone and Hancox & Rubidge (1996) documented the first occurrence of the East African dicynodont genus *Angonisaurus*, increasing thel number of dicynodont genera for the biozone to four.

Kitching (1963) described the occurrence of "fossil pockets" and "bone beds" from the *Cynognathus* Assemblage Zone and this is to date the only account of the taphonomy of the fossils from the biozone. Fossils collected from these "bone bed" localities were described in a number of earlier papers (Brink & Kitching, 1953; Brink 1955a,b; 1963a; 1965a,b).

Alfred Brown is also remembered for his collection of fossil plant material from the Burgersdorp Formation in the area surrounding Aliwal North, which was accumulated between the years 1889-1905. This material was first described and given a cursory taxonomic assessment by DuToit (1927) and later a more thorough taxonomic assessment by Anderson & Anderson (1985). Along with material collected by Kannemeyer from the area surrounding the town of Burgersdorp, these specimens are now housed in the SAM and form the best collection of fossil plant material known from the Formation. The most recent collecting of fossil plant material in the Burgersdorp Formation is that of Kitching circa 1955-1976 (in Anderson & Anderson, 1985).

Watson (1942) was the first to suggest a possible sub-division of the *Cynognathus* Assemblage Zone, based on the biostratigraphic range of *Kannemeyeria* and *Erythrosuchus*. He subdivided the zone (Table 1.2) into a lower zone (A) in which *Kannemeyeria* and *Erythrosuchus* occurred together and an upper zone (B) in which *Kannemeyeria* was absent and *Erythrosuchus* was extremely rare. This biostratigraphic range for *Kannemeyeria* was corroborated by Kitching (1977) and Cooper (1982), but refuted by Keyser & Smith (1977-78) who believed that *Kannemeyeria* occurred throughout the zone. Cooper (1982) felt that *Kannemeyeria* was restricted to the lower half of the Burgersdorp Formation and further suggested that the upper part of the *Cynognathus* Assemblage Zone, above the biostratigraphic range of *Kannemeyeria*, would eventually yield an advanced fauna, equivalent to his *Tetragonias* Zone fauna (Table 1.2). He also considered the cynodont genera *Cynognathus* & *Diademodon* to occur throughout the range of the *Cynognathus* Assemblage Zone.

The early studies of the *Cynognathus* Assemblage Zone were however limited to the Eastern Cape, southeastern Free State and Lesotho (Watson, 1914; Kitching, 1963; Dingle *et al.*, 1983; Smith, 1990a). Prior to the 1990s, these were the only areas in which the biozone was believed to occur. Kitching (1977, p.26) states " although the Beaufort beds have been carefully examined in a number of areas in the Wepener, Thaba Nchu, Ladybrand, Senekal, Bethlehem and Harrismith districts for the purpose of determining the extent of the *Cynognathus* Zone northwards in the Orange Free State, no fossil reptiles or sediments were found that could be assigned to the zone. At present it seems that there was no continuous deposition of the *Cynognathus* Zone to the north of Wepener".

DuToit (1918) on the other hand considered the uppermost sedimentary rocks of the Tarkastad Subgroup in the northeastern Free State to be a continuation of part of the Burgersdorp Formation in the southern Karoo Basin. Groenewald (1984, 1989) accepted DuToit's claims but substituted the name Driekoppen Formation for the northern deposits (Table 1.1). Welman *et al.* (1991) corroborated this thinking with the discovery of a fauna in the northern Free State, assignable to the *Cynognathus* Assemblage Zone. This discovery increased the extent of the biozone northwards by some 250 kilometres. These new outcrops of the *Cynognathus* Assemblage Zone in the northeastern Free State and at Thaba Nchu were interpreted to be a northern facies equivalent of the uppermost strata of the Burgersdorp Formation in the Queenstown, Bolotwa, Lady Frere and Engcobo districts (Welman, 1991). This finding was further used as a possible explanation for the paraconformity within the Burgersdorp Formation previously proposed by Rust (1959 1962) and Stavrakis (1980).

Botha & Linström (1978), Groenewald (1990) and Smith *et al.* (1993) also felt that there were sufficient differences in lithology between the rocks in the south and north of the basin to necessitate separate formational naming, although at present only the Burgersdorp Formation is accepted (SACS, 1980).

Fossil amphibians from the *Cynognathus* Assemblage Zone have been known for many years (Broom, 1904) and compared with other Beaufort Group biozones, the *Cynognathus* Assemblage Zone has an abundance of amphibian material (Kitching, 1957, 1963, 1978; Chernin, (1977, 1978); Hancox *et al.*, 1995; Shishkin & Welman, 1994). The main amphibian representatives within this biozone are the Family Capitosauridae, with lesser Trematosauridae, Brachyopidae and Laidleriidae (Kitching 1978). The Laidleriidae are however known from only a single specimen (*Laidleria*) and it is questionable as to whether the form is actually from this biozone or from the underlying *Lystrosaurus* Assemblage Zone (Kitching, *pers.comm.*).

Amphibians therefore form an important part of the overall fauna of the *Cynognathus* Assemblage Zone, but have tended to be neglected in favour of studies on therapsids. Kitching (1978) discussed the stratigraphic distribution and occurrence of the amphibians from the biozone and Shishkin & Welman (1994) re-described the trematosuchid amphibian *Trematosuchus* from the biozone and Shishkin *et al.* (*in prep.*) are re-assessing the taxonomy of *Kestrosaurus* and *Parotosuchus africanus*. Based primarily on these taxonomic re-assessments and new discoveries of amphibians from the upper part of the *Cynognathus* Assemblage Zone, Hancox *et al.* (1995) proposed the possibility of a threefold subdivision of the biozone. This subdivision was based primarily on the spatial and temporal distribution of three key amphibian index genera and their associated faunas.

Amphibians have also played an important role in the dating of the biozone. On the basis of the presence of *Cyclotosaurus albertyni* (Broom, 1904) proposed a Late Triassic age for the *Cynognathus* Assemblage Zone and based on the similarities of *Rhytidosteus* (Owen, 1884) to *Deltasaurus*, from the Posidonomya Beds of the Blina Shales of Western Australia, Cosgriff (1965) assigned the *Cynognathus* Assemblage Zone a Lower Triassic (Scythian) age. Most subsequent age estimations have been based on the presence of the amphibian *Parotosuchus* and on correlations with fossiliferous strata from other parts of Gondwana. At present most authors accept an Early Triassic age for the biozone (DuToit, 1954; Anderson & Anderson, 1970; Anderson & Cruickshank, 1978; Chernin, 1978), although a

Mid-Triassic age has also been proposed (von Huene, 1940) and is gaining general acceptance (Keyser, 1973; Kitching, 1977; Cruickshank, 1978a, 1985, 1986; Ochev & Shishkin, 1989; Shishkin *et al.*, 1994). The lexicon of South African stratigraphy (Johnson, 1994) however assigns the Burgersdorp Formation a Permian age. In the most recent work on the Formation, Groenewald (1996) assigns the Tarkastad Subgroup, of which the Burgersdorp Formation is the uppermost unit, an age ranging from Early to Late Triassic (247-215Ma), thereby assigning the uppermost Burgersdorp Formation a Late Triassic age.

Facies genesis for the parts of the Burgersdorp Formation, which contain fossils assignable to the *Cynognathus* Assemblage Zone, have previously been interpreted as being deposited by various different fluvial systems. Hiller & Stavrakis (1984) propose deposition by high sinuosity meandering rivers, with overbank deposition in mud-dominated playa lakes. They further advance that the system accumulated fine grained sediment in a reduced inland basin, with source areas to the south, southwest and southeast. Johnson & Hiller (1990) believed that the rocks of the *Cynognathus* Assemblage Zone were deposited by anastomosed or frequently avulsing meandering streams, with sandy channels which frequently overtopped their banks forming numerous crevasse splay deposits. Botha & Linström (1978) concluded that in the northeastern part of the basin, Burgersdorp sedimentary strata were deposited in slow flowing meandering streams, fed by alluvial fans situated to the southwest and southeast. Welman *et al* (1991) felt that the lack of well defined channel sandstones and the decrease in abundance of carbonate concretionary horizons in the extreme northern part of the basin indicated widespread lacustrine conditions.

The reconstructions of the palaeoclimate prevailing during the facies genesis of the Burgersdorp Formation has previously been based on both sedimentological and palaeontological evidence (DuToit, 1948). Based on the presence of mud cracks, small rosette shaped inclusions and the degree of taphonomic bone damage, Kitching (1977) (p. 27) states that "it seems reasonable to assume that the sediments of the *Cynognathus* Zone were laid down in a shallow and considerably reduced basin under drier conditions than those envisaged for the preceding *Lystrosaurus* Zone". The wet conditions proposed by early workers for the *Lystrosaurus* Assemblage Zone have however recently been challenged by Smith (1995) who proposed dry floodbasin conditions for the *Lystrosaurus* Assemblage Zone. Based on the presence of calcareous concretions in the sedimentary strata and salt glands in the cynodont *Diademodon*, Grine *et al.* (1979) proposed a warm to hot (arid) climate with a mean annual temperature of between 16-20°C.

1.2.2 Review of previous investigations

The preceding historical overview of the Burgersdorp Formation shows it to be poorly documented and understood, both lithologically and with respect to the biostratigraphic ranges and mode of occurrence of its faunal content. The sedimentological aspects of the Burgersdorp Formation are known only from the descriptions of DuToit (1904, 1905a, 1918), Watson (1913), Stockley (1947), Rust (1959, 1962), Johnson (1966), Kitching (1977), Stavrakis (1980), Hiller & Stavrakis (1984), Johnson & Hiller (1990) and Groenewald (1996). Of these previous studies Stavrakis (1980), Hiller & Stavrakis (1984) and Groenewald (1996) were based primarily on the lowermost Burgersdorp Formation and that of Rust (1959, 1962) on only a single locality at Bushmanshoek Pass. The work of Johnson & Hiller (1990) is predominantly a literature review of previous work by Stavrakis (1980a) and Hiller & Stavrakis (1984). Kitching's (1977) documentation of the Formation is of a very broad scale, with no real lithostratigraphic control. The lithostratigraphy and sedimentology of the middle and upper part of the Formation is not described in any detail and the lithofacies types, channel morphologies, sand body geometries and floodplain sub-environments are not yet described.

Although a major paraconformity may exist within the Burgersdorp as proposed by Rust (1959, 1962), Stavrakis (1980a) and Welman *et al.* (1991), the reasoning and description of such a surface is not definitive. Rust's (1959, 1962) delineation of a paraconformity was based on the fact that he erroneously assigned uppermost Burgersdorp strata in Bushmanshoek Pass to the Molteno Formation (Turner, 1975a). Stavrakis (1980a) agreed with Rust (1959, 1962) that the strata of the upper Burgersdorp Formation were formed under similar conditions to the Molteno Formation and that there must therefore be a major paraconformity between the middle and upper Burgersdorp. He however fails to give details of his placement of the upper contact, nor detailed reasoning for the occurrence of a paraconformity.

Welman *et al.* (1991) propose that the paraconformity identified by Rust (1959, 1962) and Stavrakis (1980a) could be accounted for by the "fact" that the northern facies of the Burgersdorp Formation could "possibly" be equivalent to the upper Burgersdorp strata in the Queenstown area. The correlation of the northern facies with the uppermost Burgersdorp Formation in the south of the basin is however challenged by Hancox *et al.* (1995) on the basis of the enclosed faunal content. The question of a paraconformity and its stratigraphic occurrence within the Burgersdorp Formation therefore remains unresolved.

Different formational names have in the past been applied to similar rock sequences in the south and north of the basin, and the disagreement amongst authors as to whether the north and south of the basin require separate formational naming is unresolved. Insufficient lithological studies have been undertaken to date and at present only one formational name is accepted (SACS, 1980; Johnson & Hiller, 1990). No formal lithological subdivision of the Burgersdorp Formation has been proposed and the lower sandstone horizon of Johnson & Hiller (1990) and the Andriesberg Member of Groenewald (1996) have not been mapped throughout the basin, and may in fact refer to the same interval. The problem of the stratigraphic placement of sandstone rich horizons therefore requires addressing.

The faunal range of *Kannemeyeria* as proposed Watson (1942), Kitching (1977) and Cooper (1982) was refuted by Keyser and Smith (1977-1978), who felt that *Kannemeyeria* occurred throughout the zone. Keyser & Smith's (1977-1978) occurrence of *Kannemeyeria* in the uppermost *Cynognathus* Assemblage Zone was however based on isolated post cranial remains (Keyser, *pers. comm.*). The recent discovery of another large dicynodont in the uppermost part of the zone (Hancox

& Rubidge, 1994) highlights the problems of basing biostratigraphic ranges on isolated post-cranial remains of dicynodonts. Uncertainty regarding the biostratigraphic range of *Kannemeyeria* therefore exists and it is important that this be solved in light of its biostratigraphic importance within the *Cynognathus* Assemblage Zone (Hancox *et al.*, 1995), as well as its global biochronological and correlative value for the non-marine Triassic.

In spite of their abundance in the *Cynognathus* Assemblage Zone (Kitching, 1978), the distribution and taxonomic representation of the temnospondyl amphibians is poorly known, with most forms being lumped into the catch-all capitosaurid genus *Parotosuchus*. Because of this fact, amphibians have previously been overlooked as potential biostratigraphic indicators. Studies by Shishkin & Welman (1995) and Shishkin *et al.* (*in prep.*) refined the taxonomic resolution of the temnospondyl amphibians from the *Cynognathus* Assemblage Zone, which in turn allowed Hancox *et al.* (1995) to show that temnospondyl amphibians are important for both the biostratigraphic subdivision of the zone, and in solving basin development problems that geological studies alone could not (Hancox & Rubidge, *in press*).

Capitosaurid amphibians are furthermore restricted to strata of Triassic age and are important for global biochronological and correlative studies, being known from deposits in: Europe (Welles & Cosgriff, 1965); China (Young, 1966; Lucas & Hunt, 1993), North America (Welles & Cosgriff, 1965), East Africa (Howie, 1970; Chernin & Cruickshank, 1971; Chernin & Cosgriff, 1975) and South Africa (Chernin, 1978; Kitching, 1978, Hancox *et al.*, 1995), Antarctica (Hammer, 1995), Australia (Cosgriff, 1965, 1972) and India (Jain *et al.*, 1964; Chowdhury, 1970a). Although all capitosaurs are thought to have been semi-aquatic, freshwater forms (DeFauw, 1987, 1989), they are of vital importance for non-marine correlation and age determinations, as closely related taxa are known from well dated marine deposits. They therefore provide the best correlative link between the standard marine succession and the nonmarine Triassic record.

Although no biostratigraphic subdivision of the *Cynognathus* Assemblage Zone has been formally accepted, various faunal range trends have been published (Watson, 1942; Kitching, 1977; Cooper, 1982; Hancox *et al.*, 1995). These trends require confirmation and biostratigraphic studies may furthermore aid in defining the exact stratigraphic positions of the various sandstone rich intervals, thereby aiding in lithostratigraphic correlation and basinal development studies.

Within the Burgersdorp Formation, both the *Lystrosaurus* and *Cynognathus* Assemblage Zones have in the past been the focus of numerous attempts at correlation with equivalents proposed from nearly all the Gondwanan basins (Anderson, 1977; Anderson & Cruickshank, 1978; Ochev & Shishkin, 1989; Anderson & Anderson, 1993a,b; Battail, 1993). In most cases these correlations have been based on the entire *Cynognathus* Assemblage Zone, as subdivisions within the biozone were not previously recognised. Correlation of the Burgersdorp Formation (*Cynognathus* Assemblage Zone) with better dated sequences in the northern hemisphere has therefore previously been hampered by the lack of detailed information on the biostratigraphic ranges of the faunal elements. This has meant that the relative age of the biozone has not been well constrained.

The lack of constraint as to the ages of the Burgersdorp Formation is based primarily on the fact that the correlation and relative age of the faunas within the *Lystrosaurus* and *Cynognathus* Assemblage Zones are debatable. The *Lystrosaurus* Assemblage Zone is currently assigned an Early Triassic (early Scythian) age (Groenewald & Kitching, 1995). Some disagreement however occurs amongst workers as to what part of the Lower Triassic is represented by the *Lystrosaurus* Assemblage Zone. For a discussion regarding the age of this fauna, the reader is referred to Ochev & Shishkin (1989), Shishkin *et al.* (1994) and Groenewald & Kitching (1995).

The *Cynognathus* Assemblage Zone is traditionally placed within the Lower Triassic (Scythian), primarily on the basis of the belief that the amphibians from the zone are congeneric with the European genus *Parotosuchus* (DuToit 1954). The biozone is presently accepted as being late Scythian to early Anisian in age (Kitching, 1995), however the age of the biozone has been the subject of considerable debate in the past. Broom (1904) considered the upper part of the *Cynognathus* Assemblage Zone to be Upper Triassic, based on the mistaken belief that material now assigned to "*Parotosuchus*"*africanus* was congeneric with *Cyclotosaurus*, and that it was very similar to the Upper Triassic *C.robustus* from the Keuper of Germany. Anderson & Anderson (1970) placed the *Cynognathus* Assemblage zone within the Upper Induan (Dienerian), based on their acceptance of the *Lystrosaurus* Assemblage Zone as being uppermost Permian (Upper Tartarian) in age. Most other workers in the 1960's and 1970's assigned a late Early Triassic age to the *Cynognathus* Assemblage Zone. Taking the base of the Triassic to coincide with the base of the Katberg Formation, the Burgersdorp Formation was considered to be of Lower Triassic (Scythian) age by Romer (1970) and SACS (1980).

Various authors have recently questioned this assignation and have reverted to a lower Middle Triassic age for the *Cynognathus* Assemblage Zone, as first advocated by von Huene (1940). On the basis of the comparative morphology of *Parotosuchus africanus* with *Parotosuchus megarhinus* and *Parotosuchus pronus*, Chernin (1978) placed the *Cynognathus* Assemblage Zone close to the boundary between the Lower and Middle Triassic. Cruickshank (1978) postulated that the *Cynognathus* Assemblage Zone proterosuchians were far more specialised than their *Lystrosaurus* Assemblage Zone forebears, and therefore probably represented genera of at least very late Lower or even earliest Middle Triassic age. Grine *et al.* (1978), Cruickshank (1986a), Ochev & Shishkin (1989), Hammer (1988, 1990, 1995) and Shishkin & Ochev (1992) all assign a Middle Triassic (Anisian) age to the biozone.

Stapleton (1978) challenged the Lower to Middle Triassic dating of the *Cynognathus* Assemblage Zone on the grounds that palynological data from the Burgersdorp and Molteno Formations indicated no major change across the boundary. Stapleton (1978) furthermore proposed that the microflora was transitional between Permian and Triassic types. He therefore placed the Permo-

Triassic boundary within the Burgersdorp Formation, thereby applying an upper Permian age to the basal part of the Burgersdorp Formation. Many of Stapleton's taxa were however badly preserved and his arguments have not found favour in the scientific community.

Based on the above arguments, the relative age of the Burgersdorp Formation has therefore been constrained as being anywhere between the Upper Permian and Late Triassic, with the age of the *Cynognathus* Assemblage Zone ranging from the Early Triassic (Scythian) (Anderson & Anderson, 1970) through to the Upper Triassic (Broom, 1904).

The distribution, diversity and taxonomy of the fossil plants of the Burgersdorp Formation is poorly known due primarily to insufficient collecting. An increased knowledge of the floral components of the Burgersdorp Formation is particularly important for the information they supply regarding past climatic conditions, as well as for their biostratigraphic usefulness. The palaeoclimate prevailing during the facies genesis of the Burgersdorp Formation is somewhat problematical, with the climate having previously been broadly interpreted as dry (Kitching, 1977) to hot and arid (Grine *et al.*, 1979).

The recent discovery of a *Cynognathus* Assemblage Zone fauna from the north of the basin (Welman *et al.*, 1991) has added further complexity to the lithostratigraphy, biostratigraphy, correlation and relative age of the *Cynognathus* Assemblage Zone. The chronostratigraphic relationships between the Burgersdorp Formation in the north and the south of the basin are not well defined, which in turn has compounded the problem of how basin fill occurred.

In general, the lack of studies on the Burgersdorp Formation is primarily due to fact that the Formation is void of any economical potential and therefore missed the attention paid to the Lower Beaufort during the boom in uranium exploration in the late 1970's and early 1980's (eg LeRoux & Toens, 1986). Most of the available literature on the Burgersdorp Formation is furthermore based on the southern part of the basin, and very little is known about the northern deposits and its newly discovered fauna (Welman *et al.*, 1991). Because of the fact that the sedimentology, lithostratigraphy and biostratigraphy of the Formation are not well documented, the facies genesis, palaeoclimate, correlation and relative age of the Formation has not been well interpreted, and its setting within the basinal development of the upper Beaufort Group is poorly understood.

1.3. Molteno Formation

1.3.1 Historical Overview

The earliest work on the Molteno Formation was primarily concerned with the coal deposits in the northeastern Cape, with the oldest record of coal in the Formation being that of Wyley (1856). Coal in the Molteno was first mined in 1864 at Syfergat near the town of Molteno itself. For the next forty years these coal deposits formed the focus of numerous studies with authors such as North (1878), Green (1883), Galloway (1889) and Schwartz (1903) describing various aspects of the coal reserves, quality and origin of formation of these seams. North (1878) was also the first to suggest a provenance for the pebbles in the sandstones of the "Coal Measures", believing them to be from the Zwartberg Range of the Table Mountain Sandstone (TMS). Dunn (1873, 1878, 1879) worked on the "Coal Measures" and considered them, and hence the Bamboesberg and Indwe Sandstone Members of the Molteno Formation, to be upper Triassic in age. Rogers (1905) similarly deduced the presence of a southerly mountain range based on the occurrence of large, well rounded quartzite pebbles, the coarse nature of the sandstones, and the northerly palaeocurrent directions.

The term Molteno in reference to a stratigraphic subdivision was first used by Green (1883) in the form of Molteno "Beds", to describe exposures around the town of Molteno, and to replace Dunn's "Coal Measures". Green (1883) also dealt with the problems of correlation and origin of the coal seams within the Molteno "Beds". The most significant early works regarding the Molteno Formation are those of DuToit who between the years 1903 and 1911 wrote a series of reports dealing with the Stormberg (DuToit, 1903, 1904, 1905a, 1905b, 1905c, 1910, 1911). DuToit (1905b) subdivided the Molteno "Beds" into three main divisions and was therefore the first person to recognise the stratigraphic complexity of the Molteno Formation. DuToit (1905c) also identified and mapped a 460m thick down faulted block of Molteno strata on the east coast of South Africa, near Port St.Johns.

Because of the presence of coal in the Molteno Formation the nineteen twenties and thirties saw major interest and prospecting within the Eastern Cape. Haughton (1924) provided a vivid, although somewhat unconventional account of the palaeoclimate and conditions of sedimentation for the Molteno Formation, in which he suggested the Formation was the product of a "true" or sub-aerial delta, deposited under cool, wet climatic conditions, with intermittent rainfall. Based on the palaeontological signature of the Formation Haughton (1924) proposed a Mid-Triassic age for the Molteno. The abundance of trough cross-stratified sandstone led DuToit (1911) to postulate shallow water conditions for deposition of the sedimentary rocks of the Molteno Formation and later (DuToit, 1926) also proposed that the granite basement underlying the rocks of the Karoo and Cape Supergroups contributed to the sedimentary strata of the Molteno "Beds" and documented that the Molteno "Beds" were present further to the north than previously thought, to Memel where they formed but a single gritty bed. Gevers (1927) mapped an area around the town of Molteno and noted features associated with the contemporaneous erosion of the coal. Van Eeden (1937) introduced the time related term Molteno "Stage" to the literature and made important thickness measurements for the Molteno strata, as well as tracing their extension as far North as Vorkykerskop, thus substantiating DuToit's earlier work.

From 1942 to 1944 B.J V.Botha carried out reconnaissance fieldwork in the Molteno and Sterkstroom districts for the Geological Survey (Botha, 1952). This led to the drilling of some twelve boreholes at Molteno and one at Sterkstroom, which greatly increased the knowledge of the stratigraphy and thickness of the

Formation. Stockley (1947) recorded thickness measurements for the Molteno "Stage" at various localities in the Eastern Cape and Lesotho, and concluded that the strata thinned northwards. Based on the presence of "red shale" in the lower part of the Molteno Formation, Stockley (1947) proposed local arid conditions during sedimentation. The descriptions of the Formation given by Stockley (1947) closely parallel those of Haughton (1924).

The early nineteen fifties and sixties witnessed renewed interest in the coal deposits and sedimentary strata of the Molteno "Stage". Berry (1952) described Molteno strata from the vicinity of Wepener, noting that the sandstones were finer grained than those further north towar 's Bethlehem. Botha (1952), described the "Stormberg Series" in an area to the north of Elliot and undertook considerable work on the petrology of the sandstones of the Molteno Formation, especially with respect to their heavy mineral content. Based on further work on the heavy mineral assemblages within the Molteno "Stage", Keen (1955) tentatively identified Molteno strata in the Waterberg area of the Springbok flats. If correct, this occurrence represents the most northerly deposits of the Molteno Formation in South Africa.

Rust (1959, 1962) provides a very detailed account of the Molteno Formation in the vicinity of the town of Molteno and at Bushmanshoek Pass. Rust (1959, 1962, *pers.comm.*) favours deposition brought about by braided outwash steams, on a proglacial alluvial fan. He furthermore used the scarcity of mudcracks in the Molteno Formation to propose a perennial river system with cold climatic conditions. Rust (1959, 1962) proposed that the quartzite pebbles in the lower part of the Molteno Formation most closely resembled quartzites from the Witteberg Group of the Table Mountain Sandstones (TMS). He recognized five successive "cyclothems" within the lower 275 m of the Molteno Formation and concluded that the Formation was the result of the second stage of the Cape orogeny. As such he was the first to place a tectonic signature to the origin of the Molteno Formation. Following Haughton (1924) he assigned the Formation a Mid-Triassic age and proposed that from a morphological viewpoint, the Burgersdorp and Molteno

Formations should be grouped together in one "Stage". In a combined sedimentological, stratigraphical and petrological study of the Molteno in the vicinity of the town of Indwe, Ryan (1963) concluded that the Molteno, Sterkstroom, Indwe and Maclear areas were the most advantageous for further coal exploration. Ryan (1963) also introduced the term "Indwe Transition Beds" for the upper half of the Bamboesberg Member.

Johnson (1966) and Smits (1966) were the first to informally use the term Molteno Formation, although Smits (1971) reverted to the use of the term stage. Formational status was accepted by SACS (1971). Botha & Theron (1967) reported on the sedimentology and stratigraphy of the Molteno "Stage" in the Eastern Cape in the Elliot and Matatiele area. Robinson *et al.* (1969) discussed the geology and oil potential of the "Stormberg" and defined the lower contact of the Molteno as a conformable, composite succession with the underlying Beaufort Group.

The most comprehensive account of the Molteno Formation to date is provided by the various works of Turner, (1969a-c, 1970, 1971a,b, 1972a,b, 1975a,b, 1977, 1978a, 1980, 1981a, 1983, 1984). Turner (1969a-c, 1971a,b) described the geology and coal resources of the Molteno Formation in the northeastern Cape Province, and gave the first comprehensive regional account of the stratigraphy and geological history of the Formation (Turner, 1975a). As a result of this regional study, a number of new stratigraphic members were recognized, including various important marker horizons (Table.1.3a).

Turner (1975a) was also the first to note that the Bamboesberg Member wedged out such that only the Indwe Member was preserved in the north of the basin (Fig 1.1). He proposed that the wedging out of strata below the Indwe was due to erosion and truncation brought about by the Indwe "transgression". Turner argues against differential subsidence to account for the changes in thickness of the Molteno Formation and states (p.25) "there is no doubt that the Molteno bevels down over 1390m of strata from the south to the northeast". More recent investigations (Turner, 1977, 1980, 1983) led to refinements of many of his original ideas, including aspects of the palaeoenvironments, palaeohydraulics and provenance of the Formation.

Turner (1975a) concurred with the early works of Rust (1959, 1962) and Ryan (1963) that the deposition of the sandstone bodies within the Molteno Formation occurred in a perennial braided river system, and following Miall's (1978) classification of braided river types, regarded the Molteno as most similar to the Platte (Turner, 1980). This assumption was however based predominantly on the internal structure of the sandstones of the Indwe Sandstone Member. Turner (1984) altered this view slightly in that he felt the preserved facies sequences in the sandstone dominated Members of the Molteno Formation were deposited by braided systems similar in character to the Bijou Creek and South Saskatchewan River models. In the last of his papers dealing with the Formation, Turner (1983) interpreted the Molteno Formation as being deposited in the proximal reaches of a braided river system draining an alluvial fan of the glacial outwash type.

Christie (1981) worked on the stratigraphy and sedimentology of the Molteno Formation in the vicinity of Elliot and Indwe in the southern part of the basin. He accepted the lowermost members of Turner (1975a), but replaced the upper members with four of his own, also recognising a number of important marker horizons (Table.1.3b). Christie (1981) proposed that the mudrock rich intervals represent deposition on broad alluvial plains. Christie (1986), Christie & MacDonald (*in prep.*) and MacDonald (1993) proposed a revised lithostratigraphy for the Molteno Formation (Table.1.3c), which is however yet to be formalised. These authors propose only one change to that of Christie (1981), in that the Loskop Member was included with the Tsomo Member, due to the fact that the term Loskop was already in use.

Eriksson (1983) interpreted the palaeoenvironmental setting of the Molteno strata in the north-east of Natal, where only the Indwe Sandstone Member is preserved. At this time he assigned the Molteno Formation a Mid-Triassic age, but later changed to a Late Triassic age for the Formation (Eriksson, 1984; Eriksson *et al.*, 1995). Eriksson *et al.* (1995) also provide a simple petrographic analysis of the Molteno Formation in Natal.

Recent work on the Molteno Formation has concentrated on the coal seam potential (Christie, 1986; Heinneman, 1988; MacDonald, 1988, 1993), and little sedimentological work has been undertaken on the Formation. The most recent study of the Molteno Formation is that of Cairncross *et al.* (1995) who documented a number of sedimentological sub-environments and discussed the palaeoecology of the Formation.

Apart from the studies on the coal seams within the Formation, most of the research previously undertaken on the Molteno Formation has been concerned with the palaeoflora of the sequence (Plumstead, 1969; Anderson, 1974, 1976 a,b, 1978; Anderson & Anderson 1970, 1979, 1983, 1984, 1989; 1995, *in press, in prep.*). Fossil plant material has been collected mainly by the Andersons, but also by Kannemeyer (pre 1889, in Anderson & Anderson, 1985), DuToit (1905b, 1911), Van Hoepen (1917), Mountain (± 1932, in Anderson & Anderson, 1985), Ellenberger (1956) and Ellenberger *et al.* (1964). First reviewed by DuToit (1927), the rich flora has subsequently been the subject of reviews by Anderson (1974, 1976a,b), Kitching (1977), Anderson & Anderson (1970, 1979, 1983, 1984, 1989, 1993, 1995, *in press*), and is currently undergoing a major revision (Anderson & Anderson *in prep.*). The megaflora (foliage, fruit, seed and stem impressions) comprise the most significant fossil group with 204 vegetative species (Cairncross *et al.*, 1995). Palynomorph studies on the Formation lag behind, having been undertaken only by Plumstead (1969), Stapleton (1978), Falcon (1986), as well as unpublished work by John Anderson and Colin Macrae (J.Anderson & Macrae *pers.comm.*).

On the basis of its polynofloral signature, Plumstead (1969) assigned the Molteno Formation a Mid-Triassic age, whereas Anderson & Anderson (1970) assigned the Formation to the lowermost Upper Triassic. On the basis of its *Dicroidium* macro and *Alisporites* microflora, Anderson (1974) assigned the Molteno to the Middle to

Upper Triassic (Ladinian to Norian).

Invertebrates are also known from the Bamboesberg and Indwe Members of the Molteno Formation, with fossil insects having been described in detail by Zeuner (1961), Riek (1974, 1976a,b), Hubbard & Riek (1977). To date some 117 genera and 333 species have been identified within the Molteno Formation (Cairncross *et al.*, 1995). These insect fossils are mostly impressions of isolated wings with rare, complete body fossil known of beetles and a recently discovered arachnid (H.Anderson *pers.comm.*). It was previously thought that insects were restricted to the Indwe Sandstone Member, with the Birds River site yielding more than half the specimens recorded until 1995 (J.Anderson *pers.comm.*). More recently the rocks of the Bamboesberg Member have also begun to yield insect remains, with approximately 300 specimens recorded at present (J.Anderson *pers.comm.*). A review of the insect fauna of the Molteno Formation and their biostratigraphic potential is currently underway (Anderson & Riek, *in prep.*; Anderson & Anderson, *in prep.*) .

Shelled invertebrates have recently been documented for the Molteno Formation as well, with conchostrachians in particular being fairly abundant on certain bedding planes (Cairncross *et al.*, 1995). The provisional taxonomic assessment of the shelled invertebrates from the Molteno Formation lists three genera and eight species of conchostrachians, and two genera and species of pelecypod (Cairncross *et al.*, 1995).

Fossil fish were first documented in the Molteno Formation by Ellenberger *et al* (1964) and since this time few further fish fossils have been discovered from the Formation, with Cairncross *et al.* (1995) listing only two genera and three species. Sytchevskaya, Anderson & Anderson (*in prep.*) recognise four fish genera in the Molteno Formation, including a small species of the genus *Semionotus* (Sytchevskaya *pers comm.*). In 1996 a fifth genus was discovered in the Indwe Sandstone Member by Heidi Anderson (H.Anderson *pers.comm.*).

Various authors have previously assigned tetrapods to parts of the Molteno Formation (DuToit, 1918, 1954, Stockley, 1947, Boonstra, 1947; Crompton & Ellenberger, 1957; Rust, 1959, 1962). Two cynodont genera, *Cynidiognathus longiceps* (Boonstra 1947) and *Scalenodontoides macrodontes* (Crompton & Ellenberger 1957) were originally documented as coming from the Molteno Formation. *Cynidiognathus* is now known to be a synonym of *Cynognathus* (Kemp 1980) and occurs stratigraphically within the Burgersdorp Formation (*Cynognathus* Assemblage Zone) (Turner, 1972b). Turner (1972b) also re-assigned *Scalenodontoides* to the lower Elliot Formation. Recently, the first complete skull of this genus was discovered from the lower Elliot in the Bamboeshoek Valley (Gow & Hancox, 1993), within the *Euskelosaurus* Assemblage Zone of Kitching & Raath (1984). This discovery would tend to verify Turner's (1972b) stratigraphic re-assessment of the original find.

Although the Molteno Formation contains a well preserved fossil flora, and lies stratigraphically between the fossiliferous Burgersdorp (*Cynognathus* Assemblage Zone) and Elliot Formations, no tetrapod remains are yet known from the Formation (Anderson & Anderson, 1993, Cairncross *et al.*, 1995). The only indication of a terrestrial fauna in the Molteno Formation come from a number of dinosaur tracks in the Maclear district (Raath *et al.*, 1990; Raath, 1996; Raath *pers. comm.*). These authors note the occurrence and stratigraphic position of the dinosaur tracks as being within the Bamboesberg Member.

Numerous review papers have also dealt with various aspects of the Molteno Formation. DuToit (1954) and Haughton (1969) review the stratigraphy and certain aspects of the sedimentology of the Molteno and Tankard *et al.* (1982) summarise the views of earlier authors who had dealt with the Molteno Formation. Visser (1984) reviewed the occurrence of "Stormberg" Group strata in southern Africa and more recently, (Visser, 199[illegible]) also the palaeogeography and climatology of the Molteno Formation. Smith (1990a) and Smith *et al.* (1993) present overviews of the Karoo and the Karoo aged basins in southern Africa, in which the Molteno Formation is briefly reviewed.

1.3.2 Review of previous investigations

Turner (1975a) referred to the need for further detailed investigations of the various Members of the Molteno Formation in order to allow for a more complete understanding of the lateral facies variations and depositional history of the Formation. Subsequent studies (Turner 1977, 1978a, 1980, 1981a, 1983, 1984, 1986; Christie, 1981, MacDonald, 1993 and Cairncross *et al.*, 1995) have added to our knowledge of the geological setting of the Formation, yet despite these advances, the lithology, stratigraphy, palaeontology, palaeoenvironmental setting and age of the Bamboesberg and Indwe Sandstone Members is still inadequately known, and the Members are not formally described. The lack of adequate lithostratigraphic control also accounts for the lack of a biostratigraphic subdivision for the Formation.

One of the major shortcomings of the previous lithological descriptions was the failure to define discrete architectural elements within the sandstones of the Formation, and an almost complete lack of studies on the braidplain material, except for coal. The coal seams of the Molteno Formation are fairly well described from the literature (Turner, 1971; Christie, 1981; Heinemann, 1986; MacDonald, 1993), however the stratigraphic position and nomenclature of the seams is a point of major contention. Coal seams in the lower part of the Molteno Formation have the potential to allow for intrabasinal stratigraphic correlation, as well as being important palaeoenvironmental and tectonic indicators. Their correct stratigraphic placement is therefore imperative to an understanding of the basinal fill.

Turner (1975a) and Christie (1981) both recognised the existence of cyclicity within the Bamboesberg Member, and proposed possible causes. These studies did not however properly define the cause of the cyclicity, be it from allocyclic, autocyclic, or a combination of both processes. This was mostly due to the failure of these authors to properly examine lateral as well as vertical variations in these units. Miall (1988a, 1996) has shown that observed cyclicity in the rock record may be produced by several different paths which may well be indistinguishable without examination of lateral as well as vertical variations.

Previous workers have interpreted the depositional settings of the Molteno Formation as ranging from proximal arid, to sub-glacial alluvial fans with braidplain and distal meander tracts (Smith *et al.*, 1993), to sub-aerial deltas (Haughton, 1924). Although the recent consensus for the facies genesis favours a braided fluvial origin (Turner 1975a, 1980, 1981, 1984, 1986, Christie 1981, MacDonald, 1993, Cairncross *et al.*, 1995), there is little consensus as to the type of braided system and much of this work suffers from a lack of spatial and temporal control. The individual Members of the Formation have received little attention, and the Bamboesberg and Indwe Sandstone Members in particular have not been stratigraphically partitioned, nor adequately reviewed in terms of modern braided river models. Most studies on modern braided rivers are furthermore concerned with gravel bedload dominated sub-glacial rivers and only the Brahmaputra is adequately described (Coleman, 1969; Bristow, 1989) to act as a model for sand dominated braided river deposition under a humid climate.

The palaeoclimate prevailing during the deposition of the Molteno Formation is also a point of major disagreement. Haughton (1924) proposed a cool and wet climate with intermittent rainfall, whereas Ellenberger *et al.* (1964) and Ellenberger (1970) envisaged a warm humid climate for the "Lower Stormberg" subdivision, which encompassed both the Bamboesberg and Indwe Members. The abundance of megafoliage fossils of *Dicroidium*, and the presence of distinct growth rings in the fossil wood of the Molteno Formation, led Anderson (1976) to propose a temperate climate with seasonal rainfall. Anderson & Anderson (1983) proposed a relatively cool, temperate climate, in accordance with the high palaeo-latitudinal position of 50-55 S. They also envisaged strong seasonal differences, with hot, dry summers and cold dark winters with moderate rainfall.

Christie (1981) (p. 169) states " the commencement of Molteno sedimentation was accompanied by a change to a wet, cool climate with precipitation which was perhaps seasonal. Turner (1983) follows Anderson (1976) in assigning the Molteno

Formation a cool temperate climate, enhancing his argument with sedimentological and mineralogical parameters such as the presence of fresh feldspar. Turner (1983) slightly contradicts his own argument in that he considered the lower Molteno and Burgersdorp Formations to be partly laterally equivalent, yet promotes a cool temperate climate for the Molteno and an arid climate for the Burgersdorp Formation. He furthermore confuses the issue with the statement (p. 84) that " the dominance of one type of depositional process (fluvial) responsible for fan building implies a fairly constant climatic regime.

Falcon (1986) found the diagnostic *Falcisporites* micro- and *Dicroidium* macroflora indicative of a "savannah-type" palaeoclimate, whereas Smith (*pers.comm.*) feels that *Dicroidium* is found under cool humid conditions and Rayner (*pers.comm.*) believes that the *Dicroidium* flora indicates a warm, humid environment. The presence of *Dicroidium* is however probably not really diagnostic of any one palaeoclimate, occurring as it does from the Lower Burgersdorp through to the Elliot Formation.

King (1990) proposed that the Molteno Formation was deposited under warm temperate conditions with winter rainfall. This viewpoint is supported by Eriksson (*pers.comm.*) who suggests that the Molteno is only a wetter version of the Elliot Formation, with similar warm temperatures. The other extreme is held by Visser (1991) who states p. 428 " a sudden appearance of *Dicroidium* flora, an absence of red palaeosols and reptilian fauna and the change in fluvial systems during the deposition of the Molteno Formation, suggests dramatic climatic changes". Visser (1991) further proposed a cold climate for the Molteno Formation, a view held in various review papers since (Smith *et al.*, 1993). Cairncross (*pers.comm.*) proposed that temperature fluctuations may have been very severe, with palaeofrosts and palaeotemperatures as low as -30°C.

According to Cairncross *et al.* (1995), the palaeogeographic position of southern Africa at the time of deposition of the Molteno Formation shows that the landmass was moving northwards towards an equatorial position (de Wit *et al.*, 1988). The led these authors to propose that the climate should have been one of increasing aridity. According to the palaeogeographic reconstructions of Anderson & Anderson (1993) the depositional basin lay between 50° and 55° south during a global period when the polar regions were not glaciated (Cairncross *et al.*, 1995).

The palaeoclimate for the Molteno Formation has therefore in the past been envisaged as ranging from cold and wet with intermittent rainfall (Haughton, 1924, Anderson & Anderson, 1970; Visser, 1991; MacDonald, 1993) to humid temperate (Ellenberger *et al.*, 1964) and little consensus has at present been reached among workers.

Although numerous fossils occur in the Molteno Formation, the age of the Formation is not well constrained, with proposed ages ranging from the Permian through to the Late Triassic. Most authors however favour either a Mid-Triassic (Haughton, 1924; Rust, 1959, 1962; Plumstead, 1969; Keyser, 1973; Eriksson, 1983; Smith *et al.* 1993) or Late Triassic age (Dunn, 1878; Anderson & Anderson, 1983,a,b; Turner, 1971, 1975a, 1983; Eriksson, 1983, 1984; Eriksson *et al.*, 1995). These different viewpoints have serious ramifications for the length of time represented by the basal contact of the Formation. Fossil tetrapods are presently unknown from the Molteno Formation (Cairncross *et al.*, 1995) and the only definite indication of the existence of a tetrapod fauna during Molteno times, comes from a number of sets of dinosaur footprints in Molteno strata in the Maclear district, which Raath *et al.* (1990) placed stratigraphically within the Bamboesberg Member.

Numerous problems therefore exist with regards to the sedimentology, stratigraphy and palaeontology of the Molteno Formation and in particular of the Bamboesberg Member. The main problems regarding the Bamboesberg Member at present are: that its geographic distribution has not been properly mapped; that the spatial and temporal changes that occur throughout the basin are not understood; that the litho- and biostratigraphy is very poorly known; and that the cause of the recognised cyclicity has not been properly addressed.

The Bamboesberg Member is important in that it forms the oldest chronostratigraphic contact with the Burgersdorp Formation in the south of the basin. Knowledge of its facies genesis and age are vital to an understanding of the true nature of the contact between the Burgersdorp and Molteno Formations, as well as to basinal fill and development of the upper part of the Karoo Basin.

1.4 The Burgersdorp-Molteno Contact

1.4.1 Historical Overview

Historically, the contact between the Burgersdorp and Molteno Formations has been defined on numerous different lithological and palaeontological criteria. Wyley (1859) and Huxley (1867) independently differentiated the "Stormberg Beds" from the underlying Beaufort Group strata, and in so doing they were the first to imply a major difference between the two sequences. Dunn (1873, 1878) was the first to notice that the colour of the "Coal Measures" contrasted strongly with the underlying "Upper Karoo" strata and believed that the contact was conformable. DuToit (1905a,b) felt that the base of the "Stormberg Group" was difficult to delineate with any accuracy, but that in the vicinity of Bushmanshoek Pass it formed a composite zone which could generally be fixed to within 15m. DuToit (1954) re-defined the base of the "Stormberg Group" as the occurrence of the first glittering sandstone of the Molteno Formation.

Rust (1959, 1962) proposed that the contact could be fixed mainly on a change in the predominant type and colour of the strata. He states (p. 172) "In places the contact is quite sharp as at Carrickmore Kloof, but near Lookop homestead the contact is not as sharply delineated. In Carrickmore Kloof the contact is indicated by a thin, but fairly persistent fine grained sandstone bed. It is overlain 20-25 feet higher up by the first prominent sandstone stratum of the Molteno stage." He continues (p. 174) [illegible] to that " The contact sandstone horizon does not consist of one persistent sandstone bed but is rather a zone of sandstones, the beds mutually interfingering, pinching out and swelling in complex manner". Due to the composite nature of the contact he believed that no satisfactory lithological marker horizon could be indicated as a lower contact with the Beaufort Group. Rust (1959, 1962) therefore proposed that a better contact might be established palaeontologically.

Turner (1975a) defined the lower boundary of the Molteno Formation for the type section at Grootdoringhoek Pass, as the base of the first sandstone of the Bamboesberg Member, noting that the contact was sharp, and that it coincided with a change from predominantly maroon mudstone in the Burgersdorp Formation, to grey sandstones in the Molteno Formation. He states (p. 23) "Where sandstone replaces shale and mudstone in the section, the contact can often be fixed on the basis of the predominantly coarser grain size of the Bamboesberg sandstones, which also tend to be slightly paler in colour".

Turner (1975a) further notes that east of the type section, facies changes and the inter-digitation of shale and mudstone complicated contact relationships. In Bushmanshoek Pass he did not believe that the base of the Bamboesberg Member could be placed with any accuracy. Due to this difficulty he arbitrarily defined the contact as follows (p. 24) "One useful line of evidence is the abundant presence of calcareous nodules in some of the olive grey sandstones. Moreover, since similar nodules have not been found so far in the Molteno Formation (Turner, 1972) it seems as good a place as any to draw the boundary."

Turner (1975a) first recognised that the Bamboesberg Member wedged out northwards with the effect that the base of the Molteno Formation in the north of the basin equates to the base of the Indwe Sandstone Member (Fig 1.1). At times he however found it difficult to place the lower boundary of the Indwe Member, stating (p. 24) " when traced laterally along the contact the unconformity appears in different guises depending on the amount of relief, and under these circumstances it is easy to see why the unconformity has been denied existence for so long since its interpretation is sometimes subjective".

Turner (1975a) further noted that the lower boundary of the Molteno Formation recorded an important palaeontological break, in that the vertebrate fossils so prolific in the Formations above and below, were absent in the Molteno Formation. Because of the lack of direct palaeontological correlatives between the Burgersdorp and Molteno Formations, Turner (1975a) found the time represented by the unconformity at the base of the Molteno Formation difficult to evaluate, but believed that the disconformity might be of a considerably greater timespan than the physical evidence suggested.

Kitching (1977) distinguished the Molteno Formation from the upper Burgersdorp (*Cynognathus* Assemblage Zone) by the absence of dark coloured to chocolate brown mudstones and shales, and by the presence of dark bluish grey shales and sparkling, coarse grained sandstone horizons containing well rounded pebbles.

Christie (1981) felt that the Bamboesberg Member could be distinguished from the Burgersdorp Formation by its dominantly arenaceous nature, stating (p. 11) "Field observations strongly suggest that the base of the Bamboesberg is most conveniently defined by the horizon at which sandstone succeeds siltstone and mudstone as the dominant rock type". He felt that the contact was conformable and could be satisfactorily defined as the erosively based, basal Bamboesberg sandstone. He also re-iterated that the strata of the Bamboesberg Member preserved thin coal deposits, whilst that of the underlying Burgersdorp Formation did not.

Visser (1984) stated that the base of the "Stormberg Group" and hence the Molteno Formation, was defined all over southern Africa by an unconformity, with deposition in the south preceded by an erosional period of limited extent, but in the order of 50Ma or more in the north (Visser, 1984). Visser (1991) states (p. 424) " An erosional period of up to 10Ma separated the fluvial Stormberg sedimentation from the underlying Beaufort beds in the south". These are the only two direct reference to the magnitude of the of the unconformity at the base of the Molteno Formation.

Johnson and Hiller (1990) defined the base of the Molteno Formation as a ± 100m thick, conformable transition zone with the Burgersdorp Formation. Their placement of the basal contact was based on an abrupt upward increase in the sandstone/fines ratio, associated with the disappearance of red mudstone. MacDonald (1993) followed Robinson *et al.* (1969) and Christie (1981) in defining the lower contact of the Molteno Formation as a composite succession, being delineated in the field by an abrupt upward increase in the sandstone/fines ratio from less than 0.25 to more than 0.50.

The lower boundary of the Molteno Formation has therefore been the subject of several attempts at definition, with much debate centred around the criteria for the placement of the basal boundary of the "Stormberg Group". At present most of the criteria are untenable, and the time represented by the contact has not been well constrained.

1.4.2 Review of previous investigations

That the base of the Molteno Formation is not well defined nor understood is clear from the confusion and vagueness in the literature as to the nature of the contact and its stratigraphic placement. The changing nature of the contact through the basin is not fully understood, and the magnitude of time represented by the contact is poorly constrained, with estimates ranging from truly conformable (Christie, 1981) to 50 MA (Visser, 1984).

Prior to the work of Turner (1975a), many workers did not recognise the Bamboesberg Member, and the lower boundary of the Molteno Formation was considered to be the same throughout the basin. For this reason care should be taken when dealing with early literature defining the contact, as it often refers to the contact between the Burgersdorp Formation and the Indwe Sandstone Member of the Molteno Formation, and not the true chronostratigraphic contact in the south of the basin. Failure of these earlier workers to recognise the Bamboesberg Member also led to the concept of a transitional basal contact for the Molteno Formation (eg

Robinson *et al.*, 1969).

Many of the criteria used in the past are vague or incorrect, while others are not acceptable in terms of the stratigraphic code (SACS, 1987; ISCC, 1994). Lithological criteria for defining the contact have in the past been based on: colour differences; the glittering nature of the Molteno sandstones; their coarser grainsize and inclusion of quartz pebbles; that the Molteno strata preserve coal; changes in sandstone/fines ratio. Palaeontological criteria are based on: that tetrapod fossils are absent in the Molteno Formation; and the presence of an abundant flora, dominated by the genus *Dicroidium*.

Although these previous works are more fully discussed in Chapter Four in light of the findings presented in this thesis, a number of these criteria may be discarded based on the current literature. In fact, of the lithological criteria, only the inclusion of quartz pebbles and the presence of coal are valid at present. Although colour change is of little value in defining stratigraphic boundaries on a regional scale (Turner, 1981), colour change may be used to define the contact in the north of the basin. In the south of the basin however, the colour of the strata actually changes some 15-20 metres before the contact (Christie 1981).

The glittering nature of the Molteno sandstones is not a useful, or sedimentologically correct criterion, as although the Indwe Sandstone Member often has a glittering appearance, so too do nearly all the coarse sandstones in the Molteno Formation (Christie, 1981). When working in the southern part of the basin this criteria is of even less value as the sandstones of the Bamboesberg Member are often difficult to distinguish texturally from those of the underlying Burgersdorp Formation (Christie, 1981). The placement of the base of the Molteno Formation at the horizon at which sandstone succeeds siltstone as the dominant lithology (Christie, 1981; Johnson & Hiller, 1990), is not based on sound lithostratigraphic principles and does not conform to the stratigraphic code for the placement of a Formational contact (SACS, 1987; ISCC, 1994).

Although the abrupt palaeontological break as noted by Turner (1975a) has been verified by numerous authors (Anderson & Anderson, 1993a; Cairncross *et al.*, 1995), palaeontological criteria are felt to be sub-ordinate to lithological criteria, as they are based on relative abundance or absence of genera. It is not stratigraphically sound to base a lithological contact on the absence of a particular fossil type (ISCC, 1994), and furthermore, both of these criteria may be brought about by numerous factors other than real absence, including changes in the chemistry of the groundwater.

The problem associated with defining the contact is therefore two-fold. Firstly, the base of the Bamboesberg Member is not well defined and its spatial nature is not understood, and secondly, the definition as accepted in the literature at present is vague. This has led to erroneous thickness estimates for both the Burgersdorp and Molteno Formation , as well as to confusion regarding the controls on sedimentation in these two Formations. For these reasons, documentation of the spatial changes that occur through the basin and a concise definition of the nature of the contact is vital to an understanding of the development of the upper Karoo Basin.

1.5 Basin Development of the Upper Karoo

Basin analysis is the integrated study of basin fill and includes such aspects as the application of the load (both tectonic and sedimentary) which creates and controls the basin architecture, its erosion and mass redistribution (Johnson & Beaumont, 1995). Mass redistribution by surface processes and sediment flux are a function of base level changes and changes in climate. Basin development studies therefore draw heavily on aspects of sedimentology and palaeontology, including facies genesis, palaeoclimatic evidence and biostratigraphic age constraints. From the preceding background and historical reviews, it is apparent that a number of these inputs are poorly constrained for the Burgersdorp and Molteno Formations.

1.5.1 Historical Overview

Because sedimentology and palaeontology are important parameters in basin development studies, the basin development of the upper Karoo may be seen to date back to the first geological and palaeontological descriptions of the strata. Modern basin analysis of the main Karoo Basin has however only come about with the introduction of plate tectonic theory, which for the first time presented a mechanism for foreland basin formation (Dickinson, 1974) and the creation of the Cape Fold Belt (CFB).

The Karoo Basin is one of the few examples in the world where the timing of tectonic activity in the fold belt and the age of the sedimentary responses have been independently constrained. Periods of tectonic activity in the CFB are documented in the works of Hälbich (1977, 1983a-c, 1992), Hälbich & Cornell (1983), Hälbich & Swart (1983), Hälbich *et al.* (1983), Visser (1992) and Gresse *et al.* (1992). These authors in essence recognise five major periods of tectonic activity for the Karoo Basin, with periods of minor activity in between. Although the Karoo Basin as a whole, and the upper Karoo in particular, has few radiometric marker horizons, the refinement of the biostratigraphy of the sequence has allowed for the relative ages of the sedimentary responses to be fairly well constrained.

In the late 1970's and early 1980's, numerous authors attempted to link plate tectonic theory to the sedimentary development of the Karoo Basin (Johnson, 1976; Hobday, 1978; Visser & Dukas, 1979; Stavrakis, 1979, 1980; Hiller & Stavrakis, 1984). Few of these works have however concentrated directly on the basin development of the upper Karoo. Visser & Dukas (1979) recognised large scale fining upward cycles within the Lower and Upper Beaufort and directly related the magnitude of source area tectonism to the penetration of the coarse grained Katberg Sandstone Formation into the basin. Stavrakis (1979, 1980a) and Stavrakis & Hiller (1984) also linked the progradation of the Katberg Sandstone Formation to tectonic activity in the CFB, equating this sedimentary responce directly to the third tectonic event (246 ± 2Ma paroxysm) of Hälbich *et al* (1983).

Stavrakis (1980a) separated the Katberg tectono-sedimentary cycle from the proto-Molteno cycle, which he believed started in late Burgersdorp times. Hiller & Stavrakis (1984) proposed that the Burgersdorp Formation was the lateral equivalent of the Katberg Sandstone Formation and that denudation of the source area controlled the sourceward shift of the Burgersdorp Formation through time. Hancox *et al.* (1995) briefly discuss the implications of their threefold sub-division to the basinal development of the upper Karoo, showing that a sourceward facies shift [illegible]ing Burgersdorp deposition was well evidenced by palaeontological parameters. Hancox and Rubidge (1995) added sedimentological parameters for the development of the Burgersdorp Formation and proposed that deposition occurred during a period of quiescence following the tectonic activity in the CFB, which controlled the cratonward progradation of the Katberg Sandstone Formation. The control of the development of the Burgersdorp Formation is however very poorly known, due mainly to the paucity of detailed sedimentological and stratigraphic studies.

The earliest basinal development models for the Molteno Formation may be traced back to the works of North (1878) and Rogers (1905), in that they were the first people to interpret the provenance of the sedimentary fill of the Molteno Formation as being the CFB. Rust (1959, 1962) presented the first evidence of a direct tectonic control for the Molteno Formation and may therefore be regarded as the progenitor of modern basin studies of the upper Karoo. He explained the stratigraphic relationships of the Molteno Formation in terms of repeated thrusting and uplift in the CFB, referring to this process as pulsatory source area diastrophism. Rust (1959, 1962) further postulated that "[illegible] diastrophism culminated in a major period of uplift which brought about t[illegible]position of the Indwe Sandstone Member as a response. Ellenberger *et al.* (1964) tied the beginning of the deposition of the Molteno Formation to the completion of tectonism in the CFB. Lock (1978) believed that the timing of the Cape Orogeny could be relatively precisely dated by sedimentary means, co-inciding with the change in conditions reflecting the Beaufort-Molteno boundary in the Early Triass'c

Turner (1975a, 1983, 1984, 1986) modified Rust's (1959, 1962) model in that he considered the numerous fining upward sequences in the Molteno Formation to be related to only one tectonic event. This event involved a single phase of uninterrupted uplift related to basin margin thrusting. Turner, (1975a) related the main phase of orogeny in the CFB to the deposition of the Indwe Sandstone Member of the Molteno Formation. Turner (1983) altered his earlier view, and correlated his six successive fining upward sequences of the Molteno Formation (his six Members) to major phases of fault controlled uplift in the southern source area (Turner, 1983, 1986). The tectonic model proposed by Turner (1983, 1986) therefore directly relates the main sequences in the Molteno Formation to major phases of fault-controlled uplift in the southern source areas.

Based on a petrographic study of sandstone compositions, Johnson (1991) showed that the CFB became the predominant provenance for the Karoo Basin only during the upper Karoo, and that the provenance changed from lower Katberg to Molteno Formation times. In this paper, Johnson (1991) also provides an overview of the tectonic setting of southwestern Gondwana during the deposition of the Karoo.

Cole (1992) postulated that periodic tectonism in the southern source areas, coupled with foredeep subsidence, resulted in the deposition of thick, laterally extensive sandstones during Katberg and Molteno Formation times. He followed Hiller & Stavrakis (1984) in equating the Katberg Sandstone Formation to the third paroxysm of Hälbich *et al.* (1983), and equated the Molteno Formation to the fourth paroxysm (229 ±5Ma). Cole (1992) also proposed an erosional lacuna for the entire Mid-Triassic, which he tied to epeirogenic uplift of southern Africa during this period.

Following the works of Johnson & Rust (1988) and Winter (1990), Groenewald (1996) presented a tectonostratigraphic model for the Katberg, Burgersdorp and Molteno Formations. This model proposes a Katberg (247Ma), Andriesberg (230Ma) and Molteno (215Ma) paroxysm which Groenewald (1996) equated to the third, fourth and fifth paroxysms of Hälbich *et al.* (1983). The most recent and complete attempt at basinal modeling of the upper Karoo is that of Catenoanu *et al.* (*in prep.*) who apply a reciprocal stratigraphic approach to the formation and fill of the main Karoo Basin.

1.5.2 Review of previous investigations

Basin development studies require numerous inputs including such factors as: the affects of base level changes; the timing of tectonic events; facies genesis; and the affects of climatic controls. The previous sections of this chapter have shown that certain of these controls are poorly constrained for the Burgersdorp and Molteno Formations. In particular, the lithology, stratigraphy and palaeontology of the two Formations is not well documented and the palaeoenvironmental models (palaeoclimate and facies genesis) proposed for the Formations are not agreed upon by workers. The ages of the two Formations, and therefore the timing of events which controlled their genesis are also poorly constrained.

The major problems associated with the basin development of the Burgersdorp Formation at present are: that the basal contact is not well defined nor understood; that the stratigraphic position of the major sandstone bodies and hiatal surfaces are not well constrained; that the placement and nature of the proposed paraconformity is not well documented; that the Formation is not well dated; and that the primary control on sedimentation is not understood.

The previous models for the development of the Molteno Formation are also problematical in that: they cannot account for the presence of quartzite boulders, upper flow regime bedforms and fresh feldspar at distances of hundreds of kilometres from the source area; that the palaeoenvironment of the Formation is poorly understood; that the age of the Formation is not well weakly constrained; and in that they do not adequately explain the preserved facies distributions.

The refinement of stratigraphic methods, subsidence analysis, palaeomagnetism, palaeoclimatology and the development of sequence stratigraphic concepts (Van

Wagoner *et al.*, 1988, 1990; Galloway, 1989; Viall *et al.*, 1991) have completely revolutionized the science of basin analysis. Sequence stratigraphy has however been so over-emphasized that other mechanisms are often overlooked (Miall, 1990, 1991, 1996). A major problem with the fill of the upper part of the Karoo Basin is that due to the isolated nature of the basin (Groenewald, 1996), cyclic sedimentation cannot be correlated to global sea level curves (Haq *et al.*, 1987; Haq, 1988) and hence a classic sequence stratigraphic approach cannot be applied. Groenewald's (1996) tectonostratigraphic approach goes some way towards solving the problems of defining sequence controls within landlocked basins, however its usefulness is limited to the upper Karoo and it requires a totally new terminology.

The upper Karoo basinal fill, including the Katberg, Burgersdorp and Molteno Formations, has been widely linked to tectonism (diastrophism) in the CFB (Cole, 1992), and a number of hypotheses occur regarding its stratigraphic evolution (Rust, 1959, 1962; Lock, 1978; Stavrakis, 1979, 1980a; Turner, 1983, 1986; Stavrakis & Hiller, 1984; Johnson, 1991; Cole, 1992; Hancox & Rubidge, 1995; Groenewald, 1996). All of the previous models for the development of the upper Karoo may be broadly grouped as process-response models in that tectonic uplift in the CFB is proposed to be the direct cause of rapid cratonward progradation of coarse sediment into the basin. This is believed to be due primarily to the elevation of the source area, and an increase in the gradients of the rivers supplying sediment to the basin. There is however some debate about the correlation of tectonic events in the CFB and their sedimentary responses. Most authors (Visser & Dukas, 1979; Hiller & Stavrakis, 1984; Cole, 1992; Groenewald, 1996) agree on a link between the 3rd paroxysm (Hälbich *et al.*, 1983) and the sedimentation of the Katberg Sandstone Formation, but less agreement occurs for the Burgersdorp and Molteno Formations. Cole (1992) links the Molteno Formation to the 4th paroxysm, whereas Groenewald (1996) links this event to the deposition of the Andriesberg Member of the Burgersdorp Formation, and rather correlates the Molteno Formation to the fifth paroxysm.

Documentation and modelling of retro-foreland basins has advanced rapidly in the past decade both with regards to their mechanics of formation (Beaumont, 1978, 1981; Jordan, 1981; Quinlan & Beaumont, 1984; Flemings & Jordan, 1989; Beaumont *et al.*, 1993; Johnson & Beaumont, 1995; Peper *et al.*, 1995; Yang & Dorobek, 1995) and fill (Flemings & Jordan, 1989, Beaumont *et al.*, 1993; Ettensohn, 1994; Johnson & Beaumont, 1995; Catuneanu *et al.*, 1997). The effects of basin flexure in relation to thrust advance, sedimentary loading and source unloading is fairly well constrained (Beaumont, 1981; Quinlan & Beaumont, 1984; Johnson & Beaumont, 1995) and it is now well documented that thrust activity and orogenic loading in a fold belt produces flexural subsidence in the foredeep, and the sourceward migration of the forebulge area. This leads to the creation of accommodation space during tectonism (Quinlan & Beaumont, 1984; Flemings & Jordan, 1989; Johnson & Beaumont, 1995) which must be filled prior to the progradation of coarse detritus further into the basin. It is therefore evident that there is a lag time between tectonic activity and the progradation of coarse detritus into the basin, and this lag period needs to be constrained for the coarse grained sandstone sequences in the upper part of the main Karoo Basin.

The flexural model of Beaumont (1981) and Quinlan & Beaumont (1984) and the reciprocal stratigraphy model of Flemings & Jordan (1989), Ettensohn (1994) and Catuneanu *et al.* (1997) have totally altered the way in which foreland basin formation and their fill is perceived. In light of these new models, old process-response theories for the development of the upper Karoo during the Triassic need to be re-examined.

1.6 Aims

From the preceding background and historical overviews, it is apparent that numerous, problems exist with respect to: the sedimentology; palaeontology; lithostratigraphy and biostratigraphy of the Burgersdorp and lowermost Molteno Formations (Bamboesberg and Indwe Members); as well as the exact nature of the contact which separates them; and their setting within the basin development of the upper Karoo.

The main aims of this thesis are therefore: to document the lithologies and stratigraphy of the Burgersdorp and Molteno Formations; to address the problems of faunal representation and biostratigraphic ranges of the fossils of the *Cynognathus* Assemblage Zone, particularly that of the dicynodont *Kannemeyeria*; to refine the biostratigraphic subdivision proposed by Hancox *et al.* (1995); to address the question of the interbasinal correlation and age of the *Cynognathus* Assemblage Zone; to define the changing nature of the contact between the two Formations on a basinal scale; to determine the magnitude of the proposed hiatus between them; and to define the nature of cyclicty in the Bamboesberg and Indwe Members of the Molteno Formation. The ultimate aim of the study is to use these findings to reconstruct the palaeoenvironments (facies genesis and palaeoclimate) of the two Formations and to model the formation and fill of the upper Karoo Basin.

The overall aim of the project is therefore to integrate sedimentological, stratigraphic and palaeontological studies of the Burgersdorp and lowermost Molteno Formations, in order to establish the sedimentary history of the sequence, and to determine the nature of the contact that separates them.

1.7 Study Area

The study area (Fig.1.2) is situated in the southeastern reaches of the main Karoo Basin and encompasses the entire geographical distribution of the Bamboesberg Member of the Molteno Formation. This area takes the form of a diamond stretching from Sterkstroom in the south to Rouxville in the north, and from Cala in the east, to near Steynsburg in the west. Although this study was concentrated in the southern part of the basin, several weeks were also spent in the north of the basin studying the newly discovered *Cynognathus* Assemblage Zone deposits (Welman *et al.*, 1991) and the Molteno Formation.

The Burgersdorp and lower Molteno Formations are well exposed in the main study area along the escarpment of the Bamboesberg and Stormberg Mountain ranges in the Eastern Cape. During early field reconnaissance, significant new exposures of the upper Burgersdorp Formation (*Cynognathus* Assemblage Zone) were discovered lying within the Bamboeshoek Valley, approximately ten kilometres to the southwest of the town of Sterkstroom (Fig.1.2; #3, #4). These exposures in the Bamboeshoek Valley provide a continuous section from the upper Burgersdorp through to the Elliot Formation, thus providing an uninterrupted vertical succession spanning the whole of the Molteno Formation. For the purpose of this investigation it was however decided to constrain the temporal range of the study to the Bamboesberg and Indwe Sandstone Members of the Molteno Formation, as these two are the only members that stratigraphically overlie the Burgersdorp Formation (Fig.1.1). On a regional structural scale, the main area of study lies between the northern boundary of the Southern Cape Conductive Belt (SCCB) and the southern boundary of the Kaapvaal Craton (KC) (Fig.1.2).

1.8 Methodology

"Fieldwork is the basis of the study of sedimentological rocks"

Blatt *et al.* (1972)

The optimal approach to understanding the sedimentary record is a combination of detailed field studies followed by laboratory analysis of carefully selected samples. To this end fieldwork was undertaken at periodic intervals over a period of six years, between March 1992 and September 1997. Attention was centered on localities that permitted detailed vertical sections and lateral profiles to be compiled and that contained fossil material (Fig.1.2).

Research was mainly focused on the basin-wide examination of the rocks of the upper Burgersdorp and lowermost Molteno Formations in terms of: their stratigraphic position; overall gross geometry; internal architectural elements; lithology; and palaeontological signatures. This was undertaken in order to achieve better resolution of the litho- and biostratigraphy of the two Formations and their facies genesis, as well as to allow for their intra- and inter-basinal correlation. The stratigraphy of the uppermost Molteno Formation was also briefly studied, but is not described in detail in this thesis. Because the lithostratigraphy of the upper Molteno Formation is not well defined, a number of local stratigraphic nomenclatures have been proposed in the past (Table 1.3 a,b,c). These local stratigraphic names could not be directly applied to the upper Molteno Formation in the south of the basin and to avoid further complicating the literature, for the purpose of this study the upper Molteno Formation was collectively termed the "Transitional" Member (non senso stricto Turner, 1975a).

Detailed documentation of lithofacies is now a standard component of the facies analysis method of interpreting sedimentary strata (Cant, 1978, 1982; Miall 1977, 1978, 1996). Lithofacies schemes were therefore erected for each of the Formations under study, with additions and alterations to the facies codes of Miall

(1977, 1978, 1980, 1996). This was undertaken, not just to pigeonhole descriptions, but rather due to the fact that lithofacies and their spatial and temporal associations represent real, significant and distinct sedimentary environments (Miall, 1996). Facies were described in terms of their primary depositional features, particularly bedding, texture, sedimentary structures, included biogenic material and grain size. Grainsizes were recorded using the Udden-Wentworth (Wentworth, 1922) rather than phi scale and no conversion to phi sizes was undertaken. Summaries of these methods and their limitations are given in Reading (1986, 1996) and Miall (1990, 1996).

To fully understand the history of fill of a sedimentary basin, a thorough documentation of the stratigraphy is of fundamental importance. Stratigraphic sections were measured at key localities across the extent of the field area (Fig.1.2), with particular emphasis placed on localities where the entire stratigraphy of the Bamboesberg Member was preserved. At these localities, vertical sections incorporating all sedimentological and biogenic features were plotted to an accuracy of ±5cm. Sedimentological considerations were focused on the proper documentation of bounding surfaces marking lithofacies transitions, primary sedimentary structures, traces and the occurrence of pedogenic features.

Much information is contained within outcrops of fluvially deposited strata that is not attainable by conventional methods of facies analysis, such as the measurement and interpretation of vertical profiles and Miall (1996) has criticised vertical profile analysis as a means of palaeoenvironmental interpretation. Bearing in mind these criticisms, use was made of vertical profile analysis for facies genesis interpretations, only when coupled with lateral control to minimise interpretation errors.

Lateral profiling is especially important for studies of braided fluvial environments, where horizontal changes in lithofacies and the style of sedimentary architecture are most marked (Godin, 1991). Lateral profiles of the main sand-bodies were therefore constructed in order to establish the geometries of the architectural elements present. This method can ideally identify several superimposed scales of cyclicity, even when they arise from completely different processes, an accomplishment that is not possible if vertical profiles alone are used. Roadcuts in particular provided excellent opportunity for detailed lateral profiling and architectural element analysis. Outcrops were recorded as two dimensional panel sections supplemented by detailed vertical profile logs. Vertical and lateral relationships between facies along the length of the outcrops were established by plotting details from field observations onto photomosaics. These photomosaics were created following the technique outlined in Miall (1985, 1988a, b). In most cases vertical profiles were measured from the top down using a climbing harness.

Lithofacies associations consist of groups of genetically related facies separated from adjacent groups by bounding surfaces of various orders. These genetically related packages of sedimentary strata are divided into a number of architectural elements that make up the overall geometry of the rock body. Bounding surface terminology used in this thesis is modified after Hazeldine (1983) and Miall (1988a, 1996), and these surfaces are classified such that higher order surfaces truncate lower order ones.

A number of stratigraphic sections were also measured in the north of the basin in order to establish the intra-basinal relationships of the sequences. Although the lower contact of the Burgersdorp Formation was not the primary focus of this study, field observations of [illegible] nature were made in the southern, western and northern margin of the basin. These findings were coupled to the literature in order to allow for the Burgersdorp Formation to be correctly placed within the sequence of events for the basin development of the upper Karoo.

Representative rock samples from different sedimentary facies types were collected at recorded stratigraphic heights, and prepared for thin section analysis and petrographic work. Framework mineralogical studies were undertaken on 53 thin sections of sandstones from the Katberg, Burgersdorp and Molteno Formations (Appendix 1). Textural analyses were undertaken by conventional light microscopy in order to: refine earlier studies on the primary provenance of the sandstone bodies; ascertain if any stratigraphic trends were observable; as an aid in palaeoenvironmental interpretations; and to aid in basinal development studies. Such studies are believed to be one of the best means of indicating the plate tectonic setting of ancient deposits (Condie, 1989; Johnson, 1991; Schreiber *et al.*, 1992). For the modal analysis, the procedure of Johnson (1991) was followed. With the aid of a Swift point counter, some 300 points per thin section were counted, as this number is regarded as statistically accurate and is thought to represent the most beneficial investment of time per section (Galehouse, 1971). The compositional categories and their abbreviations are listed in Appendix 1. No selective staining was undertaken and therefore no distinction was drawn between the different feldspar types for the purpose of framework grain analysis by point counting. X-ray Fluorescence (XRF) techniques were not applied to the sandstones and different plagioclase compositions were therefore not investigated. Ternary diagrams were plotted using Triplot version three. Petrological data was used to classify the sandstones from the two Formations, for provenance studies, and for determining the tectonic framework during sedimentation.

Grainsize analysis for the sandstones of the Burgersdorp and Molteno Formations were obtained by thin section measurement, using the method outlined by Selley (1976). This was necessary due to the fact that most Molteno sandstones exhibit secondary quartz overgrowths, which tend to obscure original grainsize. Heavy mineral assemblages were noted in terms of types and occurrence, although they were not run for XRD analysis.

Palaeocurrent measurements were recorded wherever possible to establish dispersal patterns and for an indication of source area locations. These readings were assessed according to indicator type, with parting lineation the dominant structure for the Burgersdorp Formation and lowermost Bamboesberg Member, and trough cross-stratification dominant for the uppermost Bamboesberg and Indwe Sandstone Members of the Molteno Formation. Planar cross-stratification directions were noted but not used in the final palaeocurrent analysis, as they are not reliable current direction indicators (High and Picard, 1974), especially in the Bernoesberg Member, where they are frequently normal to the current directions obtained from more reliable indicators such as trough axes (DeCelles *et al.*, 1983). Vector means and strengths were calculated using the method of Lindholm (1987), as these two values considered together give the most accurate reconstructions of flow direction (Miall, 1974; Potter & Pettijohn, 1978).

During the course of the study, a number of palaeontological specimens were collected from the uppermost reaches of the *Cynognathus* Assemblage Zone (subzone C, Hancox *et al.*, 1995) in the south of the basin (Appendix 2). Fossils were also collected from subzone B in the middle of the basin and subzone A in the north of the basin (Appendix 3). Fossil localities were recorded with a Garmin Global Positioning System (GPS) as well as with the aid of 1:50 000 topographical maps. Specimens considered worthy of curation and further preparation were taken for study to the Bernard Price Institute (B.P.I. Palaeontology) where they are currently housed. Fossil preparation was mostly undertaken by mechanical means using an Atlas Copco air scribe. Acid treatment was undertaken on various specimens, but without much success. All new taxa are fully described in Chapter Two, where the individual preparatory treatment given to each specimen is described.

Study of comparative dicynodont material for the taxonomic assessment of the new dicynodont material (Hancox & Rubidge, 1994; 1996), was undertaken at the: South African Museum, Cape Town (SAM); National Museum, Bloemfontein (NMB); Transvaal Museum, Pretoria (TM); Council for Geosciences, Pretoria (GC); Natural History Museum, London (BMNH); Zoological Museum, Cambridge (CUMZ); Universtät Tübingen Museum und Institut für Geologie und Paläontologie (UT); and the Institute of Vertebrate Palaeontology and Palaeoanthropology, Beijing (IVPP).

Samples from various facies, including coal and inter-seam material were analyzed in order to try and determine the palynological representation of the two Formations, but to date have not yielded significant palynomorphs.

1.9 Organisational Preview

Chapter Two provides detailed descriptions of the lithology, palaeontology and stratigraphy of the Burgersdorp Formation and a reference section for the upper Burgersdorp Formation is proposed (Appendix 4). New fossil taxa are fully described and taxonomically assessed and the threefold subdivision of the *Cynognathus* Assemblage Zone proposed by Hancox *et al.* (1995) is expanded upon. The layout of Chapter Three is similar to that of Chapter Two, except that the Bamboesberg and Indwe Members of the Molteno Formation are treated separately. The Bamboesberg Member is fully described for the first time in terms of its geographic extent, stratigraphy, lithology and palaeontology, and is included in the format for acceptance by the South African Committee for Stratigraphy (SACS, 1987) (Appendix 5). The spatial and temporal changes that occur within the Bamboesberg and Indwe Members are fully discussed

The data presented in Chapters Two and Three is synthesized in Chapter Four to allow for detailed palaeoenvironmental reconstructions of the Burgersdorp and Molteno Formations to be proposed. New interbasinal correlations are presented for the *Cynognathus* Assemblage Zone, based on faunal contemporeity of the proposed subzones with faunas from other parts of Gondwana, as well as China and Russia. These correlations are in turn used to refine the relative age of the *Cynognathus* Assemblage Zone. The nature of the contact between the Burgersdorp and Molteno Formation is fully described in terms of the differences that occur between the two Formations. The question of diachroneity of the basal boundary of the Molteno Formation is addressed, and the length of time represented by the contact is discussed. Finally, the results from this study are incorporated with the current literature to present a model for the formation and fill of the upper Karoo Basin.

2 BURGERSDORP FORMATION

2.1 Introduction

In this chapter the stratigraphy, lithology and palaeontology of the Burgersdorp Formation rocks, which encompass the *Cynognathus* Assemblage Zone fossil fauna are described in detail. A new species of the capitosaurid amphibian *Parotosuchus* is fully described and its importance to the biostratigraphy of the biozone is discussed. The first occurrence in South Africa of the East African dicynodont genus *Angonisaurus* (Hancox & Rubidge, 1996), as well as the first occurrence of a member of the Family Shansiodontidae are fully documented. A reference stratotype for the upper Burgersdorp Formation is proposed (Appendix 4) and the problem of the biostratigraphic range of *Kannemeyeria* is addressed. The proposed threefold subdivision of the *Cynognathus* Assemblage Zone (Hancox *et al.*, 1995) is expanded upon.

2.2 General Geological Description

The Burgersdorp Formation overlies the Katberg Formation and forms the upper part of the Tarkastad Subgroup (Johnson & Hiller, 1990) (Table 1.1). At present the lower boundary is considered to be conformable with, and partially laterally equivalent to the coarser grained braided river deposits of the Katberg Formation, and is defined as the horizon above which mudstone is more abundant than sandstone (Johnson & Hiller, 1990). The upper boundary is currently held to be conformable with the overlying Molteno Formation (Christie, 1981, 1986), and is defined as an intertongued or sharp transition zone up to 100m thick (Johnson & Hiller, 1990). Geographically the Burgersdorp Formation outcrops as an oval, extending from the town of Queenstown in the south of the basin to past Senekal in the north, and from Matatiele in the east to Burgersdorp in the west (Fig.2.1a).

The type section of the Burgersdorp Formation is situated at Nonensi's Nek (Fig.2.1b), due west of Queenstown in the Eastern Cape (SACS, 1980). This area is considered to be within the middle Burgersdorp (Johnson & Hiller,1990). Along with equally good exposures at McKay's Nek (Fig.2.1b), the area provides the best localities for lateral profiling and channel element analysis in the entire outcrop area. Johnson and Hiller, (1990) also defined a type area, situated to the north, northeast and northwest of Queenstown (Fig.2.1b). A parastratotype for the Formation has recently been proposed at Madeira Mountain (Fig. 2.1b), along with reference sections at Teebus, Hobhouse, Inzicht and Mount Le Seur (Groenewald, 1996).

The Burgersdorp Formation is not structurally complex, having been only slightly deformed into wide open, gently dipping anticlines and synclines. The strata generally dip between 1-4° to the north or northeast. Thick intrusive sills may create slight structural complexities, especially in the southeast of the basin, but more generally the intrusions take the form of dykes which displace strata by only a few metres.

2.2.1 Thickness

The Burgersdorp Formation in the south of the main Karoo Basin forms a thick succession of fines and sandstones which decreases in extent towards the north and west (DuToit, 1918). Due to the disparities in the placement of the upper and lower boundaries of the Formation, the extensive nature of the doleritic intrusions, and the fact that no single locality exists where the Formation is fully preserved, the true thickness of the Burgersdorp Formation is not well constrained.

The Burgersdorp Formation attains its maximum recorded thickness of 1000 ±150m (Johnson, 1976) in a down-faulted block on the east coast of South Africa, northeast of East London (Fig.2.1b). For the type locality, various thicknesses appear in the literature, with Johnson (1976) providing a figure of 950m (±150m), whereas Stavrakis (1980) gives a figure of 900m and Kitching (1977) only 600m. In the vicinity of Matatiele in the Eastern Cape published thicknesses vary between 460m (DuToit, 1929) and 244m (Johnson, 1976). North of the type area (Fig.2.1a), the Formation thins rapidly being only 440m thick south of the town of Aliwal North (Johnson, 1976).

To the north of the town of Aliwal North, the thickness of the Burgersdorp Formation decreases dramatically, with recorded thicknesses for areas in Lesotho ranging from only 12m to 42m (Stockley, 1947). In the north of the basin in the vicinity of the town of Senekal, measured thicknesses range from between 30-40m on the farm Gwharriekop (Senekal district) to between 20-30m on the farm Fraaiuitsicht (Rosendal district). At both of these localities the underlying Katberg Formation, and hence the base of the Burgersdorp Formation, cannot be mapped with any certainty and these figures therefore represent minimum values only.

2.2.2 General lithology

Lithologically the Burgersdorp Formation consists predominantly of mudstones and siltstones (50-80%) with inter-bedded sandstones of various morphologies (20-50%). The mudstones and siltstones tend to weather in negative relief, making the sandstone ledges the more conspicuous lithologies. Sandstone percentage is highly variable within the Burgersdorp Formation and Johnson & Hiller (1990) record values of between 20-30%, whereas Groenewald (1996) gives the range as between 15 and 45%. The range and variation in these figures is partly dependant on whether or not thin sandstones, interbedded within the thick mudstones, are included by the various authors. In the Bamboesberg Mountains, sandstone percentage for the Burgersdorp Formation ranges from between 30%-50%. In general terms, the lower of these two figures is derived by taking only the major sandstones into account whereas the upper figure takes into account inter-bedded sandstones as well.

Sandstones bodies often grade both vertically and laterally into siltstones, and clasts of silt- and mudstone may be dispersed throughout the sandstones. The sandstones of the Burgersdorp Formation are predominantly fine to medium grained and yellowish grey (5Y 7/2), light brownish grey (5Y 6/1), greenish grey (5GR 6/1), light olive grey (5Y 6/1) or greyish red purple (5RP 4/2) in colour. They tend to weather to dusky yellow (5Y 6/4), olive grey (5Y 3/2) or very dusky purple (5 P 4/2), but may also be stained black on their outer surfaces by manganese fluids. Fragmentary reptilian and amphibian fossil remains, as well as casts and imprints of fossil plant stems and leaves are in many places preserved in the sandstones.

The finer fraction consists predominantly of greyish red (5R 4/2-10R 4/2) and greyish red purple mudstones (5RP 4/2), light bluish grey (5B 7/1), greenish grey (5G 6/1) and light olive grey (5Y 5/2) siltstones, and light bluish grey (5B 7/1) fine to very fine-grained sandstones. In most cases, the different lithologies have distinct colouration, however colour change may cross lithological contacts. Well preserved, though non-abundant remains of fossil reptiles and amphibians, as well as coprolites, rhizocretions, root casts and silicified wood are preserved in the finer grained rocks.

Throughout the outcrop area, the Burgersdorp Formation is affected to varying degrees by intrusive dolerites of Jurassic age (SACS, 1980). These intrusives not only displace strata, increasing thicknesses and making correlation difficult, but also tend to alter and discolour the sediment in diverse ways.

2.3 Sedimentology

2.3.1 Lithofacies descriptions

Eleven major lithofacies are identified and described for the Burgersdorp Formation and the various facies codes are modified after Miall's (1977, 1978, 1996) generalised description of fluvial facies. No extra-formational conglomerates are encountered within the Burgersdorp Formation, however intra-formational conglomeratic accumulations are fairly common in the sandstone facies.

2.3.1.1 Sandstone Facies (S)

a) Intraclast conglomerate (So)

This lithofacies was proposed by Rust (1978) and was included in Miall's (1978) lithofacies scheme. Miall (1996) no longer considers it a valid separate category, however, because of its abundance, discrete nature and palaeoenvironmental importance it is retained here as a separate facies.

The facies is characterised by massive to cross-stratified, fine to medium grained sandstone, containing intra-formational clasts. Clasts are predominantly mud- and siltstone, with varying amounts of intra-formational debris including fossil bone, coprolites and fragmented and particulate plant material. This facies is further characterised by the total absence of extra-formational clasts. The nature of the intra-clasts differs significantly throughout the stratigraphy of the Burgersdorp Formation.

In the lowermost reaches of the Burgersdorp Formation this facies occurs as thin individual units interspersed within thick units of fines. The matrix is calcarenitic. The clasts are predominantly well rounded clay pebbles, but also include large amounts of reworked pedogenic carbonate, septarian nodules, invertebrate burrow casts and tetrapod fossil fragments, predominantly teeth and fragmentary cranial remains which show evidence of local reworking (Fig.2.2). The average size of the fine clasts is less than 5cm. This facies is thought to represent patches of re-worked floodplain material which accumulated in shallow depressions by sheetwash (Butler, 1958).

In the upper parts of the Burgersdorp Formation this facies occurs primarily at the base of thick sandstone units and has a non-calcareous matrix. The intra-clasts are predominantly well rounded ellipsoidal to discoidal mud- and siltstone clasts. Less commonly fossil bone may also be preserved (Fig.2.3). The average size range is between 1-30cm, although a large clast of ± 1.5m is preserved near the base of

Bushmanshoek Pass. Clasts may be imbricated, although more normally they occur lying flat on the bedding plain. Crude horizontal stratification of the clasts may also be developed. Facies Sc_i in the upper Burgersdorp is believed to represent the accumulation of eroded cut-bank material on channel floors (thalweg scours) and point bars following flood activity, as documented in the lower part of the Beaufort Group by Turner (1981b). Thin, convex-up mudstone flakes are considered to have formed as mud-curls in dried out pools or channel depressions. Large (>1.0m) clasts are interpreted as cut-bank collapse of cohesive mud that was not transported any great distance.

Trough cross-stratified intraclast conglomerate (Sc_{it}) forms a sub-facies of Sc_i with very similar characteristics, but occurring exclusively associated with facies St_l. Individual clasts occur at the base of the set as well as interspersed throughout on foreset laminae. These sets form discontinuous lenses between 40-80cm thick, with basal lag accumulations between 5-10cm thick. The basal erosional surface is believed to represent upper flow regime scour activity in front of migrating dunes. Similar lag deposits are known from the Lower Beaufort (Stear, 1978, 1980a) and such accumulations are thought to have been deposited under upper flow regime conditions, prior to trough-fill in the upper part of the lower flow regime.

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

Stavrakis (1980) notes that within the Burgersdorp Formation trough cross-stratification may be highly variable, with nearly all of the types recognised by Allen (1963) represented in the lower third of the Formation.

In the upper two-thirds of the Formation facies St (Fig.2.4) tends to occur as solitary or grouped sets of trough cross-strata. Sets range in thickness from 5cm to ±1m, but are more usually in the range of 30-50cm. They may be further subdivided into large (St_l) and small scale units (St_s). Individual large troughs may attain widths of 1-2m while the smaller units are rarely wider than 50cm and between 5-30cm thick [illegible] to be fine to medium grained, but where large sets grade into smaller sets there is an accompanying decrease in grainsize. Foreset dip angle ranges between 8-18°, being generally higher in the finer grained units. Occasional single scoops of *theta* and *eta* types (Allen, 1963) were noted near the top of horizontally stratified and massive sets, with erosive bases into the underlying facies. Very large scale units of facies St (1-4m thick and 2-4m wide), such as occur in the underlying Katberg Formation, are unknown in the Burgersdorp Formation.

Trough cross-stratification is commonly accepted to represent dune or megaripple migration during the transition from upper to lower flow regime conditions (Allen, 1963, 1970, 1982, 1984; Harms *et al.*, 1975 Ashley, 1990). St_s probably represents small, three-dimensional, in channel dunes or large ripples deposited under lower flow regime conditions during waning flow (Godin, 1991). Both *eta* and *theta* types are interpreted as scour and fill structures and should possibly be included above with facies Se_s.

c) Planar cross-stratified (Sp)

Planar cross-stratified sandstones (Fig.2.5) are not common in the Burgersdorp Formation. Where present this facies normally occurs as thin solitary sets (Fig.2.5) and more rarely as co-sets of tabular strata. Facies Sp is in many instances associated with facies Sh in the upper part of sandstone bodies. Set sizes range from 8-20 cm. Foreset dips range between 10-25°. Grainsizes fall in the fine sand range. In most cases the sets are of the *alpha* and *gamma* (Allen, 1963) type. Palaeocurrents obtained from facies Sp are often oblique to perpendicular to those obtained from facies St or Sh, and parallel to the dip of lateral accretion surfaces. The basal surface to the sets are usually horizontal, sharp, non-erosional surfaces and more rarely, irregular erosion surfaces.

Planar cross-stratification is the internal structure to transverse bars (Smith, 1971, 1972, 1974), linguoid and laterally accreted point bars and large sandwaves

(Harms *et al.*, 1975). *Alpha* and *gamma* types are documented as forming by the avalanching of grains down the front of transverse bars or the migration of straight crested sandwaves on point bar surfaces (Harms *et al.*, 1975).

d) Massive to semi massive (Sm)

Locally developed, mainly structureless sandstones have been noted in a variety of fluvial and fluvio glacial deposits (Jones & Rust, 1983; Turner & Monro, 1987; Turner & Martin, 1995). This facies has been largely ignored in the past and Miall (1977, 1978) does not include a facies abbreviation for such deposits. This facies code therefore follows that of Conaghan & Jones (1975) and Turner & Martin (1995). Turner & Martin (1995) recognise three types of massive sands, these being massive structureless, massive partially structured and massive structured.

In the Burgersdorp Formation, massive sandstones (Fig.2.6) are often closely associated with, and grade vertically and laterally into, facies St and Sh. They take the form of seemingly massive sandstones with tabular geometries that may preserve faint diffuse lamination. Mudstone and siltstone clasts may be randomly distributed throughout. Set sizes range from 20-200cm. The basal contact is usually sharp, but may also be gradational.

This facies would fall within the partially structured massive sands of Turner & Martin (1995), which they interpret as having formed by bank collapse or hyperconcentrated streamflow and deposition in the presence of high sediment rain. Conaghan and Jones (1975) attribute the formation of similar facies to deposition from highly concentrated, sediment laden currents under transitional or upper flow regime conditions at peak flood. McCarthy (*pers.comm.*) considers the lack of sedimentary structure in such deposits to be due to the obliteration of primary structure by bioturbation or hydraulic creep. The destruction of primary sedimentary structure may also be brought about by the liquefaction of unconsolidated sand (Reddering & Rust, 1994). Turner & Martin (1995) also propose groundwater charging as a post-depositional mechanism for the obliteration of structure.

Due to the lack of systematic study of these sandstones, their true origin remains enigmatic, with certain sedimentologists reluctant to accept them as a distinct and separate fluvial facies. The vertical and lateral gradation of facies Sm into Sh or St in the Burgersdorp Formation is most probably the result of partial post-depositional alteration of sedimentary structure, either by liquifaction or hydraulic creep.

e) Horizontally stratified (Sh)

Horizontally to sub-horizontal, parallel stratified sandstones (Fig.2.7) are the most abundant sandstone facies in the Burgersdorp Formation. They occur in sets ranging from 20cm to 1.5m thick, with individual beds ranging from 20 to 70cm, but seldom being in excess of 50cm. This facies is predominantly formed in fine-medium grained sandstones, which are often micaceous. Parting lineation (Fig.2.8) associated with the uppermost surface of individual sets is the most common sedimentary structure in the Burgersdorp Formation.

Three types of horizontally stratified sandstone are recognised, based on where in a sequence they occur, these being basal (Sh_b); intermediate (Sh_i) and top (Sh_t) sets. Three different conditions of sedimentation are implied for their formation.

Sh_b : Forms the basal facies to numerous sequences and may be overlain by similar facies to form stacked sets of Sh_b or by facies St_i or Sp. This facies tends to be predominantly fine-medium grained and commonly display parting lineation on the upper surface of individual sets. These sets correspond to the upper flat beds (UFb) of Stavrakis (1980) and represent upper flow regime deposits with maximum water depth.

Sh_i : Occur throughout sandstone sequences and as individual sets interspersed in thick mudstone units. Entire, thick tabular sandstone units may be internally structured by this sub-facies. Such deposits, sometimes up to several metres thick are known to be deposited during a single flood event (McKee *et al.* 1967). This facies is common as flood derived deposits in ephemeral streams or systems with strong seasonal fluctuations. They are thought to be produced as sheet deposits by shallow high velocity (upper flow regime) currents, however this facies is also known to be produced by low velocity flow in sand greater than 0.6mm (McBride *et al.*, 1975).

Sh. : This facies occurs at the tops of individual sandstone units and is generally fine grained, varve-like and laterally restricted. Facies Sh_l may grade laterally into facies St or Sr. This facies equates to the lower flat beds (Lfb) of Stavrakis (1980) and is thought to be a lower flow regime deposit in response to increased friction and decreased flow in shallow water. This kind of low angle parallel lamination is also documented by bedform migration in flume studies under lower flow regime conditions (McBride *et al.*, 1975).

Facies Sh is known to be formed under both lower and upper flow regimes (Harms *et al.*, 1975) and the generally accepted opinion at present (Miall, 1977, 1978, 1996) is that facies Sh is indicative of current conditions typical of the transition from lower to upper flow regimes in the case of Sh_{ll} and upper flow regime in the case of Sh_0. Unlike the situation in the underlying Katberg Formation, upper flow regime (Sh_0 & Sh_l) horizontally stratified sandstones in the Burgersdorp Formation rarely preserve discrete heavy mineral laminae.

f) Ripple cross-stratified and laminated (Sr)

Facies Sr (Fig.2.9) is restricted to fine to very fine-grained sandstones in which definite ripple topography is identifiable. Both ripple cross-stratification (bedset>1.0cm) and cross-laminated (individual laminae<1.0cm) occur within thick sandstone units and interspersed within mudstone and siltstone sequences. Sets range from 30-50cm and may have sharp bases or may be gradational from underlying St_l or Sh_l. Ripples are mainly asymmetric and slightly sinuous to crescentic in form (Fig.2.10). Amplitudes range from 0.5-2.0cm, with the norm