An Explanation of the Geological Map 1:10 000 of the Namibian borderland along the Orange River at Zwartbas - Warmbad District - Karas Region - Namibia

Erläuterungen zur geologischen Karte 1:10 000 des namibischen Grenzgebiets am
Oranje Fluß bei Zwartbas - Warmbad District - Karas Region - Namibia

Diplomkartierung

80 Seiten, 61 Abbildungen, 1 Tabelle, 1 Geologische Karte

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Abstract. The locality of Zwartbas is situated at the border of Namibia and South Africa about 15 km west of Noordoewer. The mapped area is confined by the Tandjieskoppe Mountains in the north and the Orange River in the south. Outcropping rocks are predominantly sediments of the Nama Group and of the Karoo Supergroup. During the compilation of this paper doubts arose about the correct classification of the Nama rocks as it is found in literature. Since no certain clues were found to revise the classification of the Nama rocks, the original classification remains still valid. Thus the Kuibis and Schwarzrand Subgroup constitute the Nama succession and date it to Vendian age. A glacial unconformity represents a hiatus for about 260 Ma. This is covered by sediments of the Karoo Supergroup. Late Carboniferous and early Permian glacial deposits of diamictitic shale of the Dwyka and shales of the Ecca Group overlie the unconformity. The shales of the Dwyka Group contain fossiliferous units and volcanic ash-layers. A sill of the Jurassic Tandjiesberg Dolerite Complex (also Karoo Supergroup) intruded rocks at the Dwyka-Ecca-boundary. Finally fluvial and aeolian deposits and calcretes of the Cretaceous to Tertiary Kalahari Group and recent depositionary events cover the older rocks occasionally.

Zusammenfassung. Die Lokalität Zwartbas liegt an der namibisch-südafrikanischen Grenze, etwa 15 km westlich von Noordoewer. Das Kartiergebiet wird durch die Tandjiesberge im Norden und den Oranje Fluß im Süden begrenzt. Die anstehenden Gesteine bestehen hauptsächlich aus Sedimenten der Nama Gruppe und der Karoo Supergruppe. Während der Erarbeitung dieser Abhandlung entstanden Zweifel an der Klassifikation der Nama Gesteine, so wie sie in der Literatur zu finden ist. Da keine sicheren Hinweise zur Revision der Klassifikation der Nama Gesteine gefunden wurden, bleibt die ursprünglich Klassifikation jedoch gültig. Die Kuibis und Schwarzrand Untergruppe bilden also die Nama Abfolge und datieren sie ins Vendian. Eine glaziale Diskontinuität repräsentiert einen Hiatus von etwa 260 Mio Jahren. Sie wird überlagert von Sedimenten der Karoo Supergruppe. Spät-karbone und früh-permische glaziale Ablagerungen von diamiktitischen Tonsteinen der Dwyka Gruppe und Tonsteine der Ecca Gruppe liegen über dieser Diskontinuität. Die Sedimente der Dwyka Gruppe sind fossilführend und enthalten Tufflagen. Ein Sill des jurassischen Tandjiesberg Dolerit Komplex (auch Karoo Supergruppe) intrudierte in die Gesteine an der Dwyka-Ecca Grenze. Schließlich bedecken lokal fluviatile und äolische Ablagerungen und Kalkkrusten der kretazischen und tertiären Kalahari Gruppe und jüngerer Ablagerungsereignisse die älteren Gesteine.

Acknowledgements

I thank many people who have contributed to the completion of this mapreport. It stands for the beginning of the end of my undergraduate study. And it comprises the base of my following diploma thesis, which concludes the practical pathway for my graduation.

In the first place I like to mention my parents who supported all my plans, no matter where my ideas took me and what help I ever needed. Without their financial support I couldn’t have done the job.

Volker Lorenz, my supervisor, is thanked for the good cooperation in the field, the introduction to his helpful friends in the working area and the provision of a 'Graduierten-Kolleg'-car.

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Last but not least I want to mention Carlos Peres, his family and the whole team at Provenance Camp. I am obliged to Carlos and Malcom Eisele, who provided me with lodging and food. They and all the river-guides, especially Trevallyan Cumming, are thanked for the company at the long cold winter evenings, when they made my stay in the field remarkably comfortable.

Contents

1 Introduction

1.1 Geographical overview

Namibia (former South West Africa S.W.A.) is situated in southern Africa, bordering the South Atlantic Ocean, between Angola in the north, South Africa in the south and Zambia and Botswana in the east. The country covers 825 418 km^2, at an estimated population of 1 800 000 people (CIA, 1998).

Mostly high plateaus form the interior of Namibia. Mountainous places reach up to 2 606 m (Königstein). The Namib Desert is situated along the coast, while a mountainous and undulating land passes eastwards into the Kalahari Desert. A big escarpment, a northward extension of the South African Great Escarpment, constitutes a N-S trending water divide. In contrast to the barren land at the coast and in the south, the north and especially the Northeast is fertile. There is the highest density of population.

1.1.1 Location and physiography of the study area

The settlement and Namibian border post of Noordoewer is located in the Karasburg District (Karas Region), which is the most south-easterly administrative district of Namibia. Situated along the northern banks of the deeply incised Orange River, Noordoewer is tucked away in the surrounding highlands of the Tandjieskoppe Mountains west of the National Road B1. At the opposite side of the river Vioolsdrif acts as the South African border post. The South African border land west of the Orange River is formed by an undulating and mountainous country of the northern Namaqualand south of and the mountainous Richtersveld. The study area is located about 10 km west of Noordoewer. The area south of the road D 212 from Noordoewer to Rosh Pinah is private property and belongs to different farms, whereas the area north of the road is state land. This work focuses on an area marked off by the 17°35.332' degree of longitude in the east and latitude 17°32.263'. The northern boundary comprises the 28°38.925' th parallel. The Orange River restricts it in the south. Although the village of 'Zwartbas' or 'Swartbas' lies on the South African side of the river, the name was used from several authors (e. g. McLachlan and Anderson, 1973; Pickford, 1995) in order to note the locality on the South African side.

1.1.2 Climate, flora and fauna in the vicinity of Noordoewer

Climate

Official climate data available for southern Namibia are provided by stations more than 100 km away from the investigated area. Any specification is just an approximation. To understand the mechanism how weather forms in southern Africa, the main mechanisms are outlined in the following (cf. Weischet, 1977).

Two seasonal climatic situations have to be distinguished. Winter and summer develop two different circulation patterns and temperature distributions. The basic pattern comprises a high-pressure area in the South Atlantic as well as in the southern Indic. They constitute an east-west frame, which is limited in the south by the cyclonal west wind drift. This drift zone yields the incoming of cold air fed by the Antarctic low pressure trench. Cyclones migrate easterly in the westwind drift where they happen to come onto the Cape Region. In the summer season the west wind zone passes by the Cape far off the coast half way to Antarctica. High radiation over the continent supports the origin of a low-pressure area, which attracts the Monsoon and Passat Winds from the Indic. They bring moisture and rainfall to North and Central Namibia. Intensive thundery showers are common events at the concurrence of tropical air masses. Southern Namibia is hardly influenced and gets regularly extensive dry spells.

When the season changes to winter global circulation shifts the Inner Tropical Convergence (ITC) northwards. According to this situation the cyclonal west wind drift in the southern hemisphere approaches the African continent and affects the weather decisively. As cyclones sometimes strike in hardly weakened, fringes come far into the hinterland and extend north up to the Orange River Valley. Nevertheless they normally just pass by some 10's of km in the south and spare the area with strong cold winds and rain.

The entire Namibian coast line has got its own climate. Air from the Atlantic carries insignificant moisture, because the cold Benguela Current, that is fed by the cold waters of Antarctica, can not provide any evaporation potential to moisten the air at the coast. This results in a general dispersal of clouds on the way inland. The only precipitation there is persisting fog and sporadic drizzle. The Namib Desert is a classic Tropic Desert caused by the subtropic high pressure zone. Therefrom results a continuous hot and arid situation in southern Namibia.

According to different climate classifications, the discussed climate is determined by Köppen (1936) as a BWh climate (B: Arid climate; W: Desert; h: dry-hot – annual average temperature over 18°C). Creutzberg classifies it as Persisting Dry Subtropical Climate, which is almost similar to Wißmann’s II W Climate: Subtropical Desert Climate (Blüthgen, 1964). The CIA (1998) describes the climate with following key words: "desert; hot, dry; rainfall sparse and erratic" and outlines "prolonged periods of drought" as threatening natural hazards.

Flora and Fauna

Aridity and temperature contrast give only highly specialised and adapted animals and plants the chance to settle. The slopes off the river are barren, only in some gorges, where joints and sediments can provide sporadically water some time after infrequent rainfall, small bushes establish. Cactiform plants and succulent trees (*Euphorbia*, *Aloe*) such as the quiver tree can be found rarely, but mostly in small societies, which hide in boulder-scattered slopes of weathered dolerite. Some rainfall let the slopes cover with individual blades of grass. But even this bit serves as grazing grounds for goats. They took the turn from springboks, gemsboks and other antelopes, which once populated the plains and mountains (from: personal conversation with locals). They were driven away or hunted to extinction only 50 years ago the same way as leopards and other beasts of prey. Hippos already disappeared from the river at the beginning of our century. Small mammals are left, such the as different species of mice, the rock dassie, further scorpions, snakes and a wide range of insects. The original fauna, however, has therefore changed under human impact. The controlled river and the steady water flow attracts birds as ever (Cumming, T., 1998 personal comm.). They live in the woods and glades, which line the river banks. Even African fish eagle, different species of herons, king fishers, cormorants and ibis live by the river the whole year long, which serves as an oasis in the desert.

1.1.3 Land Use in the Noordoewer vicinity

Aridity limits agricultural exploitation. Crop farming demands the installation of expensive irrigation schemes. They allow cultivation of the fertile floodplains on the banks of the Orange River with vegetables and fruits. The river, which is regulated by locks further upstream provides water for this purpose as well as for drinking.

The second leg of the local economy - important for the needy people - is goat farming. Farmers graze their herds on the state land at the feet of the Tandjieskoppe Mountain, where they can find hardly enough for feeding.

An other economic factor, which has only established in the past few years, is tourism. Growing importance of tourism, especially adventure holidays, have resulted in a demand for commercial raft and canoe trips on the Orange River. Several businesses have already settled along the river.

1.2 Problem definition

Some aims were pursued by the field work.

- Logging of the lithological succession and the stratigraphical classification
- Mapping of the structural situation
- Composition of a geological map 1:10 000
- Taking samples from the shale and tuff horizons of the Dwyka Group

Samples were taken in order to be analysed and discussed in my subsequent Diploma thesis, in which the deposits of the Dwyka Group will be subdivided by a detailed tephrostratigraphy. The depositional history will also be interpreted.

1.3 Condition of exposure and mapping method

Condition of exposure

The lack of vegetation reveals excellent outcrops all over the study area. River cuts and steep slopes and cliffs of outliers and the escarpment north of the road D 212 enabled the logging of a detailed stratigraphy. Interformational boundaries were easy to recognize, especially as the lithological variation is expressed in the relief. Since the main strata comprised of shales of the Dwyka and Ecca Groups are very fissile, large areas are covered with debris. Thus scree-deposits cover the slightly inclining slopes at the bottom of the escarpment and the outliers. More problems arose by tracing the tuff horizons of the Dwyka Group and to compose a continuous tephrostratigraphy. The best preserved rocks are exposed directly at the Orange River, whose cliffs provided the majority of the logged data and samples.

Designated localities and the application of the term 'river'

Important localities were localized by GPS-coorinates and were sometimes designated by particular names to simplify the localization (Table 1, Fig. 1): The sharp bend of the Orange River, where the Nama-Dwyka-boundary joins the river, was named Fossils Bend (vertex: S 28°41.432'/E 017°33.256'). The cliff further upstream at the head of the rapids is called Jet Cliff (rapids: S 28°41.191'/E 017°33.620'). The wide valley, which meets the river 30 m eastwards is called Hare Valley at its lower course, and Owl Gorge at the upper course, where the gorge emerges the dolerite cliff. The next river course to the east cut off the cliff named Goats Cliff (centre: S 28°40.490'/E 017°34.223'), which lies at the mouth of Centipede Gorge (centre: S 28°40.891'/E 017°34.272'). In the west a wide valley lies between the dolerite plateau and the last dolerite capped outliers. It was regarded as Puff Adder Valley (head: S 28°39.687'/ E 017°32.406'). At S 28°40.971'/E 017°32.649' a dried-up waterfall was stated as another orientation guide (Waterfall in the northwestern corner of the Nama Group outcrops). The gorge which leads from the road D 212 south-eastward and joins the gully running down from the Waterfall was called the Raven Gorge (head: S 28°40.927'/E 017°32.380')

During the compilation of this paper the problem raised that no continuously flowing river, except the Orange River, is present in the study area. Nevertheless courses of such ephemeral rivers are important topographical marker and moreover represent the best outcrops, why they were often used to describe localities. Therefore the term 'river' also applies to dry river courses in the following discourse.

Outcrop ID / given names	Description	Coordinates
# 1 Fossil Bend	Banks and cliffs	S 28°41.432'/E 017°33.256'
# 2 Center of Hare Valley	River cut	S 28°40.682'/E 017°33.763'
# 3 Centipede Gorge	Cliffs of a gorge	S 28°40.891'/E 017°34.272'
# 4	Pass on a mountain ridge	S 28°40.277'/E 017°34.516'
# 5 Centre of Goats Cliff	Under-cut slope	S 28°40.490'/E 017°34.223'
# 6 Duifie Gorge	Incised gorge	S 28°40.628'/E 017°35.023'
# 7 Waterfall	Dried-up waterfall and subsequent river course	S 28°40.971'/E 017°32.649'
# 8	Slightly incised river bed	S 28°41.277'/E 017°32.952'
# 9	Gently inclined slope passing into a vertical wall	S 28°41.573'/E 017°32.771'
# 10 Head of Raven Gorge	River bed	S 28°40.927'/E 017°32.380'
# 11 Jet Cliff	Cliff and land indentation in the Orange River	S 28°41.191'/E 017°33.620'
# 12 Owl Gorge	Walls of a dried-up broad gorge	S 28°39.945'/E 017°33.574'
# 13	Pass on a mountain ridge	S 28°40.166'/E 017°31.851'
# 14	Wall of a river course	S 28°40.349'/E 017°34.825'
# 15	River Cut	S 28°39.304'/E 017°33.664'
# 16	Plain in the southwest of Fossil Bend	S 28°41.506'/E 017°33.113'
# 17 Head of Puff Adder Valley	Hill with a view down the valley	S 28°32.263'/E 017°39.434'
# 18 Provenance Camp	Base camp for canoe trips on the Orange River	S 28°41.174'/E 017°33.501'
# 19 Junction at the ostrich farm	The road to Nuwe Modderdrif meets the road D 212	S 28°41.103'/E 017°33.028'
# 20 Bushman engravings	Wind scoured limestone floors are scattered with engravings	S 28°39.964'/E 017°29.806'

Table 1
Description and localization of the investigated outcrops and typical localities. Important localities and their contiguous vicinity, such as extensive walls or cliffs, were designated with particular names.

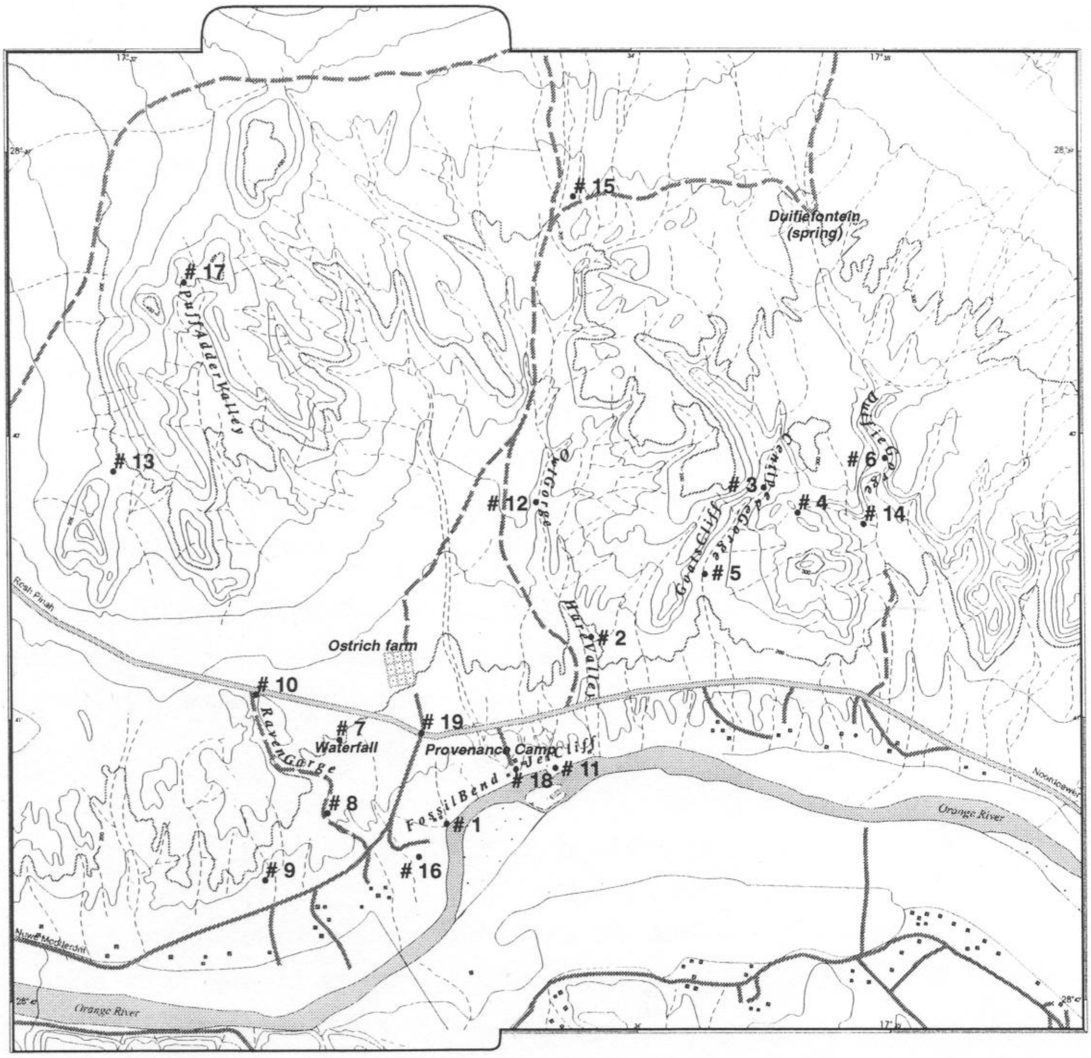


Figure 1
The map gives an overview of the outcrop localities. Abbreviations refer to the Outcrop ID constituted in Table 1.

The EACS (Estimated Average Clast Size) and the CPD (Clast Packing Density)

The mapped and logged succession contains several sections of diamictite. Two terms are introduced to differentiate more accurate the texture and structure of the diamictitic deposits in reference to Visser (1986): The Estimated Average Clast Size (EACS) and the Clast Packing Density (CPD). The EACS is a simple estimate of the average clast size. The CPD is determined by measuring clast cross sections in randomly selected 1 m^2 of outcrop area.

Classification of the tuff beds and tuff horizons

About 65 distinct tuff beds are interbedded in the lower 95 m of the Dwyka succession. During the logging several tuff beds have been combined to tuff groups, which are classified by **Latin numbers**. The classification primarily combines individual tuff beds, which are close together. A second criterion was the particular thickness of the layers. Thick ash layers were preferably ascribed to a particular group of ash layers, while thinner ash layers in the neighbourhood were included into this group. Particular tuff beds are marked by an attached **Latin letter**. Both countings apply successively upwards. This results in a classification code made up at least by a Latin number and occasionally a Latin letter. Thus, for example, the forth tuff bed in the third tuff group is marked by the abbreviation **III d**. Eventually 38 tuff groups have been established to lay the foundation for the development of a tephrostratigraphical characterisation of the location in the subsequent diploma thesis.

2 Geological Setting

2.1 Geology of southern Namibia

The stratigraphy of southern Namibia is composed of five main periods of lithigenic activity (SACS, 1980):

(**A**) Mainly calc-alkaline basic, intermediate and acid volcanic rocks with only few sedimentary rocks of Vaalian to Lower Mokolian age (± 2100 to ±1500 Ma) constitute the Orange River Group along the southern border. The calc-alkaline, subvolcanic Vioolsdrif Intrusive Suite extensively intruded the Orange River Group with granodiorite and porphyric adamellite and minor hornblendites, diorites and various granites.

(**B**) Pre-tectonic gneisses and metasedimentary rocks, charnockitic, gabbroic and serpentinic rocks, syn-tectonic granitic rocks, and late to post-tectonic granitic rocks resemble a broad four-fold subdivision of the Namaqualand Metamorphic Complex of late Mokolian age (up to ±900 Ma).

(**C**) Rocks of the Early Namibian Richtersveld Granite/Syenite Complex are only found in patches at the border to South Africa, but shall be mentioned here as a matter of completeness. The Gariep Complex is located along the southwestern coast of the country and consists of arenites, carbonates, pelites, ignimbrites and basic lavas, which are mainly metamorphosed into chlorite schist. It represents the southern part of the Pan-African mobile belt, which was formed during the Damaran orogenic phase (±900 to ±450Ma), when the supercontinent Gondwana formed. The shallow marine Nama Group at the eastern margin of the complex is made up of quartzite, sandstone, shale and limestone sequences (up to 500Ma). The clastic material was derived from the Gariep Complex and in smaller amounts from the eastern Kalahari Craton. The basin is located nowadays in the south-eastern part of the country. Intrusive granites, syenites, botonites, alnoitic tuffisite and carbonatite are commonly scattered in the area.

(**D**) The Karoo sequence (from ±300Ma) in the southern part of the country is associated with the disintegration of Gondwana, the opening of the South Atlantic and rift tendencies in east Africa brought a phase of extensional conditions. Large areas subsided and caused deposition eventually all over Gondwana. Basal glaciogenic rocks of the Dwyka Group are overlain by shale, sandstone, mudstone and coal-bearing carboniferous shale of the overlying Ecca Group. Extensive dolerite sills and swarms of dykes are of Jurassic age. Intra- and post-Karoo intrusions made up of syenite, foyaite and carbonatite (e.g. Dikker Willem Carbonatite Complex west of Aus) are found at the coast south of Lüderitz. Cretaceous and related volcanic rocks turn up in the very Southeast.

(**E**) Tertiary to recent carbonate-cemented clastic sediments and calcrete are sparsely found in the south, but most of the westward-flowing rivers have a fill of this age. Some of the fluviatile sands and conglomerates are calcrete-cemented. Most recent wind-blown sands are predominantly situated at the coast.

2.2 Focus on the main strata of the study area

Deposits of the Precambrian/Cambrian Nama Group and the Carboniferous-Permian to early Jurassic Karoo Supergroup cover large parts of southern Africa. Namibia, especially the south, comprises well-developed successions. The extension of the Nama Group is limited on the Kalahari Craton, but the Dwyka Group spreads over most parts of Gondwana (Grill, 1997). At Zwartbas both depositional sequences are exposed (Fig. 2). The outcropping Nama rocks were deposited in the Nama Basin, while Karoo rocks fill the Warmbad Basin and Karasburg Basin respectively. The Karoo deposits of the

Warmbad Basin are confined by the Orange River in the southwest. The Warmbad Basin was originally connected with both the South Kalahari or accordingly Aranos Basin in the north and the Great Karoo Basin in the south, but became isolated by warping and erosion (Martin, 1981a).

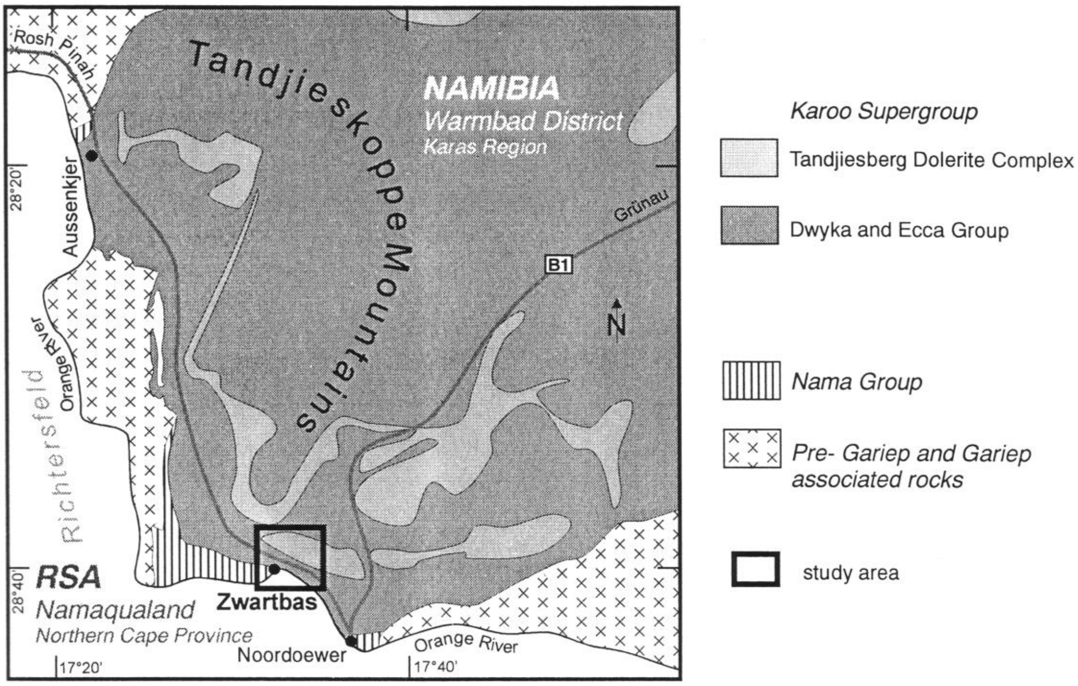


Figure 2
The map gives a regional overview of the geology in the Zwartbas vicinity. The Karoo is confined by plutonic, metamorphic and volcanic complexes of Pre-Gariep and Gariep Belt rocks. Small patches of Nama are preserved in-between them. (After Haughton and Frommurze, 1936; Gresse and Scheepers, 1993)

A small indentation of Nama deposits reaches to the Orange at Zwartbas and Aussenkjer, confined by plutonic, metamorphic and volcanic complexes of Pre-Gariep and Gariep associated rocks (cf. 2.1 – (**A**), (**B**) and (**C**)) in the Southeast and west. In the Southwest and South the Karoo onlaps on Nama rocks (cf. 2.1 – (**C**)). Essentially the Dwyka and Ecca Groups comprise together with the Jurassic Tandjiesberg Sills the Karoo Supergroup (cf. 2.1 – (**D**)). Due to a lower weatherability, the latter give rise to isolated hills and ridges, standing up from the general plain. Debris of younger erosional phases lie in the newly incised valleys (cf. 2.1 – (**E**).

The Nama Group

Nama Group sediments have been deposited in a peripheral foreland basin between the Kalahari Craton in the east and the contemporaneous Damara and Gariep mobile belts in the North and Southwest (Fig. 3). They have been the southern branches of the Pan-African-Brasiliano orogen (~650-450 Ma) during the construction of the Gondwana supercontinent, when the Congo and Kalahari Craton collided with the Rio de la Plata Craton (Gresse, 1995; Gresse et al., 1996). This heights provided the material to fill the basin, which constitutes a late- and post-orogenic foreland basin formed on the southern African plate, which was subducted underneath the Rio del la Plata Craton. The Nama Basin covers an area of the size of 900 km by 300 km and contains deposits with a maximum thickness of 2.5 km. Two ridges of the flexed Kalahari Craton, the Osis Ridge in the north and the Kamieskroon Ridge in the south, separates the marginal onlapping sediments of the Nama Group in three sub-basins. The northern Zaris and central Witputs Basin is filled with sediments of the Nama Group, the southern Vanrhynsdorp Basin comprises the Vanrhynsdorp Group (Gresse et al., 1996). The stratigraphy in all three basins is suggested to be genetically related to orogenesis, flexural bulging and sea-level changes in the basins' history (Gresse and Scheepers, 1993). Foredeep flysch and ramp carbonates pass upwards into reddish conglomeratic molasses derived from the emerging mountain belts at the western and northern orogenic margins.

Folding and thrusting during the Damara and Gariep orogens only affected the northwestern and southwestern fringes of the Nama depository (Tankard et al., 1982). Nowadays localised exposures are observed in Namibia and the Namaqualand (R.S.A), often overlain by Karoo or younger sediments.

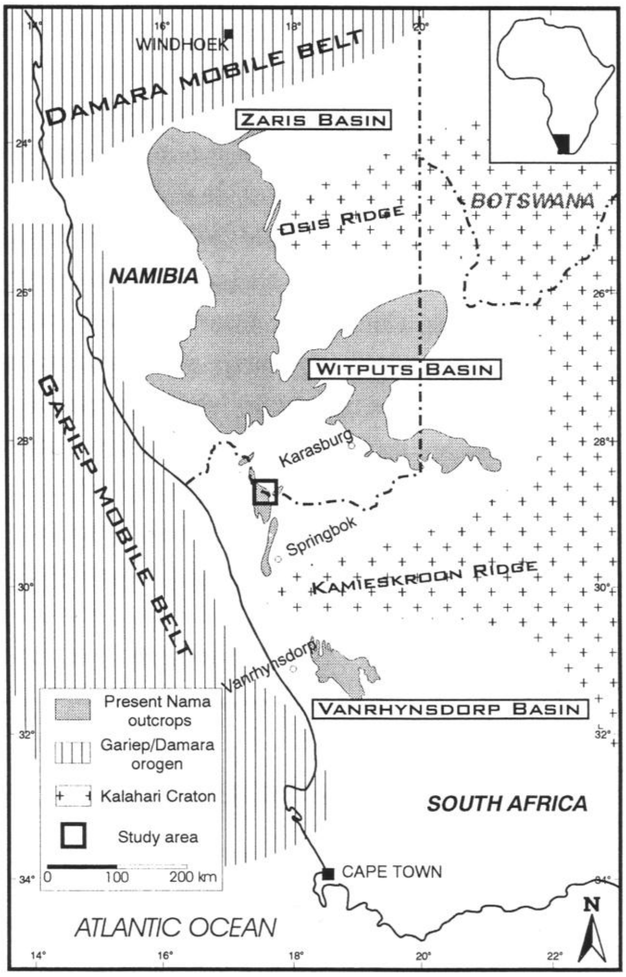


Figure 3
This map displays the present Nama outcrops preserved in particular basins between the source areas of the orogenic belts in the north and west and the craton in the east. (Composed from (Gresse, 1995; Gresse et al., 1996))

The term "Nama" was introduced by Schenck, 1893, after he shortened the former term "Namaqua-Schiefer, -Sandstein und -Kalkstein" he already used 1885 (in SACS, 1980). From then correlation efforts and opposing discussions documented a complicated exploration of the Nama Group. In the 80's and 90's mainly Germs and Gresse combined ideas and established a comprehensive image (Germs, 1971; Germs, 1983; Germs and Gresse, 1991;). Recent studies concentrate on age determinations and correlation with equivalent deposits in South America (Gresse et al., 1996; Meert et al., 1997; Saylor et al., 1998).

The Karoo Supergroup

Karoo Supergroup deposits are distributed over large areas of Gondwana. Approximately 300.000 km^2 are presently exposed only in southern Africa (Smith et al., 1993). This mass fills several depositional basins in southern Africa, the largest and name-giving is the Main Karoo Basin in South Africa (Fig. 4). Namibia’s Karoo deposits are more spatially distributed and often covered by post-Karoo deposits. The deposits resemble those in the eastern neighbouring countries Botswana and Zimbabwe. Initial depressions were formed by the ice load during the Dwyka glaciation periods in the early Permian-Carboniferous. Further basin development was controlled by the tectonic activity of the Cape Fold Belt at the southern craton margin, and eventually influenced by the East African Rift System at the northern vicinity boundary (Tankard et al., 1982). Volcanism on active plate margins originated interbedded ash-layers, from which reliable chronological information was derived. Most extensive surface outcrops and most complete stratigraphic records provide the back-arc/foreland "Main Karoo Basin" in South Africa. Furthermore most detailed studies have been applied to it due to its economical importance.

The term "Karoo" was first introduced by Bain in 1856 (in SACS, 1980), who described "Reptiliferous series" excluding the basal tillites of the modern Dwyka-Group. In 1867 Jones (in SACS, 1980) included the basal conglomerate in the Ecca beds and 1875 Dunn (in SACS, 1980) introduced the name Dwyka Conglomerate. Only a few years later in 1888 Schenk (in SACS, 1980) took it out of the Ecca beds again, until in 1903 it constituted a subdivision in Roger's newly established "Karoo System" (Dwyka, Ecca, Beaufort and Stromberg), which is still in use (in SACS, 1980). In southern Namibia the Karoo has been studied since the beginning of the century (Haughton and Frommurze, 1928; Haughton and Frommurze, 1936). Later studies mainly by Martin and Wilczewsky (1970), McLachlan and Anderson (1973), Schreuder and Genis (1974), Martin (1981a and 1981b), Visser (1983), Pickford (1995) and Grill (1997) concentrated on the glaciogenic part, while Kingsley (1985; 1990) investigated the non-glacial Ecca Group. Recent studies in northern Namibia made an effort to correlate the strata with the equivalents in South America and South Africa (Ledendecker, 1992). Stollhofen (1999) used the Karoo sediments of Namibia to develop a model of former intracontinental rifting on a passive continental margin of today. Most recent studies of the Dwyka and Ecca Groups in the Huab and Waterberg areas were carried out by Wanke et al. (1999) and Holzförster and Stollhofen (1999). Grill (1997) worked on aspects of sedimentary facies and sequence stratigraphy of the Karoo in the Aranos Basin. Bangert et al. (1998 and 1999b) used ash-layers to establish a detailed tephrostratigraphy in the Ganigobis Shale Member of the Dwyka Group in the Aranos Basin and juvenile zircons for age determination. Furthermore he works on a correlation of the Ganigobis Shale Member and the basal Dwyka Group at Zwartbas (Bangert et al., 1999a).

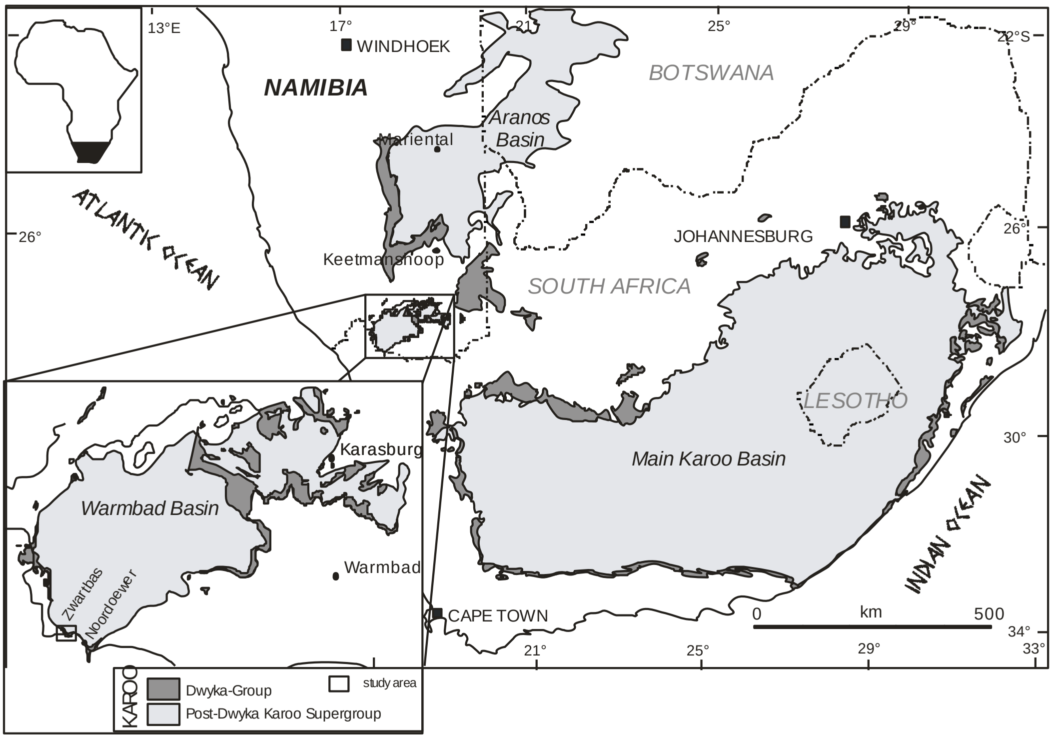


Figure 4
The map shows the exposed Dwyka in southern Africa. The pop-up window zooms in the Warmbad Basin.
(Composed from Martin (1981a), Visser (1983) and Bangert et al. (1998))

The Kalahari Group and recent deposits

Post-Karoo deposits of the Cretaceous-Cainozoic Kalahari Group are represented by conglomerates, limestone/marls, pan deposits, calcrete and sand (Stengel and Busche, 1993; Marker and Holmes, 1993; Eitel, 1994). They thicken towards the east and overlie the older rocks as a continuous layer. The youngest deposits are recent wind-blown sands, hill slope debris and alluvium, which dominantly fills dry river beds.

3 Lithostratigraphy at Zwartbas

The stratigraphy at Zwartbas starts with siliciclastic, calciclastic and carbonate succession of late Proterozoic rocks of the Nama Group. They are unconformably overlain mainly by shales of the Permian-Carboniferous Karoo Supergroup. The basal sediments of the Karoo Supergroup are mainly composed of tillites, diamictites and shales of the Dwyka Group, which transgress into continuous shales of the Ecca Group. Younger Karoo dolerites intruded the shales at the Dwyka-Ecca boundary. Calcrete was formed in the Cretaceous and Tertiary and are considered to belong to the Kalahari Group. Alluvia, flood deposits, hill slope debris and river terraces are witnesses of recent deposition.

Rocks of the Nama Group crop out in the southwestern part of the attached map. The Karoo strata are exposed in an E-W extension. Younger rocks are found along the Orange River, in depressions and dry river courses. An overview of the succession at Zwartbas shows Fig. 5. Detailed profiles are displayed in Appendix on page 70 to 80.

3.1 Deposits of the Nama Group

Layers of the Nama Group at Zwartbas are mainly exposed between the Orange River west of Fossil Bend, the study area's boundary, and the road D 212 (see attached map). Additionally a small shoreline-prominence reaches into the Orange River, just below the Jet Cliff. The outcropping strata of the Nama Group at Zwartbas comprise rocks of the upper Kuibis Subgroup and lower Schwarzrand Subgroup (Haughton and Frommurze, 1936; Germs, 1971; SACS, 1980; Gresse and Germs, 1993) - both of Vendian Age (Meert et al., 1997). The sequence (Appendix page 71 and 72) starts with a quartzite and pebbly sandstone, succeeded by a sequence of calcisiltite and calcarenite, which passes into a massive chert bearing limestone. Eventually a shale, which is partly quartzitic and/or diamictitic, overlies the limestone unconformably. The shale is cut again unconformably by erosional channels filled with limestone conglomerate or breccia. The basal tillites of the Dwyka Group cap the succession of the Nama Group on a glacial unconformity. The strata of the Nama Group are folded, but have not exceeded low-grade metamorphism.

An unambiguous designation of the exposed strata to formations and members was difficult (see chapter 3.1.6). Thus names in brackets are the most probable classifications. This paper divides the discussed succession in four main units, which all represent distinct members.

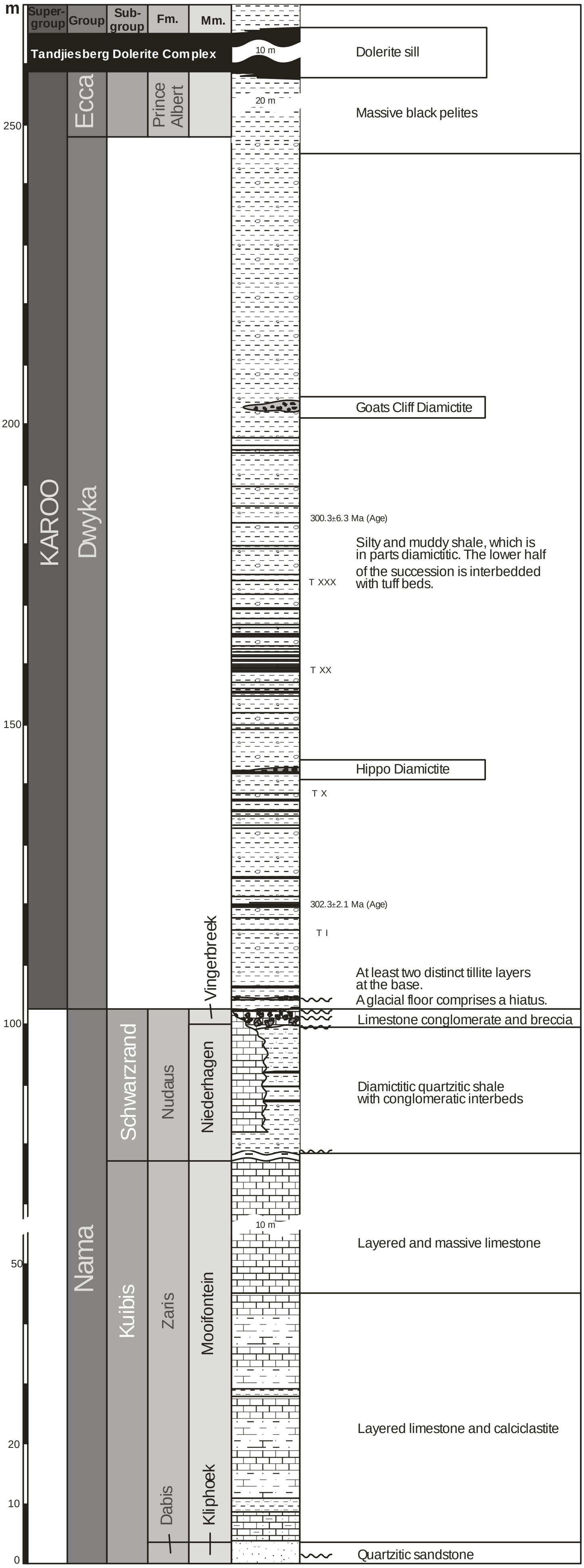


Figure 5
The stratigraphy of the relevant strata of Nama and Karoo deposits at Zwartbas.
(Nama: after Gresse and Germs, 1993; Karoo: this work)

3.1.1 Red pebbly sandstone and green quartzitic sandstone (Kliphoek Member)

Exposure: The only outcrop of the quartzitic sandstone and pebbly sandstone is confined to outcrop # 9 at the farm road to Nuwe Modderdrif. The quartzite crops out in the centre of a fold 800 m southwest of the T-junction at the ostrich farm. An area of about 30 x 30 m is exposed.

The lowermost rocks of the stratigraphy exposed in the study area are a green quartzitic sandstone and a reddish pebbly sandstone, which are at least 4 m thick altogether. They crop out at the centre of the fold north of the farm road to Nuwe Modderdrif (outcrop # 9), which will be described in chapter 4. The quartzitic sandstone of fine- to middle-sand is moderately sorted and mature. Incised channels are filled with pebbly sandstone. Clay cemented middle-sand carries sub-rounded to rounded pebbles of dark grey to grey limestone, bright grey coarse sandstone and dark green or red fine quartzite, ranging predominantly from 2 to 4 cm in diametre and rarely extending up to 20 cm (Fig. 6). Folding and thrusting has deformed most of the rocks and overprinted sedimentary structures, leaving a melange.

Sedimentary Environment

Quartzitic sandstone and an incised channel of pebbly sandstone (conglomerate) suggests a fluvial facies, maybe of deltaic origin (cf. Germs, 1983).

3.1.2 Calciclastite and the layered limestone (Mooifontein Member)

Calcisiltites, calcarenite and siltite

Exposure: This calciclastite crop out northerly along the road to Nuwe Modderdrif 0.5 to 0.8 km west of the T-junction at the ostrich farm.

The quartzitic sandstone is overlain by a calciclastic and carbonate interval with sharp interval boundaries. Black layered limestone, varying from some decimetres to some metres thickness, intercalate with 1.5 to 2.5 m thick calcisiltitic and calcarenitic units. These rocks are mixtures of predominantly brownish yellow, sub-rounded and well sorted carbonate silt- and sand-sized material and make up fine to coarse interbeds of friable, porous packstone, which generally range from 3 to 7 cm in thickness. The upturned calciclastite layers recede from the surrounding limestone due to their higher weatherability. Sometimes quartzose calcarenites are interbedded, which contain sub-rounded quartz grains of middle-sand size. Moreover two several-metre-thick units of greenish yellow limy siltstone are present. The occurrence of the black-white-layered (5-10 cm) limestone decreases subsequently upwards until the sequence turns into a continuous limestone unit (see paragraph below).

Figure 6
A red pebbly sandstone with quartzite and gneiss pebbles constitutes a channel fill (Kliphoek Member).
Locality: The centre of the fold at outcrop # 9.

Layered limestone and massive limestone

Exposure: The continuous limestone unit constitutes the most extensive unit of the Nama Group in the study area. It is confined by the road D 212 in the north, the Raven Gorge in the east and the Orange River in the south. In the west the layers extend out of the study area.

An about 20 m thick limestone overlies the calciclastic sequence. The lower 8 m are composed of wavy bedded, some millimetres to centimetres thick layers of dark grey to blue and bright grey layers of different weatherability (Fig. 7). Brighter layers, which are less resistant to weathering, are made up of fine, crystallized carbonate, whereas darker layers consist of micrite. This micrite-sparite interstratification forms a layered carbonate deposit, which can be considered as stromatolites. Their production was caused by repeated entrapment of lime mud and other extraneous particles from suspension by shallow water algal mats (Friedman et al., 1992). Stromatolites in the Nama Group are noted by Germs and Gresse (1991) and Saylor et al. (1998). Diagenesis transformed and combined layers to varied stages of crystallization. The former particular laminae are often overprinted, but the interstratification of the variably coloured diagenetic layers are far visible.

Figure 7
The picture shows an upturned layered limestone (Mooifontein). Wavy layers of stromatolites are composed by bright grey layers of sparitic limestone which are intercalated with dark grey layers of micritic limestone.
Locality: 100 m northeast of outcrop # 10.

A massive at least 12 m thick dark limestone completes the succession (Fig. 8, see Fig. 16). It shows poor bedding and lacks sedimentary structures. At least chert nodules lying loose but aligned in beds in the terminal 5 m of the succession. The cherts project of the limestone due to their resistance to weathering. Micro-joints of several systems were obtained during folding (see chapter 4). The origin of the chert nodules in the limestone is ascribed to volcanic ash layers. Their spatial distribution is indefinite, but a common occurrence was recognized in the northwestern outcrop of the limestone. In the western exposure the limestone shows karst landforms with a rough surface and caves (see Fig. 8).

Figure 8
Massive limestone forms a karst relief in the western area of the Nama exposure.
Locality: Overview over the limestone hills, 100 m west of outcrop # 10.

The occurrence of fossils in the limestone, noted by some authors (cf. Germs, 1983), could not be verified during the mapping project. The attraction of the dark limestone for man, even before the first geologist came, is documented in bushman engravings on a limestone floors. Some of them lie northwestern of the study area, about 0.5 km east of the road D 212 to Rosh Pinah (S 28°39.964'/ E 017°29.806').

Silty limestone

Exposure: Upturned layers of silty limestone line out a depression of thrustfault-associated folding 300 m south-southwest of outcrop # 10 (S 28°41.157'/E 017°32.564'), where the quartz veins in the limestone wedge out towards the northwest. Further centroclinally dipping silty limestones form an oval patch within the limestone in a tectonic depression 600m south-southeast of outcrop # 10 at S 28°41.214'/E 017°32.679.

The layered limestone is topped with a bright skin-coloured silty limestone. Due to the erosion of the hangingwall a thickness estimation is difficult, but the preserved thickness does not exceed 70 cm. Now and then lamination was observed at the silty limestone and ripple structures are occasionally present as sole marks. Crests and troughs of the weakly unsymmetrical ripples are rounded and have a wavelength of 15-20 cm. The boundary between the subjacent limestone and the silty limestone is sharp. The boundary to the overlying quartzitic shale was not observed, as rivers follow the boundary and cover it with alluvium (i.e. Raven Gorge). It is unclear, if the silty limestone is to assign to the carbonate unit of the Mooifontein Member or the siliciclastic unit of the overlying Niederhagen Member. But it is obviously part of the Nama Group, as the layer was involved by folding (Fig. 9). At the northern exposure boundary of the Nama Group the silty limestone is overlain by either tillite or shale of the Dwyka Group. Superjacent Nama rocks were not seen. Moreover the role of the Silty limestone layer in the stratigraphical evolution is uncertain, as no hangingwall rocks of the Nama Group were preserved.

Figure 9
A structural depression in the limestone is overlain by upturned centroclinally dipping silty limestone (Mooifontein Member).
Locality: S 28°41.214'/E 017°32.679.

Limestone/dolostone mounds

Exposure: Limestone/dolostone mounds are laterally confined and occur sporadically in the quartzitic shale, which overlies the Silty limestone. Exposures lie in an imaginary triangle spanned between the corners Waterfall (outcrop # 7), outcrop # 10 and the confluence of the Waterfall's river and Raven Gorge river.

The overlying quartzitic shale hosts huge mounds of carbonate rock, which taper to the top. They extend up to 20 m laterally and 10 m vertically at the Waterfall (Fig. 10) and some metres large carbonate mounds project from the plain (outcrop # 10) 80 m southwest of Fossil Bend. They can hardly be erratics because of their size, but must be autochthonous. In contrast to the layered limestone below, which was ascribed to the Mooifontein Member, the mounds in the Waterfall area mainly consist of massive grey carbonate. Weathering leaves a beige-yellow corrosion crust on the carbonate. A previous dolomitization of the former limestone caused probably this different weathering colour. In some places the carbonate rock seems to comprise ooides, at least weak evidence was found in the Waterfall area. As the base of the mounds is surrounded by quartzitic shale, it was not recognized from which layer they project.

Figure 10
The picture shows an about 20 m high carbonate mound (Mooifontein Member) hosted by shale (Niederhagen Member). A limestone conglomerate and breccia (Vingerbreek Member) cuts the shale unconformably.
Locality: 20 m south of the dry Waterfall (outcrop # 7).

Southwest of the meeting of the Raven Gorge river and the road to Nuwe Modderdrif, a carbonate mound projects from the surrounding. The dolostone mound is mentioned here, since it might help to explain the genesis of these mounds. It shows the same layering as the dark layered limestone, but also shows the same yellow weathering colour as the massive carbonate mounds mentioned in the paragraph above. Normal dolomitization is a surficial process. The involved layers here belong to different strata. This implies that the surface during the dolomitization was so undulating, that stratigraphically different strata were involved in this process. This concludes that both the black-white-layered limestone and parts of the beige-yellow weathered carbonate rocks belong to the same member. Thus the carbonate mounds are considered as remnants of the hangingwall succession of the layered limestone. Therefore the limestone mounds are also ascribed to the Mooifontein Member.

Sedimentary Environment

The arenitic layers are mainly reworked carbonates of subtidal water conditions (cf. Saylor et al., 1995). The occurence of stromatolites indicates a deposition in a tidal flat (Friedman et al., 1992). The massive limestone points to deep water conditions. This is confirmed by the presence of interbedded cherts, as the tuffs must have been deposited below the wave base to be unreachable for reworking turbulences. The sharp unit-boundary to the silty limestone suggest a quick change of the depositionary conditions. The ripple marks may again suggest deposition in tidal influenced environment. The presence of ooides in the limestone mounds points to a similar environment as during the formation of the stromatolites, since ooides are preferably accumulated by algae mats (Friedman et al., 1992). The dolomitization points to increasing salinity of the seawater resulting in an abundance of the required magnesium.

3.1.3 Quartzitic shale and diamictite (Niederhagen Member)

Quartzitic shale and diamictite probably overlies the silty limestone, but the sequence boundary was nowhere seen. Ferruginous conglomerate beds intercalate the quartzitic shale.

Quartzitic shale

Exposure: The quartzitic shale crops out continuously in the area more or less enclosed by the N-S flowing Orange River south of Fossil Bend and its imaginary extension north to the road D 212. This road follows the northern outcrop-boundary of the quartzitic shale to the west until Raven Gorge and its imaginary SE-extension to Orange River limits the exposure in the west and south.

The quartzitic shale starts with a bright green feldspathic quartzitic silty shale which is fining upwards and passing into a darker green and black mature fine shale. The quartzitic shale disintegrates in up to 10 cm long pencil slates, whereas the shale at the top of the succession is fissile and splits into small about 1 to 2 cm large slates.

Diamictite

Exposure: One Exposure of the diamictite lies at the location where the river below the waterfall meets the Raven Gorge river. An other diamictite in the quartzitic shale unit crops out at Fossil Bend and underlies the Dwyka Group tillite at western Orange River bank.

At the Raven Gorge river isolated sub-rounded to rounded up to 40 cm large clasts of massive limestone are found within the lower part (15 m) of the quartzitic shale and describes this part as diamictite (Fig. 11). The quartzitic shale, which was described above, constitutes the matrix. Moreover small quartz and quartzite clasts (up to 2 cm across) float in the quartzitic shale close to a frequent occurrence of limestone clasts. The common EACS is 20 to 30 and the CPD starts from 50 and exceeds several hundred, as the clast occurrence is very sporadic.

Figure 11
Limestone clasts are disseminated in the basal quartzitic shale (Niederhagen Member).
Locality: 20 m west of outcrop # 8 (S 28°41.277'/E 017°32.952')

On the western bank of the Orange River at Fossil Bend a diamictite crops out, which could not classified stratigraphically. Probably it corresponds to the stratigraphic level of the diamictite mentioned above, but has a different composition of the clasts. Here dominantly granitoides, gneisses, carbonates, such as marble and limestone, and minor schists compose the clasts and therewith differs lithologically from the limestone-clasts dominated lower diamictite. The EACS ranges from 5 to 10 and the CPD varies from 10 to 20. About 30 m west of outcrop # 16 large limestone boulders with a diametre of more than 2 m occur (Fig. 12). They must have been transported by glaciers as they are too big for any kind of movement in a fine grained matrix. At the top of the bank southwest above Fossil Bend the quartzite is fissile and disintegrates into pencil slates. Close to the river at the lower bank, where the corrosional influence of the river increases, the rocks seem to be more compact and firmly cemented. Here the rocks are covered with a dark-brown ferric crust. The composition of the clasts resemble that of the upper bank. The higher grade of metamorphism could be obtained either by increased load due to higher subsidence (lower topographical elevation today) or by increased pressure during the compressional folding (see chapter 5).

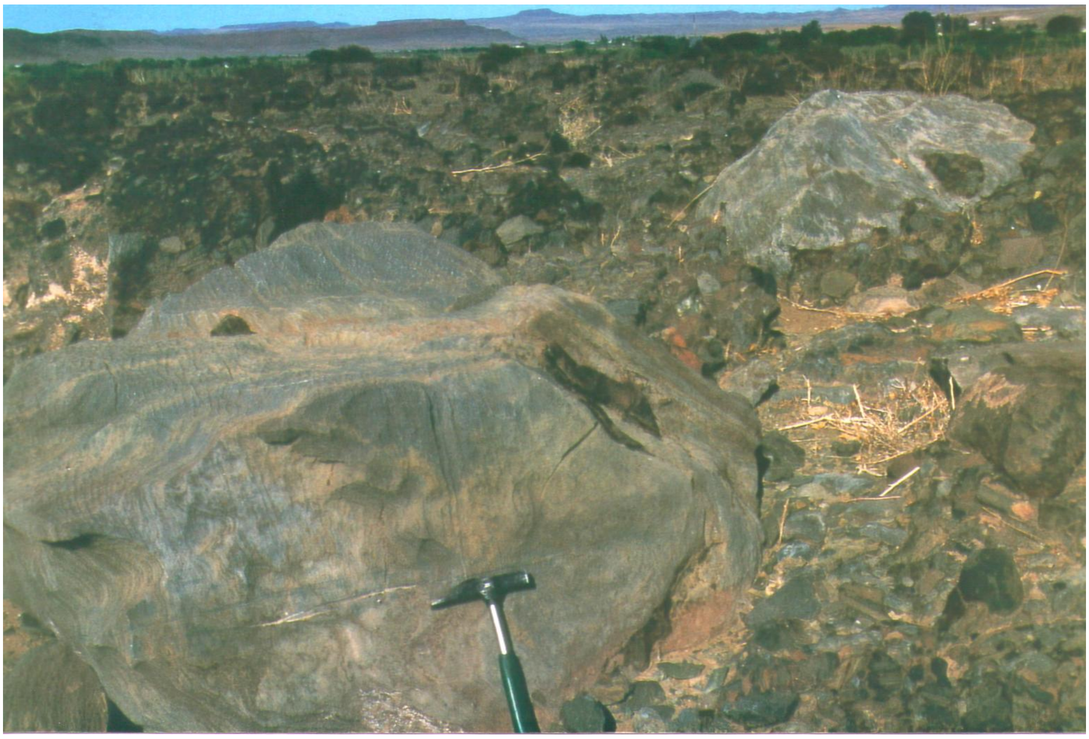


Figure 12
Large limestone boulders occur in the quartzitic shale.
Locality: 30 m west of outcrop # 16.

Striated surface – glacial or tectonic origin?

Exposure: About 3 m above the assumed silty limestone-quartzite boundary a conglomeratic bed crops out at the channel floor in Raven Gorge. At the base of the northern wall about 1km downvalley from the head of the gorge (outcrop # 10) at the road D 212.

Just some centimetres elevated from the river floor in Raven Gorge, a more or less even surface is scraped up with about 1 m long parallel scars and grooves (strike: 060°). Grooves and interspersed crests respectively are only 2 to 3 millimetres wide and deep. The margins of the about 30 cm broad striated surface are poorly preserved, so that the lateral extension could not be determined. Only 150 m down-valley the occurrence of clasts, which are assumed to be dropstones in the same stratigraphical level or just above, suggests that the striae are of glacial origin (Fig. 13). Whereas due to a poor outcrop quality it is not to preclude that this is a simple slickenside. The structural situation during post-Nama time could provide an explanation. As will be discussed in chapter 5, the folding and eventually thrusting produced shear planes, which are conformable to the eastward thrusting and verging of the faults and folds. Striking 50°, the striation is more or less consistent with the general eastern trend.

Figure 13
The picture shows striations on a surface at the base of the quartzitic shale (Niederhagen Member) strike 060°, *Locality:* 150 m downvalley from outcrop # 19; bottom of the northern wall (S 28°41.152'/E 017°32.514').

Conglomeratic beds

Exposure: The quartzitic shale crops out continuously in the area more or less enclosed by the N-S flowing Orange River south of Fossil Bend and its imaginary extension north to the road D 212. This road follows the northern outcrop-boundary of the quartzitic shale to the west until Raven Gorge and its imaginary SE-extension to Orange River limits the exposure in the west and south.

Conglomeratic beds of usually 20 to 40 cm but sometimes up to 1.5 m thickness are intercalated between the quartzitic shale. A gritty ferruginous cemented matrix of quartzose sand with carbonate grains carries angular to well-rounded pebbles of dominantly limestone and quartzite and schist. The matrix supported beds consist of moderately graded middle sand at the base and grade to fine silt at the top. The grain size of the clasts varies from middle sand to boulders. Clasts up to 100 cm across are mainly found in the lower ill-sorted conglomerate beds and scale down to max. 2 cm in diameter in the sorted upper beds. The average grain size of the beds generally decreases upwards. A few scour marks are present at the base of the lower beds and suggest erosion prior to their deposition. The marks correspond to an expected eastern flow direction. Conglomeratic beds in the upper section of the quartzitic shale have planar bases. The conglomerates become more and more scarce to the top of the succession, sometimes pinch out and are reduced to lenses of some centimetres in thickness. To the east the beds become thinner and better graded (Fig. 14). Convolute bedding in these thin beds infers gravitational movement after their deposition. The conglomeratic beds are regarded as turbidites due to their frequent appearance, lateral extension, gradation and erosional bases associated with flute casts.

Figure 14
The picture shows a graded about 10 cm thick conglomerate bed in the quartzitic shale (Niederhagen Member).
The bed is obviously graded and passes into a ferruginous fine sand top.
Locality: 30 m west of outcrop # 16.

Sandstone lense

Exposure: A 5 x 5 m laterally extending sandstone body was found in the quartzite at outcrop # 16 (30 m southwest of Fossil Bend).

The grey-green middle to coarse sandstone contains disseminated pebbles of mainly sub-angular limestone up to 40 cm across, rarely accompanied by some 2-5 cm large quartzite slates (Fig. 15). In contrast to the conglomerate beds, the preserved exposure of this sandstone is laterally limited to 10 m in east-west and 6 m in north-south extension. The base of the sandstone is slightly incised into the quartzitic shale. This points to a channel fill. Though tangential foresets were recognized, they could not be put into reasonable relation. However, they incline to the east, which is consistent with the striations on the striated surface as well as the structural situation.

Sedimentary environment

The origin of the striated surface is ambiguous. Both a glacial origin with regard to the adjacent clasts or an interpretation as tectonic shear plane are possible. Since the isolated limestone clasts and boulders in the diamictitic parts point to glacio-marine conditions during the sedimentation, the glacial interpretation is favoured. Thus a proglacial marine environment is most likely. Rejecting this idea, prodelta to delta front environment must be considered by the occurence of turbidites. The fluvial sandstone moreover supports a prevailing deltaic environment.

Figure 15
A sandstone body appears within the quartzitic shale (Niederhagen Member). The eastward inclining tangential foresets are outlined by imbricated clasts. The structure suggests a transport direction to the east.
Locality: Outcrop # 16.

3.1.4 Limestone conglomerate and breccia (Vingerbreek Member)

Exposure: The limestone conglomerate and breccia spread 100 m to the south along the southern side of the road D 212 from the Waterfall as eastern boundary to the Raven Gorge as western boundary. At Jet Cliff another small patch of this conglomerate forms the shoreline prominence reaching into the head of the rapids of the Orange River. A location of the same size yields the striated top of this rock 50 m east of the vertex of the Orange River at Fossil Bend.

An unconformity cuts the underlying shale. It is overlain by an about 3.5 m thick conglomeratic sequence (Fig. 16). Two beds constitute the fining-upward unit. The sequence begins with an about 1.7 m thick graded, well-sorted, monomict conglomerate with sub-angular to rounded limestone boulders and pebbles, which are predominantly matrix supported. Micritic lime mud constitutes the matrix. A bimodal grain-size spectrum is present. One clast size maximum ranges from 1 to 20 cm in diameter, the other ranges from 60 to 130 cm. The black limestone weathers pinkish, the calcareous dark matrix alters to grey. This conglomerate constitutes the bedrock of the Dwyka glaciation at the till plain along the road D 212 east of outcrop # 10. At Jet Cliff a similar rock forms the striated bedrock, but the rounded boulders are replaced by angular limestone fragments supported by a calcareous matrix.

The superjacent 1.8 m thick conglomerate cuts the underlying shale with a channelized unconformity. Whereas the base is similar to the subjacent conglomerate, the top differs by an obvious decrease in grain size down to a coarse-sand grain-size. This clast-supported sediment is ferruginous cemented.

Figure 16
Behind the blocks at the bottom of the picture shale is visible (Niederhagen Member), which is unconformably overlain by a fining-upward sequence of limestone conglomerates (Vingerbreek Member). The second limestone conglomerate was obviously incised in the subjacent unit. The erosional base is outlined by an arch-like prominence of the second unit.
Locality: Waterfall

Sedimentary Environment

Germs ascribes at least the unconformity to a glaciogenic origin and the proposed deposition of the conglomerate at cold-water conditions (Germs, 1971; Germs and Gresse, 1991). Saylor et al. (1995) reject this interpretation and consider a relative sea level fall responsible for the enormous incision, which was finally filled with debris flows.

3.1.5 Post-Nama quartz veins

Exposure: In the northwestern outcrop of the Nama Group two parallel quartz veins dissect the limestone. The veins extend from 150 m north of the farm road to Nuwe Modderdrif to the Nama-Dwyka boundary (S 28°41.325'/E 017°32.332).

In the limestone of the Nama Group two parallel northwest to southeast trending quartz veins occur (Fig. 17). The variety of rose quartz was sometimes found beside the common milky quartz in the up to 2 m wide veins. In the south the veins pinch out before the scarp north of the farm road to Nuwe Modderdrif. In the north the veins are covered by Dwyka deposits, so that their northern extension was not to determine. The veins were scooped out by erosion and form parallel ditches. Pieces of quartz scatter the floors and patches of rose quartz mixed with limestone clasts stick on the walls in some places. Clasts are sharp and angular, up to 20 cm across, have no preferred orientation and float in the quartz. The lithology of the limestone country rock and the rock fragments correspond. The quartz is believed to be a hydrothermal deposit. It could not be determined, whether the limestone fragments were produced by tectonic or hydrothermal processes.

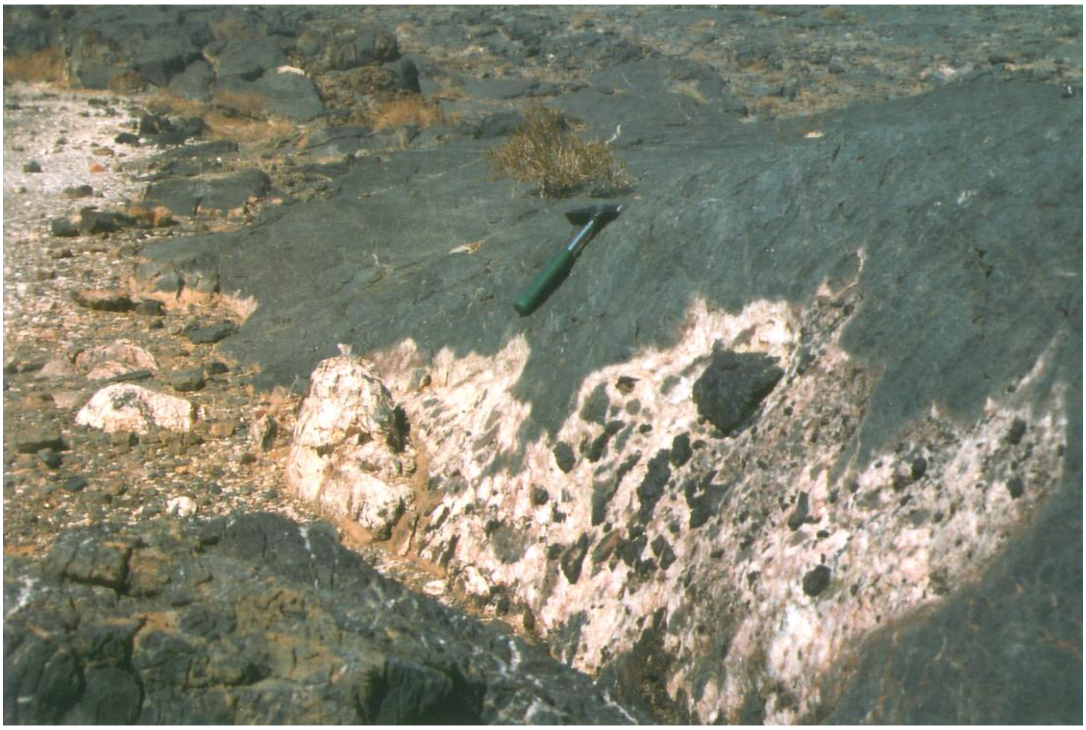


Figure 17
The picture shows a quartz vein in Nama limestone. The vein is about 1.5 m wide and recedes from the limestone plateau. The wall on the opposite side is covered with limestone fragments in rose quartz.
Locality: Limestone plateau (S 28°41.325'/E 017°32.332).

3.1.6 Discussion about the classification of the previously treated rocks

The classification of the deposits in the study are, which are ascribed to the Nama Group, is still insufficient. Additionally the poor literature, which is available for this locality, is either contradictory or inaccurate.

Problems arose in the effort to classify the limestone. Gresse *et al*. (1996) report that volcanic ash layers in form of chert beds are found throughout the succession of the upper Kuibis Subgroub. In respect of the cherts this corresponds to the classification of the limestone in this paper, as the Mooifontein Member of the Zaris Formation represents the terminal Kuibis Subgroub. Glacigenic deposits in the overlying quartzite unit ascribed to be Nudaus Formation (SACS, 1980) support the classification of the limestone to Mooifontein Member. Haughton and Frommurze (1936) also consider the beds at Zwartbas to belong to the Schwarzkalk Formation, which is included into the Zaris Formation today (SACS, 1980). However, these results are apparently in a contradiction with the limestone conglomerate further up in the succession, which Germs (1995) considered to be of reworked Mooifontein limestone at Aussenkjer. An explanation could be the existence of a palaeorelief, which provided the limestone in an uplifted area, from where it was eroded and eventually redeposited in a stratigraphically higher part.

Perhaps the striated surface found in the quartzitic shale plays an important role. If the scratches constitute a more or less horizontal slickenside instead of a glacial surface, the stratigraphic assignment gets exceedingly difficult. The diamictitic and quartzitic shale may represent a thrusted nappe, whose stratigraphical rank has to be discussed. Glacial conditions, anyway, may ascribe the unit to the lower Nudaus Formation according to SACS (1980), supported by regional correlation in previous studies (Germs, 1983; Germs and Gresse, 1991). But Germs limited the Niederhagen Member to the Schlip area in the north, so that the quartzitic rocks here can rather be correlated with the Vingerbreek Shale. More recent studies by Saylor and Grotzinger (1996) and Saylor et al. (1998) reject such an interpretation, because no evidence of glacial deposits in the lower Schwarzrand Subgroup is present at all. The unconformity between the limestone (Mooifontein Member) and the quartzitic shale (Niedernhagen Member), whether glacial or not, forms a palaeorelief with incisions up to 30 m deep. The massive oolitic limestone mounds, which are enveloped in the shale (Vingerbreek Member), seem to represent the hangingwall succession of the layered stromatolitic limestone. Both facies can be dolomitized near by the unconformity. Diamictitic shale fills the incisions. This sedimentary succession resembles fairly accurate the succession of the Upper Schwarzrand Subgroup in the Aus and Fish River area described by Saylor and Grotzinger (1996). Especially the occurrence of a diamictite in the Nomtsas Formation there, which is obviously the only diamictite in the Nama Group succession (Saylor et al., 1995), and the earlier interpretation of glacial activity during Nomtsas time (Germs, 1983) suggest a possible correlation with the layers at the Orange River. Besides this, rocks of the Nomtsas Formation were often deposited in valleys and gorges incised into the underlying layered and chert-bearing limestone of the Spitzkopf Member (Saylor and Grotzinger, 1996), which corresponds lithologically with the layered limestone at the Orange River.

Resuming this discussion the classification of the rocks, which are presumed to belong to the Nama Group, can be questioned. The minor accordance of the field observations with the reports in literature may conclude that the stratigraphical classification of the Pre-Dwyka layers at Zwartbas to the Nama Group, is simply mistaken. In reference to the occurrence of diamictites the rocks can classified to other groups. Glacial evidence was e.g. confirmed in pre-Nama Gariep-associated rocks of the Witvlei Group or Equivalents (Saylor et al., 1998). The former classification to the Nama Group by Haughton and Frommurze (1936), Germs (1983) and Germs and Gresse (1991) put such a reclassification more than ever into perspective.

3.2 Deposits of the Karoo Supergroup

The Karoo sequence rests on a clear unconformity, which reflects a hiatus in the stratigraphy nearly through the entire Palaeozoic. Referring to Bangert et al. (1999a) and Saylor et al., (1998) the Nama Group and Lower Karoo Supergroup stand stratigraphically about 260 Ma apart. The glacial floor separates the folded Nama rocks (Vendian) from more or less even-bedded Carboniferous-Permian Karoo deposits (Appendix page 73 to 80). Polished surfaces with furrows and scratches are witnesses of glacial erosion at the beginning of the Karoo Age, followed by a succession of shale. The Karoo Supergroup is composed by two facies: the glacio-marine shales of the Dwyka Group and the overlying marine shales of the Ecca Group. The distinctive feature of the Dwyka Group is a frequent occurrence of dropstones, which marks the glacially influenced sedimentation. The lower part contains concretionary horizons, bentonitic ash layers, tillites, dropstone-rich diamictites and coarse grained clastic deposits. However, in the upper part dropstones are missing, which indicates a change to non-glacial marine conditions. The glacio-marine unit is about 145 m thick. The dropstone-free unit has a thickness of about 20 m, until it is capped by a dolerite intrusion again of 20 m thickness. Since the hanging wall is not situated in the study area, it was not part of this investigation. A Jurassic intrusive body of the Tandjesberg Dolerite Complex penetrated the shales. The dolerite forms an escarpment about 1-2 km north of the river that extends parallel along the road from Noordoewer. The outcropping dolerite shapes the plateau rim. Under- and overlying shales form slightly inclining slopes, in which rivers incised gorges and shaped scarps and cliffs. Slopes around the inselberge and outliers are often covered with slates of the shale and with hill slope debris of the dolerite.

3.2.1 Deposits of the Dwyka Group

The Dwyka Group is defined as glacio-marine part of the Lower Karoo Supergroup. A basal tillite sequence covers the glacial grooves in the subjacent rocks, followed by an argillaceous sequence of partly diamictitic shale, which is made up of numerous cycles of muddy and silty shale. The shale display ferritic and calcareous lenticular concretions and fossiliferous nodules. Ash-fall tuff horizons, which laterally often pass into calcareous concretionary horizons, disseminate throughout the lower succession. The entire succession contains dropstone-enriched units which differ in dropstone distribution density, size and lithology.

The lithofacies of the shales and diamictites building up the Dwyka succession varies frequently in a narrow frame. Additionally ash-layers, concretionary horizons and fossil-bearing units overlap and merge with different lithofacies types. Thus the lithostratigraphy will be discussed in chapter 3.2.1.1 in order to give an overview. The next chapter gives a representative example of lithofacies descriptions. Therefore the facies interpretation of particular units is anticipated to combine similar sections and abbreviate and dispose the presentation.

3.2.1.1 Lithostratigraphy

Glacial striae, tillite and diamictitic shale (20 m)

Deposits of the Dwyka Group are separated by an unconformity from the bedrocks of the Nama Group. The unconformity is originated by glacial erosion leaving unconformably incised, channelized and scoured surfaces covered with thin veneers of tillite. The basal glacigenic succession is completed by an about 3 m thick dropstone-bearing diamictitic shale, which contains varved interbed with a constant thickness of 0.5 m. The subsequent shale unit above displays disseminated dropstones. These occur up to about 20 m above the Dwyka base at tuff group T V. The lowermost occurrence of ash layer is 12 m above the unconformity.

Shale (45 m)

A 21 m thick dropstone-free shale unit succeeds. In the middle section of the shale concretionary nodules and horizons are frequent. The upper half of the unit displays abundant fossils. An overlying 1 m thick laterally continuous diamictite consists of sub-angular rock fragments floating in a calcareous clay matrix. To accredit its importance as marker horizon the diamictite was assigned to a specific name: **Hippo Diamictite**. Above the diamictite succeeds another shale unit for 25 m. The shale contains numerous concretions and fossils.

Diamictitic shale and siliciclastic interlayers (25 m)

The reinsertion of dropstones in the hangingwall mudstone introduces again diamictitic shale which is about 27 m thick. Sandy horizons appear here uniquely within the whole shale successions.

Shale (15 m)

A 15 m thick shale unit devoid of dropstones overlies the diamictitic shale. The uppermost properly identified ash layer occurs 3 m above the base of the shale. Locally the succession is interrupted by a contorted diamictitic bed 7 m from its base. Regarding the locality it was named the **Goats Cliff Diamictite**.

Diamictitic shale (40 m)

The superjacent diamictite is about 40 m thick. It is the highest diamictite bearing abundant dropstones. A 12 m thick sequence of white weathering shale constitutes an obvious marker horizon for the top of the Dwyka succession. It is a far visible marker horizon and therefrom it was specified with a particular name: **White Horizon**. Some decimetres above this sequence the last dropstones were recognized in the overlying shale.

Shale (undetermined thickness)

The overlying shales are ascribed to the Prince Albert Formation of the Ecca Group due to the total lack of dropstones.

3.2.1.2 Lithofacies

3.2.1.2.1 Subglacial and continental proglacial facies association

Glacial Floor

Exposure: Glacial floors, partly associated with till plains, are found from 100 m to 500 m east of the junction at the ostrich farm along the southern side of the road D 212 to Rosh Pinah, at Fossil Bend and at the start of the rapids at Jet Cliff.

Glacial floors form the discontinuity between the Nama Group and the Dwyka Group. Whenever the subjacent rock consists of limestone conglomerate or breccia of the Vingerbreek Member (Nama Group), the bedrock is scoured and grooved by glacial erosion (Fig. 18). Striation orientations reflect the ice flow direction mentioned in 3.2.1.6. In contrast, overridden (quartzitic) shale of the Niederhagen Member (Nama Group) does not reveal erosional features (see Fig. 20). As the shale of the Niederhagen Member is less resistant to erosion in comparison to the limestone conglomerate and breccia (Vingerbreek Member), the glacier incised unconformably deep channels into the quartzitic shale and formed an undulating palaeorelief. The glacial surface on the fissile quartzitic shale is not preserved, as the exposed rock splits into slates immediately. At Fossil Bend, where the quartzitic shale becomes firmly cemented, compact quartzite constitutes a competent bedrock.

Figure 18
The Nama bedrock is striated and sporadically overlain by yellow tillite. Here the bedrock comprises a compact quartzitic shale. *Locality:* West bank of Fossil Bend.

Basal yellow tillite

Exposure: The yellow tillite was found from 100 m to 500 m east of the junction at the ostrich farm along the southern side of the road D 212 to Rosh Pinah, east of the river bed at outcrop # 8, at Fossil Bend and at the start of the rapids at Jet Cliff.

Marlstones overlie the glacial floor which frequently carries rock fragments. The layers are up to 50 cm thick and continue laterally. Two types of tillite are present. At outcrop # 10 a red tillite appears (see paragraph below), but commonly a yellow type is widespread and represents the basal tillite, e.g. at outcrop # 8, Fossil Bend and Jet Cliff. Both tillites can easily be distinguished by their colours, although they seem not to differ much in their lithology. Both are diamictites with a fine calcareous mud matrix, in which fragments of gneiss, granites, pegmatites, schists, quartzites and sporadically carbonates, cherts and jaspers float. Lithology and average size of the clasts resemble the lithology and size of the dropstones in the shale (see 3.2.1.2.2). The clasts are up to 10 cm large, but the common EACS is 2-3. The CPD ranges from 5 to 8. Cone-in-cone structures confirm a carbonate content. In many places only the marls are still preserved in depressions or grooves, the superjacent rocks were removed (Fig. 19). When they overly limestone conglomerate and breccia or massive quartzite, the scoured bedrock is well preserved. When the tillite rests on quartzitic shale, the base is channelized and the palaeorelief height decreases (Fig. 20). An inclining palaeotopography caused by a quartzitic bedrock at outcrop # 8 is illustrated in Fig. 23. The close attachment of the marlstones to the glacial floor, their lithology and their pebbly detrital content classifies it as a tillite. At Jet Cliff the yellow tillite overlies an up to 70 cm thick diamictitic shale unit. The shale itself rests on the glacial unconformity. This implies that between the scouring of the bedrock and the deposition of the tillite the deposition of argillaceous material was enabled. An explanation gives a temporary ice retreat at the ice margin (see below).

Figure 19
Yellow tillite (upper right corner) lies in glacial grooves in the Nama limestone conglomerate.
Locality: Till plain northerly above the Waterfall.

Figure 20
Yellow tillite overlies green quartzite unconformably. The cleavage of the shale coincides with its bedding. A channel was incised into the quartzitic shale by glacial erosion and filled with tillite.
Locality: River bed, outcrop # 8: S 28°41.277'/E 017°32.952'

Basal red tillite – striated tillite

Exposure: About 1 km west of the T-junction at the ostrich farm on the road to Rosh Pinah a track turns off the road and follows the Raven Gorge southwards (outcrop # 10: S 28°40.927'/E 017°32.380').

Besides the yellow tillite a red coloured tillite was found. The red till occurs at outcrop # 10 only. They obviously do not differ much in lithology, as mentioned above. Red tillites were found to overlie regularly the glacial floor, but never a shale unit. Nevertheless it is not possible to ascribe the red tillite exclusively to the same glaciation phase which produced the scoured bedrock, since also veneers of yellow tillite cover the glacial floor. Moreover a red tillite was observed, which was itself striated (Fig. 21). The striae trend N-S according to those found in the bedrock and indicate the same line of motion. The marlstone, however, must have been consolidated prior to its striation. Therefore a considerable time must have elapsed between the deposition of the red tillite and its scouring. This again points to a temporary retreat and a second advance of the glacier front (cf. paragraph below). A fluctuation of the ice within a short distance could also explain the similar lithology of the tillite deposited during both phases of advance, since then the reworked material of the first deposition did not influence much the composition of the tillite derived from a second advance. Moreover coincides the source area of both tillites due to the same line of motion of the ice.

As it was not possible to figure out if the red tillite obtained its colour primary or secondary, it is difficult to take the colour as distinctively characteristic to estimate the sedimentary environment. Since both tillite varieties are found close to each other and belong to the same formation it is unlikely that only the red tillite was oxidized. Further clues will be given by a fluvial red sandstone in the close vicinity of to the red tillite (see paragraph below).

Figure 21
This red tillite shows a striated top surface.
Locality: Head of Raven Gorge, outcrop # 8, see hammer for scale.

Fluvial red sandstone

Exposure: About 1 km west of the T-junction at the ostrich farm on the road to Rosh Pinah a track turns off the road and follows the Raven Gorge southwards (outcrop # 10: S 28°40.927'/E 017°32.380').

Patches of a red sandstone overlie the red tillite (Fig. 22). The red moderately sorted, graded and grain-supported middle- to coarse-sandstone is cemented by clay. Sporadically pebbles and boulders of sub-angular to sub-rounded quartzite and carbonate float in the sandstone. Sometimes coarser quartzite sand-grains are aligned in the bedding planes. Fracture planes expose small-scale tangential- and trough- cross-bedding. The maximum exposed and preserved total thickness of the sandstone layers is about 65 cm. It outlines an actual river bed. The sandstone thickens towards the centre of the river bed and the grain size of the larger pebbles increases (an about 50 cm large quartzite pebble was found).

Figure 22
A red sandstone body of middle-sand with coarser clasts overlies the red tillite.
Locality: **O**utcrop # 10, road shoulder. See lense cap for scale.

The genetic connection of the red and the yellow tillite and the fluvial sandstone

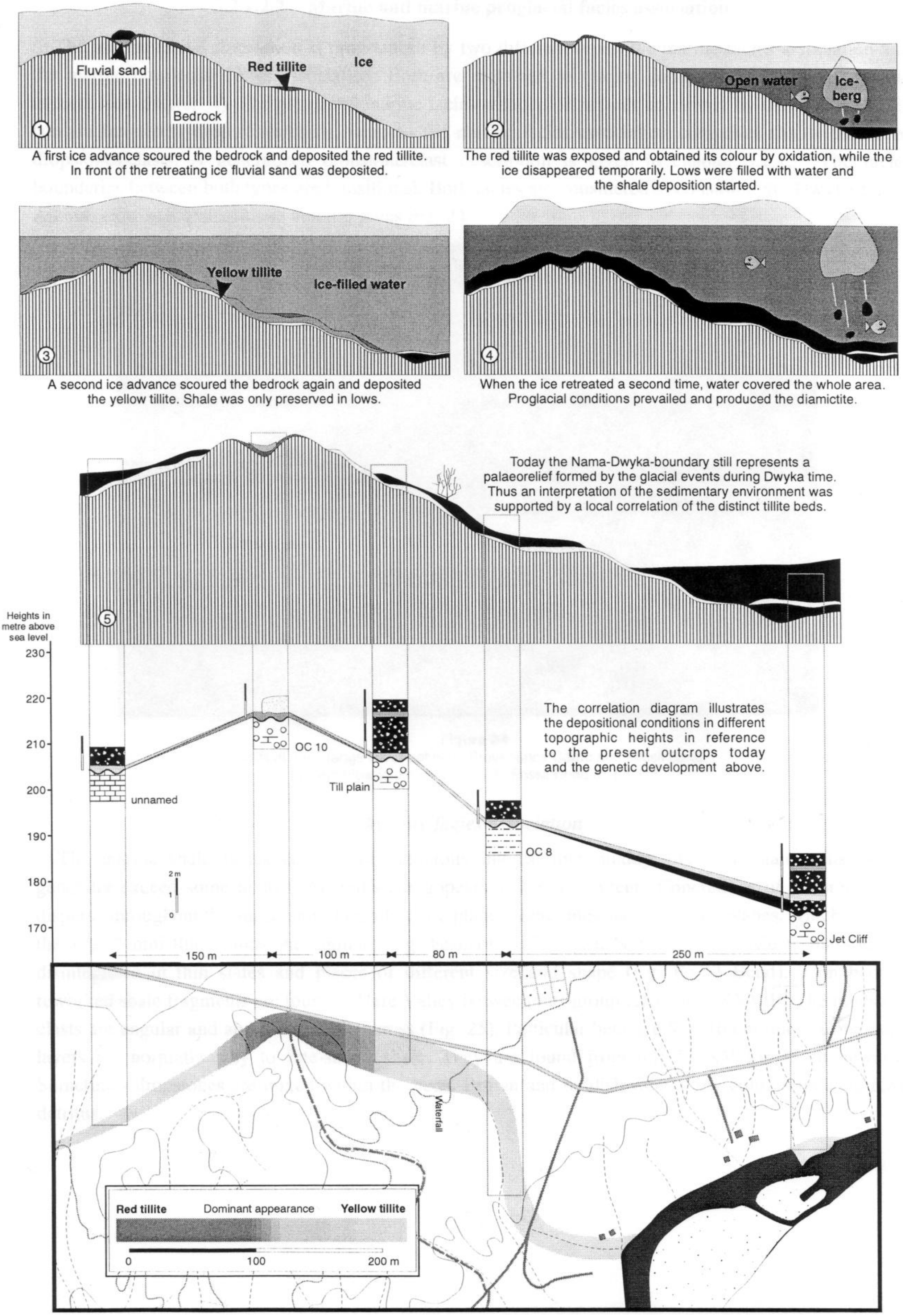
In the following the observations on the red and the yellow tillite and the sandstone mentioned above are composed to an environmental model during the initial glaciation. Further considerations about the origin of the sandstone refer to its colour. The red colour could be obtained either primary or secondary (corresponding to similar considerations about the red tillite). Thereby it is remarkable that only tillites in the vicinity of the red sandstone happened to oxidize. Lateral migration of iron from the sandstone to the tillite can not precluded, but red tillite also occurs above the highest preserved sandstone. Such considerations require information about the original extension of the sandstone body. Referring to the present information an exposition during deposition is more probable. A closer look on the attached map shows that the red sandstone and the red tillite are situated on a palaeorelief high, which was existent prior to or must have been formed during the initial glaciation (The difference in elevation of the exposed tillite above shale at Jet Cliff and the red tillite at the Head of Raven Gorge is at least 50 m). This palaeorelief will deliver the explanation.

The course of events could have been like this (see Fig. 23): The withdrawing glacier deposited tillite. Proglacial streams drained along depressions which were produced by the glacier and filled their channels with sandy deposits. Both sand and till were left on land highs, which were not covered by water (Head of Raven Gorge). The exposed rocks were oxidized. Lower areas were covered with water and enabled the sedimentation of diamictitic shale. Ice-rafted transport of material, indicated by the dropstones in the shale between the glacial floor and the yellow tillite at Jet Cliff, implies that the glacier did not retreat much or not at all. Perhaps the glacier just floated up, as already mentioned above. Finally the ice advanced a second time, scoured the red tillite and deposited the yellow tillite at least at Jet Cliff. The yellow tillites at Fossil Bend and outcrop # 8 are most probably derived from the second glacial advance. They were deposited in a topographical higher situation, so that the ice reached the ground and scoured it a second time. Former tillites were removed. Nevertheless tillites at the vicinity of the red sandstone were scoured but not removed due to a decreased load of the overlying ice, since glacier compensate the subjacent relief and become thinner towards and upon relief highs.

A summary of the preceding discourse shows that the yellow and red tillite probably have to be treated as two distinct tillite beds derived from two subsequent ice advances. During the first advance the bedrock was scoured and material was deposited under subaerial conditions. The second advance again scoured the bedrock and the former deposits of red tillite. Moreover yellow tillite was deposited either on the rescoured surface and on shale which was sedimented during the phase of retreat. Thus the similarity observed in the field is coincidental.

Sedimentary environment

The deposition of the tillite is an unambiguous indicator that subglacial conditions prevailed. The coincidence of proglacial fluvial red sandstone and red tillite suggests locally subaerial proglacial conditions (cf. Brunn, 1996). The striated tillite and the appearance of a tillite bed separated from the glacial floor by a shale unit show that the glacier advanced a second time. The juxtaposition of diamictitic shale and tillite in the same stratigraphic level as the red tillite suggests coeval glaciolacustrine/-marine and subaerial conditions.



A first ice advance scoured the bedrock and deposited the red tillite. In front of the retreating ice fluvial sand was deposited.

The red tillite was exposed and obtained its colour by oxidation, while the ice disappeared temporarily. Lows were filled with water and the shale deposition started.

A second ice advance scoured the bedrock again and deposited the yellow tillite. Shale was only preserved in lows.

When the ice retreated a second time, water covered the whole area. Proglacial conditions prevailed and produced the diamictite.

Today the Nama-Dwyka-boundary still represents a palaeorelief formed by the glacial events during Dwyka time. Thus an interpretation of the sedimentary environment was supported by a local correlation of the distinct tillite beds.

The correlation diagram illustrates the depositional conditions in different topographic heights in reference to the present outcrops today and the genetic development above.

Figure 23
The cartoon illustrates the genetic origin of the yellow and the red tillite and the fluvial sandstone.

3.2.1.2.2 Marine and marine proglacial facies association

The marine facies association is pronounced by two different types, the marine facies association and the marine proglacial facies association. Both are reckoned to marine conditions by palaeontological aspects (see chapter 4). The proglacial marine facies association is built up mainly by diamictites which contain frequently dropstones/clasts, whereas the marine facies association comprises shales devoid of dropstones/clasts. A generalized dropstone/clast description is given in chapter 3.2.1.3. The facies boundaries between both types are transitional. Both facies are considered to constitute the Dwyka Shale. An overview of a typical shale outcrop gives Fig. 24.

Figure 24
Cliffs at the Orange River between Provenance Camp and Fossil Bend.
Locality: View to the west towards Fossil Bend on the left.

Marine facies association

The marine shale facies consists of numerous intercalating muddy and silty shale units, which generally exceed some metres. Altered shale appears yellow and green. Concretions of different types disperse throughout the succession. Fresh fracture planes sometimes show bedding planes, which separate the 1 to 3 mm thick mudstone laminae, e.g. head of Owl Gorge. Normally the shale is massive and disintegrates in thin slates and pieces of different size and shape (e.g. Fossil Bend). Thin beds of reworked shale fragments are found at Hare Valley between tuff group XXXIV to XXXVIII. The mudstone clasts are angular and about 1 to 2 cm across (Fig. 25). Particular beds are 5 to 10 cm thick. Contiguous layers are normally silty to fine-sandy shale. They are found from tuff XXXV for 15 m upwards. Sometimes dropstones are mixed within the beds. Brown and reddish weathering colours indicate ferric detritus.

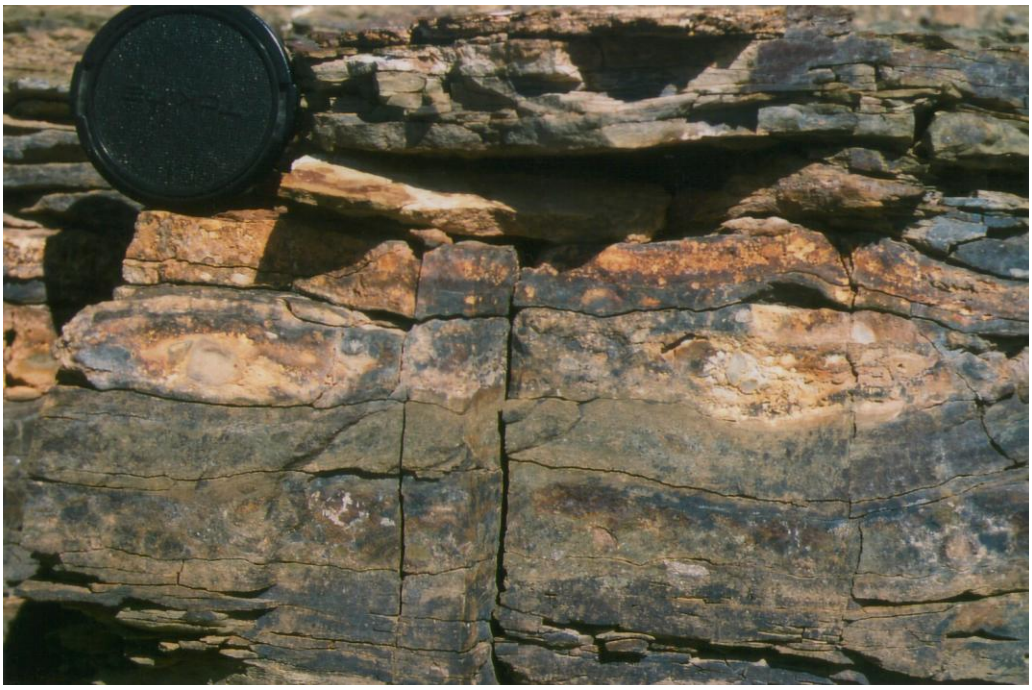


Figure 25
Occasionally small beds of reworked angular shale appear. The fragments are 2 to 4 cm large.
Locality: Hare Valley about 250 m north of the road D 212.

Marine proglacial facies association

Shale and diamictitic shales pass into each other and are hard to distinguish as the finding of dropstones is accidental. Thus units classified to be diamictitic are units with an increased content of dropstones, but this does not preclude that dropstones nevertheless occur sporadically throughout the complete succession. Dropstone-bearing rocks are usually interpreted to be deposited under periglacial marine environment. But also interglacial conditions can produce dropstones, especially around their ice covered poles or there where glacier enter a larger body of water. Furthermore it must be outlined that ice does not constitute the only resource of clast-transport. Some marine plants, such as seaweeds, are attached to the ground. As they grow their buoyancy increases so much that they unplug parts of the ground and float off. This mechanism, however, is not considered to be significant to explain the abundant occurrence of dropstones in the investigated area. The common CPD ranges from 70 to 100 in the basal diamictite. Diamictitic shale further up in the stratigraphy sometimes exceeds CPD 200. The EACS normally ranges between 3 and 8. As explained below (see paragraph ***Dropstones***) surpassing EACSs are present locally. Large dropstone boulders chiefly of plutonic or metamorphic rock, up to 1.5 m across, occur between tuff group XXXII and XXXIV, 80 m west of Hare Valley and about 50 m north of the road D 212.

Diamictitic interlayers

The Hippo Diamictite

Exposure: The Hippo Diamictite is traceable from Fossil Bend throughout Provenance Camp to the meeting of the road D 212 and the Hare Valley.

About 40 m from the base of the Dwyka Group a stratum of coarse diamictite is present which is highly resistant to weathering. Regarding its irrefragable nature the layer was named Hippo Diamictite. It is an unsorted, non-graded, matrix-supported diamictite with a grey calcareous silty matrix. The silty matrix carries clasts, which lithologically resemble the dropstones in the diamictitic shale, but with a considerably decreased CPD of 10 to 20 and an EACS-range from 10 to 20. Sedimentary structures lack at all. It serves as perfect marker horizon which can be traced as relief step throughout the study area due to its low weatherability. Its thickness varies laterally from 35 cm to 80 cm, but stays persistent. Erosional features at the base were not observed. It overlies the subjacent shale conformably. This rejects an interpretation of the Hippo Diamictite as mass flow. It rather represents a phase of increased terrigenous input in reference to an increased deglaciation activity. Withdrawing glacier tend to more frequent calving. The more icebergs get detached and drift off, the more material is carried off. This explains the abundant occurrence of clasts within the diamictite. Similar surpassing temporary discharge of coarse grained iceberg-rafted debris (Heinrich layers) in the North Atlantic was discovered by Heinrich (1988). He ascribed them to instabilities of the ice-stream flow within the Laurentide Ice Sheet (Heinrich, 1988; Seidov and Maslin, 1999).

The Goats Cliff Diamictite

Exposure: The Goats Cliff Diamictite forms steps in the river beds at the bottom of Goats Cliff and in the transition of Owl Gorge and Hare Valley.

A convolute bedded marlstone with increased clast content turns up about 100 m above the base of the Dwyka Group (Fig. 26). It was named after the type locality 'Goats Cliff Diamictite'. Predominantly quartz, quartzite and gneiss constitute the lithology of the clasts with a typical EACS of 4 to 6 and a CPD of 40 to 50. The sediment is wrapped up and contorted. This convolute bedding suggests creeping or sliding of the material by either gravity or glacial tectonics. No exposure of this layer was recognized at a wall. They are only found in the river beds, where they form channel steps. Thus no determination of their thickness was possible. The very confined lateral extension and the convolute structure favour an interpretation of the Goats Cliff Diamictite as tillite.

Figure 26
The Goats Cliff Diamictite is a convolute bedded marlstone which bears clasts.
Locality: River bed at the upper Goats Cliff: outcrop # 5.

Varvite/laminite

Exposure: Below Jet Cliff, a competent bed forms a terrace at the bank. Another locality just lies below the White Horizon at the western boundary of the mapping area.

At Jet Cliff an about 50 cm thick varved bed lies 1-1.5 m above the base of the Dwyka Group. The bed consists of alternate layers of green clay and brown silt. This massive bed exceptionally withstands weathering and forms an erosional terrace. Dropstones up to 10 cm across float in a clay and silt matrix. Clean fracture plains show a distinct sequence of laminae. The brown laminae are about 3 mm thick, whereas the interbedded green laminae are only 2 mm thick. A fracture plane displayed 28 distinct laminae within a 74 mm thick section. The rhythmic change is believed to comprise an annual cycle of deposition in a body of still water (Talbot and Allen, 1978). Thus on average, an annual cycle is 5.2 mm thick. Therefore it took about 192 years to deposit 1 m of now consolidated sediment at continuous conditions. A trace fossil on a distinct bedding plane in the lower third of the varvite is the lowest fossil found in the succession (see Chapter 3). Above the Waterfall at the road to Rosh Pinah the same trace fossils were found in the same bed.

Banded clay also crops out below the White Horizon (see 3.2.1.2.3) at the western boundary of the mapping area. About 300 m north of the road to Rosh Pinah a steep slope of shale rises up to a thin exposure of the White Horizon, which is immediately capped by the dolerite (S 28°40.404'/ E 017°32.795'). About 15 m above the White Horizon 12 annual cycles were counted in 6 cm of consolidated mudstone. In contrast to the varvite at the base, the sedimentation rate has been doubled: each year 10 mm of mudstone were deposited.

The White Horizon

Exposure: The White Horizon commonly crops out close to the shale-dolerite boundary at steep slopes below of the dolerite escarpment. As a white band extends the horizon from the eastern to the western study area boundary.

About 10 m below the Dwyka-Ecca-boundary, where the last discovered dropstone was found, a harder, almost white weathering rock is exposed (Fig. 27). This layer was named the White Horizon, as it is laterally consistent and thus comprises a marker horizon for the transition of the Dwyka Group into the Ecca Group. The White Horizon consists of an about 11 m thick sequence of white beds, particularly noticeable in Centipede Gorge and Owl Gorge. About 4 m white-weathered shale is overlain by 1.5 m dark-coloured shale which again is succeeded by a white horizon of 0.5 m thickness. Above another 3m of dark shale a 1.5-2 m thick white horizon completes the sequence. Red ferric laminae are prominent sporadically. The sequence is laterally persistent and provides a considerable marker horizon in the upper part of the section. Haughton and Frommurze (1936) explained the bright colour with an altered and recrystallized calcareous portion in the matrix. Dropstones appear occasionally in the White Horizon.

Figure 27
The White Horizon is a white weathering muddy shale, which is far visible. The exposed wall is about 10 m high. *Locality:* Centipede Gorge.

Sedimentary environment

A continental glacial facies represented by the red tillites turns into proglacial marine (indicated by fossils, chapter 5) facies with dropstone-bearing diamictites and shales. This interpretation is conform with the concepts of Visser (1997), who divided the Dwyka Group in 4 deglaciation sequences each typically starting with a diamictite facies which is succeeded by a shale facies. A possible division of the Zwartbas succession correlates the red tillite to the first, the yellow tillite to the second, the Hippo Diamictite to the third and finally the Goats Cliff Diamictite to the fourth deglaciation sequence. Thereby units which are poor in or free of dropstones are interpreted as an interglacial marine facies. Marine fossils accredit the black pelites to be certainly marine. The formation of rhythmites, varvites or laminite are interpreted in different ways. Whereas McLachlan and Anderson (1973) mention that varves were only produced in fresh or at least brackish water, Friedman et al. (1992) and Woodworth-Lynas (1996) note, that varves were not necessarily deposited in glaciolacustrine conditions but are also found in environments of prevailing glaciomarine conditions.

3.2.1.3 Dropstones/clasts

The occurrence of dropstones is a significant indicator of a glacier-associated environment. Glaciers transport exarated rocky material as glacial drift and deposit it during ablation of the ice. Sometimes the ice terminates in proglacial lakes or in the ocean. When the ice flows into the water it floats up and loses ground-contact. From time to time parts of the glacier become detached and drift off. Calved icebergs still carry glacial drift, which 'drops' into the water while melting, dissipates in finer distal sediments and results in diamictitic rocks.

The development of the diamictitic shale is cyclical. Size and lithology of the dropstones vary much throughout the succession (see profiles in Appendix page 73 to 80). The general lithology comprises quartzites, vein quartz, granites, gneisses, volcanics and carbonates. Most common dropstones are hardly rounded plates of grey to green schist and quartzite. In the gneissic dropstones foliation is outlined by dark layers of biotite. Amygdaloidals in volcanics are frequently filled with calcite. The lodgement till at the base of the succession also contains cherts and jasper, which seems to diminish further up. The diamictite commonly has an EACS of about 2-5 (Fig. 28). Thus locally found dropstones are up to 1.5 m across (west of Hare Valley: S 28°40.637'/E 017°32.876 - just above T XXXIII). These blocks are either gneiss, granite or volcanic (Fig. 29).

Figure 28
This large dropstone of ribbon gneiss was found between tuff XXXIII and XXXIV represents the maximum dropstone size.
Locality: 20 m east of Hare Valley, 60 m north of the road to Noordoewer.

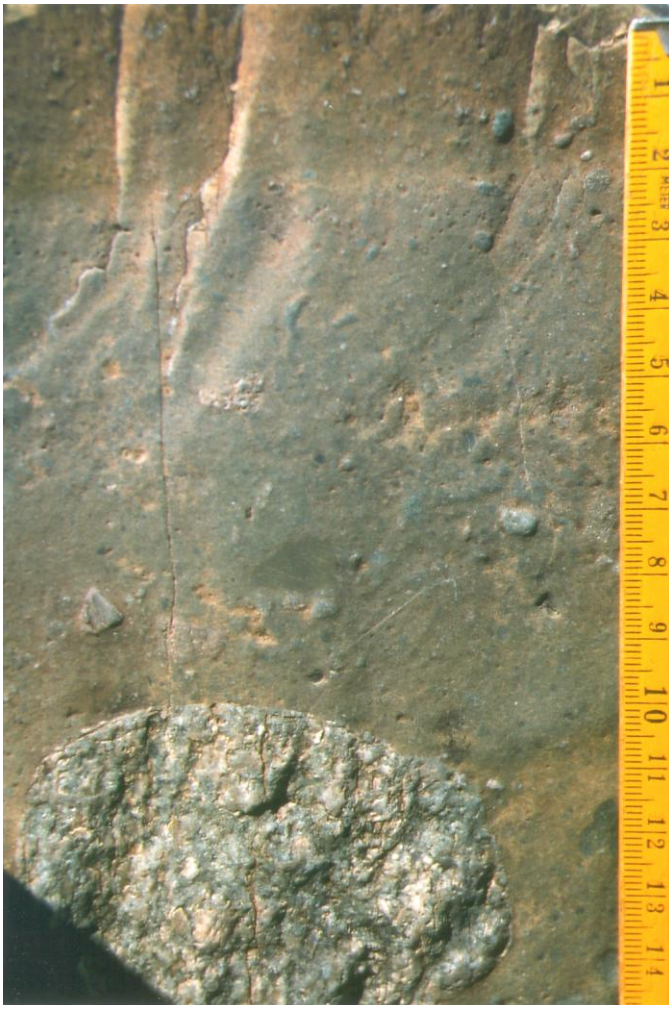


Figure 29
An example for the clast size range displays this massive siltstone.
Locality: Jet Cliff.

An exposed 2 by 2 m bedding surface of the varved bed at Jet Cliff yields following distribution of main components (EACS: 3; CPD: 50-60):

quartzite	62%	
granite/gneiss	23%	
schist	17%	max. ∅ = 12 cm
others	1%	n = 117

In some calcareous nodules sandy material of mainly quartz was found. Middle and coarse sand compose this porous sandstone with angular contours. It is the only type of rocky material occurring in nodules. The concretion of calcium carbonate (see 3.2.1.4) was supported by the porosity and the coherent large reaction surface on the boundaries. According to the shape and the porosity this sandstone is interpreted as former unconsolidated, but frozen glacial drift enclosed by ice of an iceberg (Fig. 30). Ice constituted the cement, when the sand broke off the iceberg and sunk. Thus the sand has never undergone abrasion while consolidated and therefrom the sandstone obtained its angular shape. Later the sand was diagenetic solidified.

Dropstones are the distinct characteristic for the Dwyka Group (Kingsley, 1985; Visser, 1983). In the White Horizon dropstones are only sporadically present. Several metres above the White Horizon the dropstones totally disappear and no dropstone was found in the succession further up. This diminishing dropstone occurrence and finally the total absence is interpreted as the transition of the glacio-marine dropstone-bearing Dwyka Group into the marine dropstone-free Ecca Group.

Figure 30
A dropstone of immature fine to middle sandstone. The grains are sub-angular. Sometimes quartz grains with the size of 2-3 mm are found. It might be interpreted as glacial drift, which was deposited while being frozen.
Locality: Fossil Bend.

3.2.1.4 Volcanic ash-layers

In the lower section of the Dwyka Group, up to 95 m from the base, 65 distinct ash-fall derived volcanic tuff beds have been discovered. Fig. 31 shows their distribution throughout the lower part of the succession. They generally are of yellow colour, sometimes appear white and thicker, especially, when gypsum has crystallised and increased the thickness of the original tuff bed. Normally the ash layers are less than 1 mm to a few mm thick, particular layers range up to about 4 cm. About 50 m to 70 m from the base of the Dwyka Group they reach the highest density in the shale unit, where 30 ash layers could be found within 20 m. Best and least altered tuffs are exposed at the cliff along the Orange River. Clay minerals have replaced the original ash material, wherefore the tuff horizons should be described as bentonites today. The tuffs appear relatively soft, especially when the material is wet. The ash beds apparently do not contain pelitic material, which is a sign of rapid deposition. Only tuff beds III b and c are separated by a darker bed of probably increased pelitic material. The total thickness of 2 cm is shared with 1.2 cm by III c and 0.3 cm by III b (Fig. 32). The interspace consists of tuffitic shale. Moreover bioturbation of the tuffs are rather rare. They are laterally continuous and excellently traceable.

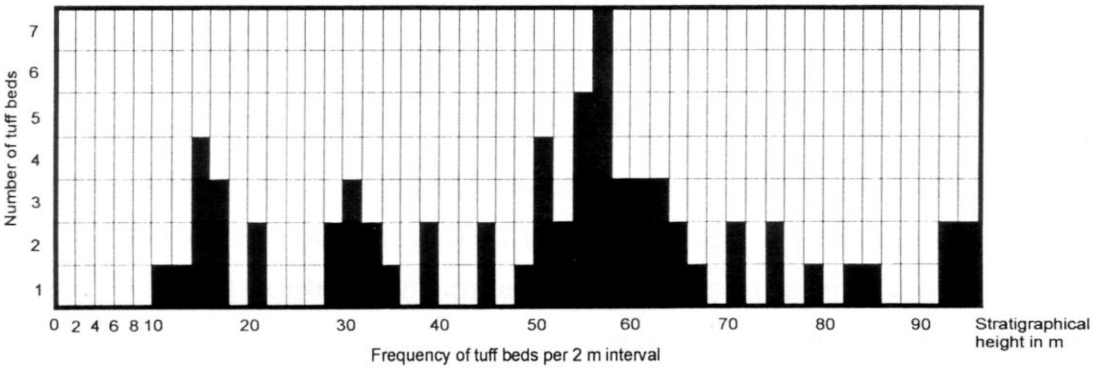


Figure 31
The diagram shows the frequency of tuff beds per 2 m interval. It covers the tuffs from the base up to 96 m above the Dwyka Group.

Figure 32
Ash-layer III b+c form the bright thick layer at the bottom of the picture. Between the hammer head and the dropstone, T III d forms a thin bed. *Locality:* Cliff 50 m east of Provenance Camp.

3.2.1.5 Nodules and concretionary bodies and horizons

Throughout the complete Dwyka succession the shale display different concretionary horizons. Some of this horizons continue laterally and can be used for correlation within the study area.

Black rounded nodules and irregular concretionary bodies

Black perfectly rounded or oval nodules and larger bodies with sinuously rounded bodies, occasionally fossil-bearing, occur almost throughout the whole Dwyka Group succession (Fig. 33, 34). They consist of shale hardened by carbonate. The nodules occur either isolated or are enriched in horizons. They normally vary from 5 to 20 cm in horizontal and from 10 to 40 cm in vertical diametre. At XI, XII and above XXXIII pervasive bodies of black concretions appear. They are up to 30 cm thick, but extend laterally several metres. McLachlan & Anderson (1974) explain the origin of the black nodules under calcium carbonate saturated conditions by the precipitation of carbonate - induced by pH-decrease - around a nucleus, e.g. a cadaver, coprolite or wood (see Chapter 3).

Yellow concretionary horizons

Yellow laterally persistent concretionary layers up to 60 cm in thickness are also spread across the pelites. Since they sometimes pass into tuff beds, it is possible that they developed from altered ash layers. Thus they were not generally ascribed to the tuffs, but have been assigned to them whenever correlative evidence was obtained. Cone-in-cone structures indicate carbonate content.

Brown concretionary horizons

Eventually a concretion type occurs, which resembles the yellow concretion type described above. Both coincide in shape and average thickness. But the considered type appears in a dark brownish colour probably obtained from a ferric content. In some places ferric cone-in-cone structures with a metallic shine overhang the weathered surface. Moreover the concretions occasionally show horizontal gypsum-like fibrous structures. These structures could be gypsum pseudomorphoses of carbonate material. The carbonate was overprinted by ferric oxide, which probably replaced or enveloped the calcium carbonate.

Figure 33
Extensive black concretionary bodies with rounded sinuous margins. They occur only between tuff group XI and XII.
Locality: At the Orange River, 80 m west of Provenance Camp. See hammer for scale.

Figure 34
The concretionary horizons in the shale some decimetre above tuff XXXIV show a high variability in thickness. Bulged subjacent and adjacent shale layers indicate the post-sedimentary vertical extension.
Locality: Cliff at Hare Valley. See hammer for scale.

Sedimentary environment

The concretionary horizons disappear at about the same stratigraphical level as the dropstone. This stratigraphical level was presumed as Dwyka-Ecca-boundary. This abrupt lack of concretions might cohere with a ceasing glaciation. The termination of glacial erosion and the loss of carbonate input involved, such as derived from the glacier milk, could explain the transition into a massive shale devoid of concretions.

3.2.1.6 Palaeodirections

Palaeoice flow

Measurements of the striation trend in the bedrock at Jet Cliff, Fossil Bend and on the till plain south of the road D 212 100 to 500 m east of the junction at the ostrich farm give a NNE-SSW orientation for the ice flow (Fig. 35). This agrees with the inferred N-S orientated palaeoice flow noted by Martin and Wilczewsky (1970) and Visser (1983).

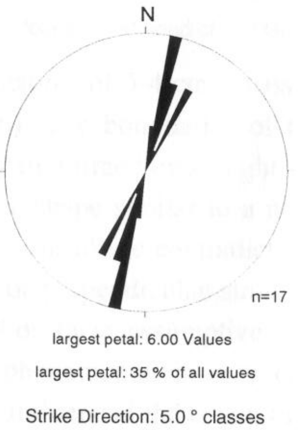


Figure 35
This is a rose diagram of the glacial striation trends, which were grooved into the Nama bedrocks by the Dwyka glacial event. Measurements taken from Jet Cliff, Fossil Bend and the till plain on the southern side of the road D 212 200 to 800 m west of the junction at the ostrich farm.

Palaeotransport direction based on wood alignment

Elongated wood parts display the palaeoflow-direction of their medium of transport, because the long axis of the wood fragments aligns parallel to the flow to reduce flow-resistance. Several logs were found at Fossil Bend (see chapter 4.4). The logs show repeated orientation changes within the different stratigraphical levels. Wood fragments of tuff group VI yield E-W to ESE-WNW trending alignment. About 3 m further up (IX, and above X) wood fragments are NE-SW orientated. After 15 m (XVI) orientated wood set in again, but varies the following 16 m, until it ends up in an ESE-WNW trend immediately under tuff group XXVIII.

These results should be handled with care, as the log deposition and alignment happened coeval with the sedimentation of argillaceous material. The lamination of these deposits and the exceptionally well preserved fossils within these rocks imply prevailing still-water conditions where the material rather settled gravitationally vertical through the water column. Thus the alignment can also be rather accidental and a misinterpretation impends.

3.2.2 Deposits of the Prince Albert Formation of the Ecca Group

The shale facies

Exposure: In the eastern part of the study area the Prince Albert Shales crop out at the base of the dolerite sill and above. In the western part only sporadic exposures are assumed below the base of the dolerite and a general exposure above the sill.

The formerly as non-glaciogenic considered Upper Dwyka Shales (Kingsley, 1985) are today regarded as the Prince Albert Formation of the Ecca Group. They comprise massive blue to black shale. A lack of dropstones is the main characteristic of the shale, wherefore the exact Dwyka-Ecca-boundary is difficult to locate (see above). The dark shale about 5 m above the White Horizon was estimated as the base of the Prince Albert Formation. Within the shale succession lies a unit of quartzitic green shale. This quartzitic shale crops out about 500 m north of the dry waterfall at the head of Owl Gorge. Since the layers there are rotated, they could not be classified stratigraphically. A bedding plane with curious structures dips about 30° to the east (see paragraph below). No evidence was found that the layers are overturned. Both diagenesis and rotation were probably caused by the intruded dolerite in the proximity.

Undetermined structures

Exposure: Undetermined structures were found at the head of Owl Gorge (S 28°39.153'/E 017°33.742).

Rectangular to polygonal structures of 3-4 cm across cover an inclining bedding surface in a more or less symmetrical order (Fig. 36). The boundaries of the rectangles trend in perpendicular lines. The interspace between the polygons are formed by straight, acute crests. The interpretation of these structures is problematic. As they show the shape similar to a negative cast of desiccation cracks, the layer must have been turned over. Moreover shrinkage contradicts the pelagic conditions suggested by the adjacent rocks. Furthermore the pattern of perpendicular straight lines might suggest a joint associated origin. Today no jointing was observed on these assumptive former planes. Another interpretation could be the influence of weather, but this phenomenon is very confined within the same formation. Finally the intrusion of the sills might have influenced the origin of this structure regarding dehydration and heating processes.

Figure 36
Undetermined structures on a bedding plane of upturned quartzitic shale.
Locality: S 28°39.153'/E 017°33.742'.

Sedimentary environment

The pelites constitute a mainly distal, shallow marine facies. The possible occurrence of desiccation structures implies a sporadic drainage. This, however, contradicts the general opinion that hemipelagic conditions prevailed (Kingsley, 1985), which is confirmed by the adjacent shale.

3.2.3 The Keetmanshoop Dolerite Complex

In southern Namibia between Karasburg and Noordoewer two sills penetrated Karoo sediments in different stratigraphic levels. These Tandjiesberg Sills are part of the Jurassic Karoo Igneous Province as the Keetmanshoop Dolerite Complex (Gerschütz, 1996; Martin, 1981a) is. In both cases two superimposed sills have intruded sediments of the Dwyka Group as well as the Prince-Albert and Whitehill Formation of the Ecca Group. In the Noordoewer vicinity they lie about 200 m apart. Whereas the lower sill penetrated the shales at the Dwyka-Ecca boundary, the upper sill penetrated the Whitehill Formation and caps the Tandjieskoppe Mountains today. The upper sill does not extend into the study area, but is far visible at the top of the Tandjieskoppe Mountains. The following discourse treats only the lower sill at Zwartbas.

Dolerite sill

Exposure: The dolerite sill extends along the northern boundary of the study area. The sill forms the scarp which lies along the road D 212 about 0.8 to 1.5 km to the north.

The lower sill in the study area is about 35 m thick and consists of black, hard, massive dolerite. Ophithic to sub-ophitic rock fabric has been formed, which can be seen by white lath-shaped plagioclase phenocrysts. They are well visible as up to 5 mm long and 1 mm broad white dashes on exposed and reddish-brown altered surfaces. No vesicular structures, even not at the contacts, were recognized.

Figure 37
The photograph shows the vertical variation in disintegration of the dolerite. Above a distinct boundary, the dolerite desquamate more massively than the lower fissile part.
Locality: Lower Duifie River course (100 m north of outcrop # 14).

The dolerite sill can be divided into three distinct sections due to their variable weatherability. The basal section disintegrates in small chippings, the central section however splits into centimetre- to metre-sized pieces and leaves sub-rounded boulders up to 3 m in diameter (Fig. 37). The latter is topped by a crumbling rock similar to the rock at the base again. Mineral sizes vary commonly from 2.0 to 4.0 mm in the central and 0.5 to 1.5 mm in the basal and top section. The rapid change in the rock competence at the section boundaries suggests a coherence between the grain-size and the weatherability of the particular sections. The basal section extends vertically about 10 m, the central section about 15 m and the top section again only about 10 m. The contact to the under- and overlying shales are always sharp (see also Fig. 43). No evidence was found that the varieties have been originated by ensuing emplacement phases. Nevertheless the intrusion of the dolerite at a time is favoured, particularly since the bottom and top contact zones and the internal dolerite section boundaries are parallel. The over- and underlying hostrock has chilled the intruding magma at the top and at the base of the more or less horizontally and conformably intruding sill and produced the crumbling marginal zones. This implies that rather the dolerite itself was affected by chilling during the emplacement than the sill indurated, baked, burned and fritted the hostrock. Thus a critical isotherm parallel to the sill's surface separates the more slowly cooled, well crystallized and more competent centre from the chilled, poorly crystallized and crumbling periphery. A heat flux perpendicular to the sill's surface from the magma to the colder hostrock benefited the formation of the section-boundaries parallel to the bottom and top contacts (Fig. 38).

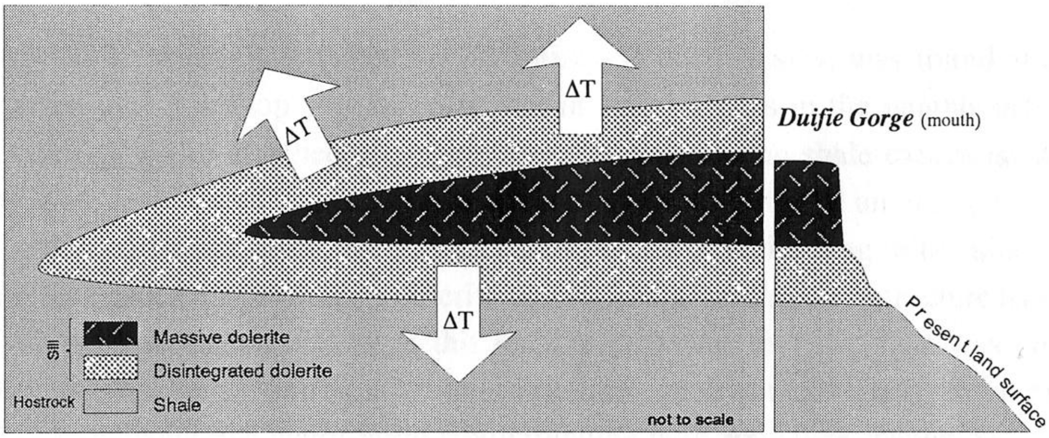


Figure 38

This figure illustrates the origin of the distinct sections of the sill. Marginal heat flux produced the finer grained and less competent top and bottom section. The right profile was taken at the Mouth of Duifie Gorge and shows the connection of relief and outcropping rock.

Especially in the eastern and central part of the study area the igneous body lies concordant to the bedding. In the Puff Adder Valley the sill penetrated the shale discordant (Fig. 39). A view from the head of the valley southwards reveals the discordant boundary of the bottom of the sill and shale. Patches of dolerite exposures are situated in a vertical and horizontal disorder and can therefore be ascribed to either post-intrusive tectonic activity or discordant emplacement (see also Fig. 61). The underlying shales are moderately flexed with a generally eastward dipping trend at the valley head, but with an increasing dip to the valley mouth. A distinct fault was not recognized.

Sections of the base of the sill provide an estimation of the emplacement orientation. More or less vertical dolerite-hostrock contacts have been formed by laterally varying emplacement levels during the migration of the sill through the more or less even-bedded hostrock (see Fig. 39). Thus the sill migrated parallel to the strike of this vertical contact and did not ascend along the contact plane. Joints supported the magma to form such interstratigraphical steps parallel to the migration direction. Weaker rocks could be easier displaced, whereas the sill incised into lower stratigraphical levels. Estimations on the orientation of vertical sill boundaries at outcrop # 15, outcrop # 12 and above outcrop # 3 gives a northwestern-southeastern trend for the sill transgression.

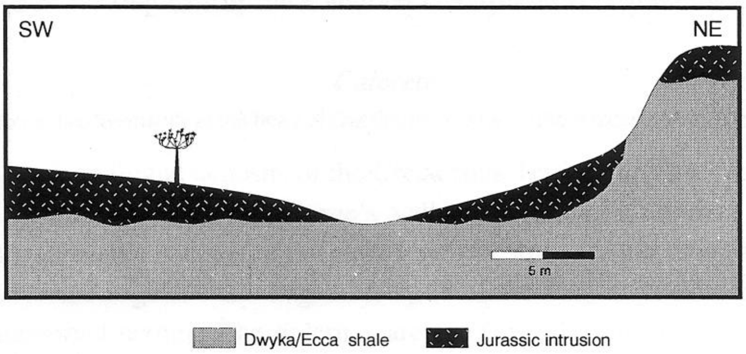


Figure 39
The cross section outlines non-faulted sill-hostrock-contacts in different stratigraphical levels. The vertical contact strikes in migration direction.
Locality: of the pass at outcrop # 13.

Dolerite dyke

Exposure: A dolerite dyke was found in the centre of the northern boundary of the study area at outcrop # 15 (S 28°39.304'/E 017°33.664')

A vertical dolerite dyke, which is connected with horizontal dolerite sills, was found at outcrop # 15. The locality is situated above the top sill-boundary and inclining shales in the neighbourhood infer that the area was deformed (see also attached geological map). Moreover the shale experienced a low grade metamorphose and was transformed into quartzitic shale. An exposure shows an about 1.3 m wide dyke, which terminates at the centre and at the bottom of the wall in horizontally lying minor sills (Fig. 40). The off-set of the minor sills is 0.5 m. Crumbling dolerite with a similar texture and structure as the dolerite at the contact zones constitutes the magmatite at this locality. It seems that the dyke was created along a thrust fault and served as feeder for minor sills. This structural weak zone at the northern extend of Owl Gorge is believed to be situated in a major north-south trending fault zone (see chapter 5).

Due to the small outcrop size a horizontal migration in a dike-shaped minor sill can also be assumed. Both interpretations would describe an exception in the study area.

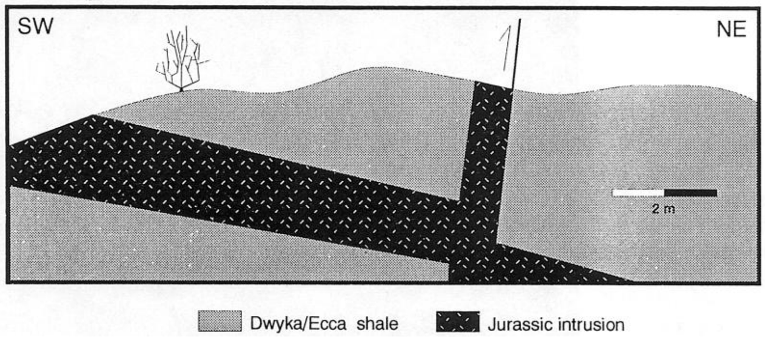


Figure 40
The cross-section shows a dolerite minor sill which was displaced by a fault accompanied by a dolerite dyke.
Locality: Pass at outcrop # 15.

Host rock features of the pelites of the Dwyka and Ecca Groups

Shaly host rocks of the Karoo Supergroup are modified mechanically by forces caused by the migration of the sill. At the head of Centipede Gorge and at the head of Puff Adder Valley shales of the Ecca Group were flexed during sill emplacement. In the Puff Adder Valley the shale was highly flexed (see Fig. 61). The folds, which occur a few metres below the dolerite, are 5-15 m and the fold limbs dip in high angles of about 60°. Thus the emplacement exerted strong enough forces that small scale compressional tectonism could take place (Price and Cosgrove, 1990). The fold axes trend W-E and are perpendicular to the sill transgression direction and the orientation of local intrusion-induced compression respectively.

3.3 Deposits of the Kalahari Group and recent deposits

Calcrete

Exposure: Calcrete was found predominantly at the head of Owl Gorge and its northern extension, e.g. at outcrop # 15.

In some places calcretized fluvial deposits of the Cretaceous-Tertiary Kalahari Group covers the Karoo sediments. At the upper end of the Owl Gorge's valley an extensive calcrete layer of a maximum thickness of 3 m rests on highly weathered dolerite (Fig. 41). Rounded pebbles and boulders of dolerite up to 50 cm in diameter and angular shale fragments up to 15 cm float in a calcareous silty-sandy matrix, and form a matrix-supported texture. The dolerites are not fluvially rounded, because they disintegrate already in situ by spheroidal weathering and the source area is close to this locality. Occasionally the flat fragments of shale are orientated and slightly imbricated, indicating the same run-off direction as today. The grain size of the matrix changes within longitudinal bodies, and an undulating (erosional?) contact to the underlying dolerite implies a fluvial origin.

Figure 41
Veins of white carbonate material passes through the dolerite at some locations. This calcrete veins were formed in a exceptionally deformed area, where the disrupted rock has undergone a pedogenic transformation into calcrete. Calcrete cemented fluvial deposits cover the dolerite.
Locality: Head of Owl Gorge:
S 28°39.839'/E 017°33.616'.

In the vicinity of the upper Owl Gorge, there where the 4x4-track joins the river bed just beside the track at a small ridge which divides the river bed into two channels before they drop down a dry waterfall, a thin but laterally continuous calcrete layer was found. The white 4-6 cm thick calcareous layer has sharp contacts to the sill above and the shale below (Fig. 42). The calcrete contains sporadically small, less than 2 cm wide angular shale fragments. White thin veins (less than 1 cm) of calcareous material pass through the globular splitting dolerite and join with the overlying calcrete layers at outcrop # 15 (see Fig. 41). Thus the disintegration and calcrete formation reached deep into the bedrock. This exclusive deep disruption of the dolerite coincides with the structural situation. It is believed that a fault zone extends through the Hare Valley, Owl Gorge and further north (see chapter 5). The calcareous layer might be a result of alteration, solution of carbonate in the dolerite or former overlying rocks, further mobilisation in the hydrosphere and finally of precipitation within the aquifer at the dolerite-shale-boundary.

Figure 42
A calcareous white 4 to 6 cm thick layer at the shale-dolerite-boundary carries angular shale fragments. It is thought to be calcrete.
Locality: Head of Owl Gorge: S 28°39.853'/E 017°33.618'.

Alluvium

Exposure: Alluvial sands extend along the Duifie river from the escarpment to the mouth at the Orange River. Furthermore alluvial fills were located in the gullies north of Provenance Camp.

A well-bedded sequence of fine grained sand and silt crops out in river beds at the slightly inclining slopes north and northwest of Provenance Camp, confined by the road to Rosh Pinah in the south and the dolerite-capped escarpment in the north (Fig. 43). They are predominantly charged with well-sorted deposits of fine-sand size. Shaly clasts are rare and only some mm large. The sediment is thinly layered and often shows tangential foresets, which are directed towards the Orange River. All these observations propose a slowly moving, highly suspended flow. Eitel (1994) described similar grain movement caused by rain splashs at the Skeleton Coast (northwestern Namibia), which are supplied by erratic drizzles. Mainly fine air-blown silt and sand are washed out from slopes, which are covered with hill slope debris. The rainfalls are usually not strong enough to initiate land slides or to mix large fragments. These floods have a limited range, slow down shortly after mobilization and settle out. While they are moving, they behave like a sheet flood without remarkable erosion or channel development.

Similar deposits are found in the main valley of the Duifie River. Here they fill the broad valley floor, where the river emerges the dolerite scarp. Fig. 44 shows the ill-sorted, non-graded, matrix supported and poorly consolidated sediment, which rarely contains dolerite boulders (20 to 40 cm, max. 120 cm in diameter) and shale fragments (max. 15 cm in diameter). The sequence reaches a maximum thickness of more than 7 m. Imbricated shale fragments are the only indicator of fluvial transportation. Despite high undulated palaeorelief of the valley, no signs of turbulently flowing water were found, especially not at the base. The river could hardly been erosive enough to cut out the relief due to the low elevation gradient throughout the examined lower valley section. At the contact to the shale the fill shows no out-wedging or on-lapping, but adjoins the inclined unconformity horizontally. Imbrication of shale fragments points to a transport direction to the south towards the Orange River. This means that the material was derived from the escarpment. The deposits can be regarded as sheet flood deposits.

Figure 43
Thin layered silt and fine sand fills river channels and gullies.
Locality: River cut 150 m northwest of Provenance Camp. See lens cap to scale.

Figure 44
Fine grain deposits overlie the Dwyka Shale. The moderately consolidated silt-sand deposits carries shale and dolerite clasts.
Locality: View from the southern gorge rim to outcrop # 6. Maximum outcrop height on the right is about 7 m.

Hill slope debris

Exposure: Hill slope debris are found at the slopes of outcropping shale at the bottom of the dolerite capped escarpment along the road D 212.

The slopes at the bases of the escarpment are covered with small fragments of the fissile shale. They are also found in the beds of recent rivers. Boulders of dolerite scatter the bottom of the slopes and are also often found in river beds. The dolerite boulder are normally 10 to 40 cm across, but also blocks of some decimetres occur.

Orange River Terraces

Exposure: Orange River Terraces are located on the top of the cliffs along the Orange River. They were found at the northern bank of the Orange River at Fossil Bend and eastwards.

Gravel terraces 20 m above the present low level of the Orange River were named Orange River Terraces. Dissected by incoming valleys the gravel terraces extend along the river, overlying the Dwyka Group cliffs from Fossil Bend (outcrop # 1) to the eastern area boundary. The gravel is well-rounded, non-graded, moderately sorted (pebble size 20-80 cm in diameter) and pebble supported. Coarse sand constitutes the matrix. A maximum thickness of more than 5 m is preserved at Fossil Bend (Fig. 45). Lithologically the terrace comprises pebbles in a high diversity. The main component is green, fine to coarse grained quartzite, green altered schist and granite. Further gneisses, volcanics, syenites and epidotites, and different varieties of quartz, red jasper, opal (white, brown, reddish-pink agate), and ferruginous layered shale are found. The base is enriched in reworked Dwyka Shale. The age of the gravel could not be determined exactly. Since the mouth of Duifie river at the Orange River was cut in the Orange River Terraces and filled with alluvium of the Kalahari Group, the terraces are considered to be younger than the Kalahari Group.

Figure 45
The pit of an abandoned diamond mine shows the enormous thickness and the homogeneous texture of the gravel of the Orange River Terraces. The total visible section in the pit is 4.5 m high.
Locality: The pit lies west of Fossil Bend on the cliff.

3.4 Rhyolite dykes

Exposure: Rhyolite dykes are found to dissect the dolerite sill at outcrop # 4, the dry waterfall north of Centipede Gorge, in the gorge at S 28°39.720/E 017°32.784 and its northern extension.

Greenish to grey fine-grained, massive dykes, up to 50 cm thick, pass through the dolerite. The microcrystalline structure foreclose a compositional determination. A X-ray diffraction (XRD) powder analysis showed that the principal minerals are quartz and plagioclase (albite), whereas orthoclase and varieties of the chlorite- and serpentine-group constitute the auxiliary components. Chlorite and serpentine are probably alteration products of micas, pyroxenes and amphiboles. The assumptive primary mineral assemblage of mainly quartz and felspar, and further some amphibole and pyroxene corresponds with the normative composition of an acid magma. Schreuder and Genis (1974) consider similar dykes on the farm Aussenkjer as rhyolite-dykes. In outcrop # 4 such a dyke corresponds to a fault zone. Slickensides on the dyke surface shows that the northwest to southeast trending dykes match the general pre-and post-intrusive structural trends. Although the faults sometimes can be traced in the shale, no volcanic rocks were observed within the disrupted shale. There are only calcite filled joints, which sometimes wedge out after some hundred of metres, crossing through the shale (Fig. 46). The mechanism and pathways of the injection of the rhyolitic magma is unclear. A horizontal progression of the magma in the 'dyke' is considerable. After the ascend of the magma through a small laterally confined vent in the shale along the fault zone, the rhyolite injected horizontally along the fault only when it passed into the dolerite. Despite of the fundamental difference between both magmatic rocks the dolerite and the rhyolite, their coexistence can be explained with magmatic differentiation in a single magma reservoir. so neither their age nor their true genesis was understood. They seemed to be injected a considerable time after the dolerite. The dolerite must have been cooled already when the rhyolite was injected, because the cooling of the rhyolite was much quicker than that of the dolerite, leading to a finer rock.

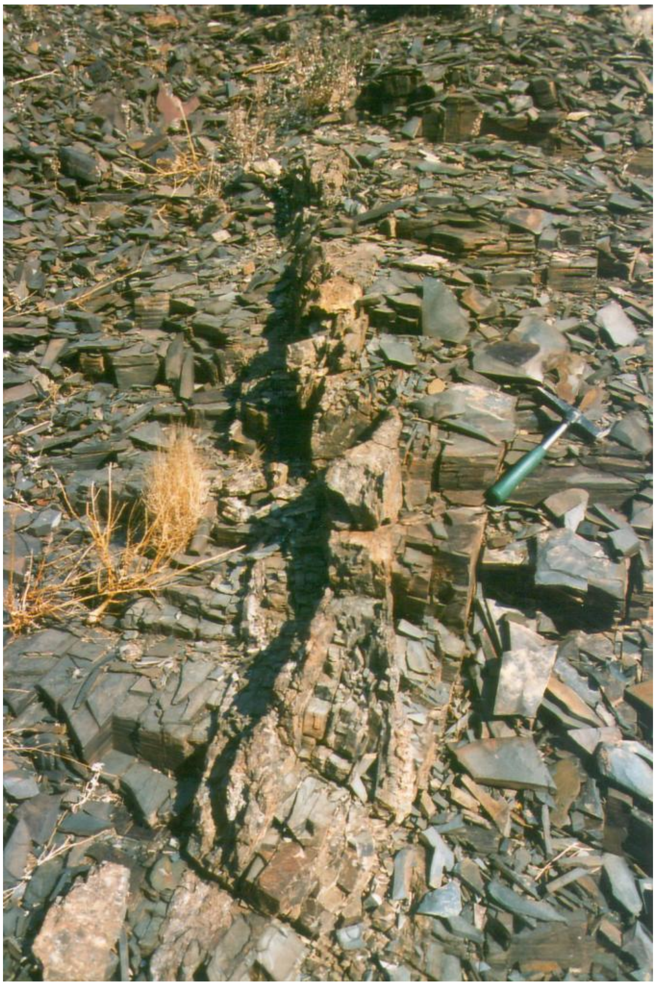


Figure 46
The picture shows calcite filled joints in a fault zone which passes into rhyolite dykes at the point when they reach the dolerite sill.
Locality: 50 m northeast of outcrop point # 3.

4 Fossils

Although many authors report on fossil-bearing beds in the Nama in southern Namibia (Germs, 1983; Gresse and Scheepers, 1993; Saylor et al., 1995), especially in the limestone units, no evidence was found at Zwartbas.

However, the glaciogenic Dwyka Shales contain fossils in the lower part of the succession. Besides numerous petrified wood and plant remnants, fishes, coprolites and few shell bearing species were found. The most common fossils are invertebrate ichnogenera, e.g. domichnia, fodinichnia and pascichnia. Discoveries were chiefly made at Fossil Bend, as the lower 80 m of the succession are well exposed along the Orange River. Fig. 47 gives an overview of the fossil distribution in the lower Dwyka.

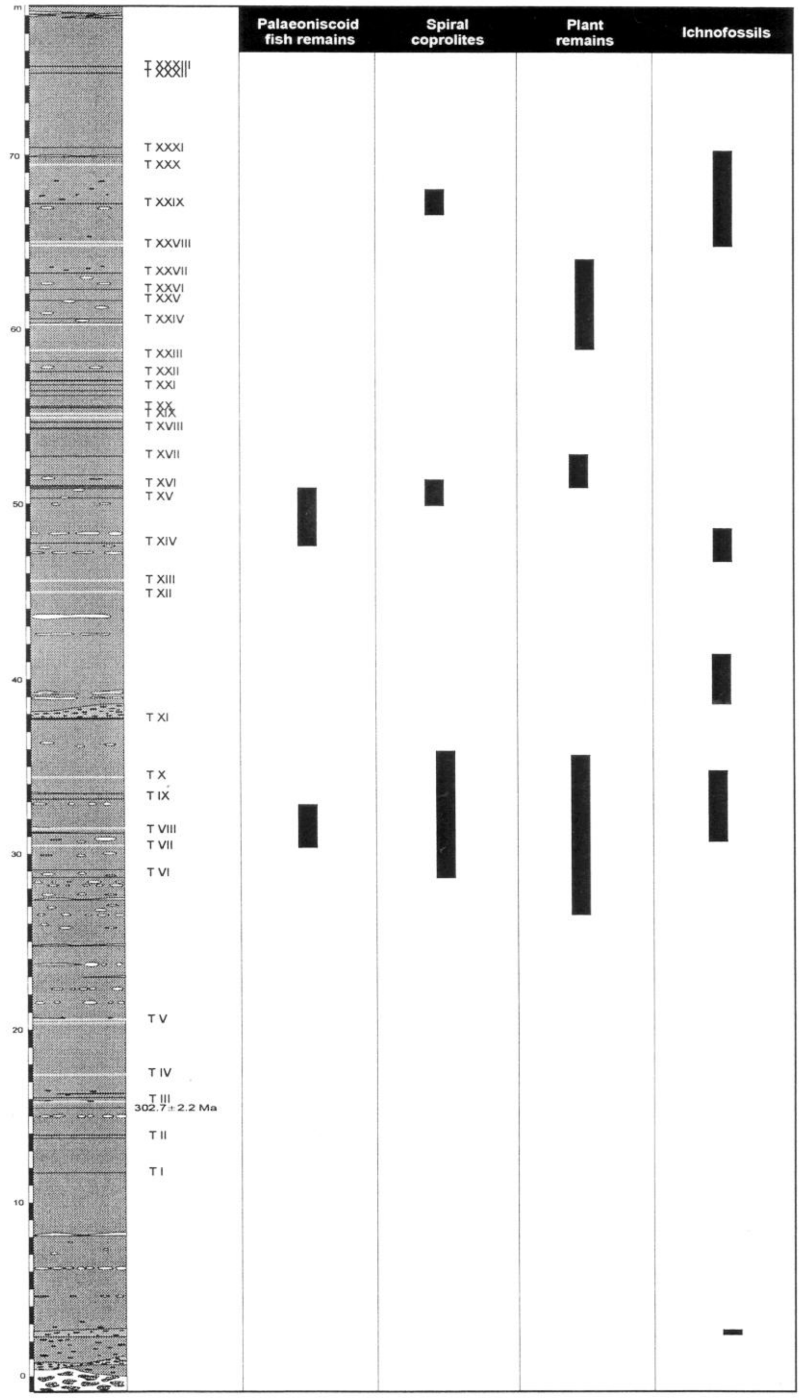


Figure 47
This figure gives an overview of the distribution of distinct fossils in the lower Dwyka succession up to tuff T XXXIII.

4.1 Invertebrates

Undetermined mollusc

Finding above the Jet Cliff.

Between tuff horizon IX and X an external mould of a yet undetermined shell was found. Only one valve or at least a part of one valve could be excavated. The mould probably gives a lateral view on an unsymmetrical valve of a bivalve. The shell is crescent shaped with a bending ridge extending from the umbo to the convex ventral side (Fig. 48). Ramified crests of the size of a fraction of a millimetre, similar to the pattern of the skin of the human hand, cover the shell. The longer wing on the ventral side shows a 3 cm long, 0.5 mm wide and at least 0.5 mm deep recess. McLachlan and Anderson (1973) report of a Lamellibranch classified as *Phestia* sp., whose contour and shape approach the new finding.

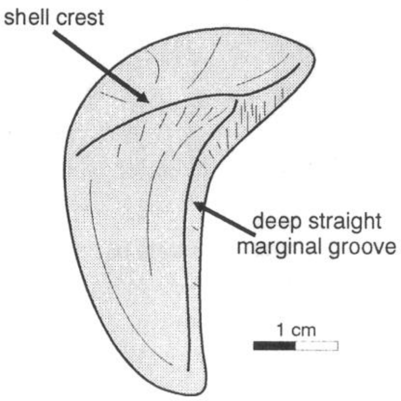


Figure 48
Undetermined shell found above IX b (above Jet Cliff). The surface is structured with thin finger-print-like grooves. A pronounced crest extends from the left to the right. The lower right shell margin is structured with a 1 mm deep, 0.3 mm wide and 5 cm long groove.

Undetermined gastropoda

Finding at Fossil Bend.

Further a white spiral shell appeared isolated between XXIV and XXV. The 0.6 cm long, evolute trochospiral gastropod shell could not be specified accurately.

4.2 Invertebrate ichnogenera

Burrows

Taenidium serpentinum

Findings at Fossil Bend and Goats Cliff. **Det.: Bromley (1996)**

Black nodules in the stratigraphic levels of tuff group X, 2 m to 3 m above XI, between VII and XV and sporadically 4 m to 6 m above the Goats Cliff Diamictite are covered with 3 to 5 cm wide, several cm long worm-shaped burrows, which seem to bulge out of the surface of the nodules (Fig. 49). Fracture surfaces show meandering sediment-filled burrows without a burrow lining. The burrows are either oriented horizontally or obliquely to bedding and are segmented by menisci, which lie 2 to 3 cm apart.

Chondrites intricatus

Findings at Fossil Bend and above the Jet Cliff. **Det.: Uchman (1995)**

From tuff group IX to 3 m above XI intrafaunal burrows, which can be visualised by imagining an upside-down tree, with a main burrow "trunk" and increasingly complex branches downward into the sediment are regarded as *Chondrites intricatus*. The fossil was frequently seen on fracture surfaces of concretions. *Chondrites* suggests marine conditions and is often associated with low-oxygene substrates.

Figure 49
The surface of a concretion shows several burrows of *Taenidium serpentinum* isp.
Locality: Fossil Bend.

Thalassinoides isp.

Findings at Fossil Bend. **Det.: Uchman (1995)**

The layers of tuff group IX also contain a branching burrow (Y- or X-shaped branches) with either horizontal to oblique box-like network and enlargement at junctions between some branches. The walls are smooth. *Thalassinoides* isp. commonly appears on silty shale or fine sand layers, which often contains *Chondrites intricatus*.

Tisoa isp.

Findings at Fossil Bend and Hare Valley. **Det.: Fürsich, F. T. (1999 personal comm.)**

Between tuff group XI and XIII several of the brown concretions have two cylindrical hollows, which are 1-3 cm across and reach 2-3 cm vertically into the top surface. The hollows always appear in pairs and are 1-4 cm apart from each other. They probably belong to two parallel burrows of *Tisoa* isp. A connection between the burrows was not observed. A similar, but horizontally lying and in tubular black concretionary nodules enveloped species occur from XXVII to XXXI. There are normally two 1-2 cm wide, 30 to 40 cm long tubular burrows combined in one concretion (Fig. 50). Also the coexistence of three parallel burrows was recognized here. Fig. 51 shows the vertical burrows of *Tisoa* isp.

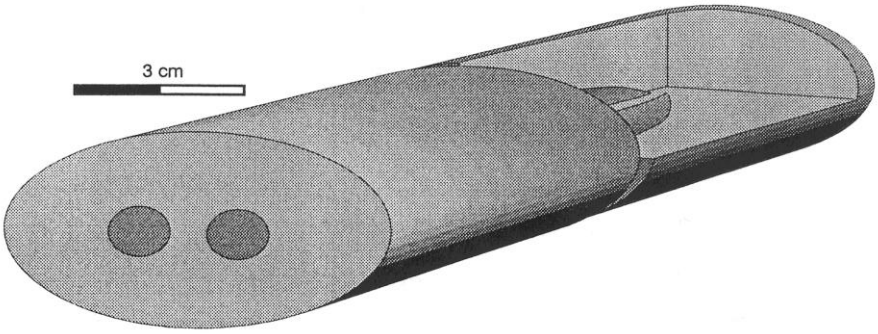


Figure 50
A cross section through a flat lying tubular concretion containing *Tisoa* isp. The two parallel burrows are not terminally connected.
Locality: The west flank of Hare Valley about 200 to 400 m north of the road D 212.

Figure 51
Pairs of tubes of *Tisoa* isp. recede vertically from the surface of a brown concretion just above tuff group XI.
Locality: Fossil Bend

Skolithos isp.

Findings at Jet Cliff, Fossil Bend and Goats Cliff. **Det.: Bromley (1996)**

A simple, tube-like up to 3 cm long and 0.8 cm wide, vertically oriented burrow, which typically shows a much greater length versus width is the stratigraphically most abundant and pervasive fossil. *Skolithos* isp. appears only with few interruptions from tuff group II to XXX.

Palaeophycus isp.

Findings in Centipede Gorge. **Det.: Bromley (1996)**

The stratigraphically uppermost fossil occurrence in the study area is 4 m above the White Band (Centipede Gorge: river bed below the waterfall at the head of the gorge 15 m to the east). The 2-3 mm thick simple burrow that can, but typically does not show branching, is oriented horizontally or obliquely to bedding.

Undetermined domichnia

Findings at Fossil Bend.

At tuff X and about 2 m above the Hippo Diamictite above tuff group XI, 2-3 cm long and 0.5 cm thick infaunal tubular burrows are found horizontal or oblique to the bedding. They have a 0.1 cm thick distinctive burrow lining and are often calcite filled. Similar domichnia also occur about 4 m above the second tillite. In both levels these fossils are rare.

Trace fossils

Helminthopsis isp.

Findings at the shore prominence at Jet Cliff. **Det.: Uchman (1995)**

Only 1.1-1.6 m above the basal tillite, a competent varved layer bears the lowermost fossils. A bedding surface, 20 cm from the base of the layer, is scattered with first-order-meandering pascichnia of *Helminthopsis* isp. (Fig. 52).

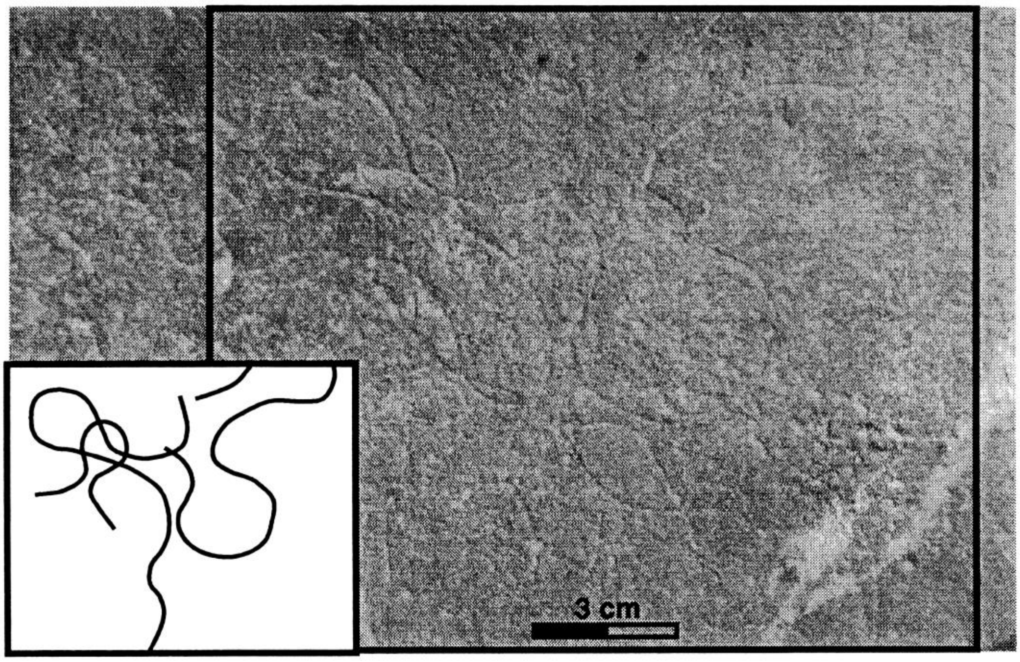


Figure 52
Helminthopsis isp. first-order meandering pascichnia on the varved siltstone.
Locality: Jet Cliff.

4.3 Vertebrates

***Namaichthys schroederi* sp.**

Findings at Fossil Bend and above Jet Cliff. **Det.: Grill (1997)**

From 2 m below tuff group T VI to 1.5 m below tuff group T XI (8 m) several fossils occur. Fish remains are mainly found in calcareous nodules between T VI and T IX (about 30 m to 33 m from the Dwyka Group base). Singular bones, scales or sometimes moulds of more or less complete, but deformed bodies about 25 cm long are present (Fig. 53). Pyrite veins sometimes spread across fish-remnants-bearing concretion. They are often associated with fish scales and bones. The fishes correspond with other findings in Namibian Dwyka Group.

Figure 53
Fish scales and a cast of a fanning-out fin of a palaeoniscoid fish *Namaichthys schroederi* sp.
Locality: Above Jet Cliff.

4.4 Wood and plant fragments

Permineralized wood

Findings at Fossil Bend and above Jet Cliff.

Frequent fossils are permineralized wood fragments. Small branches with a diametre of 2 or 3 cm appear beside wooden logs with diametres up to 30 cm. These fossils are concentrated in three different levels. The shale from tuff group T VI to T X displays the most abundant logs in the entire succession. Further logs are sporadically interspersed between tuff group XV and XVII and finally between XXIII and XXVIII. They are found either enclosed in concretions or isolated (Fig. 54). Moreover they are either coalified or silicified. Cross-sections are normally oval shaped as the logs are flattened, obtained by the load of the overlying rocks. Growth rings are usually well preserved and vary from 2 to 10 mm. Coalified wood sometimes shows pyrite concentrated on growth ring boundaries and along vessels. The significance of log alignment in reference to palaeocurrent orientation determination is discussed in chapter 3.2.1.5.

Figure 54
The picture shows an isolated log fragment.
Locality: 200 m east of Fossil Bend.

Phyllotheca

Findings at Fossil Bend. **Det.: Bangert et al. (1999a)**

Further nodules with several 2 to 4 cm long parallel, iron-brown coloured fibres, each less than 1 mm thick, were found. They are associated with close neighbouring more or less cocentrical finer filaments. These fibrous structures were interpreted as long plant leaf or parts of a stem. They are commonly associated with the occurrence of logs. This plant fragments are considered to be *Phyllotheca*.

4.5 Fossil feces

Spiral coprolites

Findings at Fossil Bend and above Jet Cliff. **Det.: McLachlan and Anderson (1973)**

At Zwartbas the spiral coprolites are the most abundant fossils. They occur in the levels of tuff group VI to XI, XV to XVI and around XXIX. The coprolites are up to 10 cm long and have a radial diameter of about 2 cm. Figure 35 c shows the cigar-shaped form, which was obtained by carpet-like roll-up of

2-3 mm thick excremental material (Fig. 55). A shark of the class *Chondrichthyes* with an intestinal spiral valve is considered to be the producer of the spiral coprolites by McLachlan and Anderson (1973).

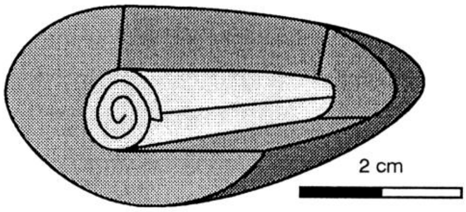


Figure 55
Section through a mould of a spiral coprolite. The cigar-shaped form of the rolled-up excrements is obvious.
Locality: Abundant occurrence at Fossil Bend.

4.6 Calcispheres

Findings at Fossil Bend and above Jet Cliff

Frequent, but stratigraphically sporadic fossils are 0.5-1.0 mm wide calcispheres from tuff group VI a to XXV, which are concentrated in thin layers (2 mm) in 4-6 mm distance. The spheres are only found in concretions, whereas they were not recognized in the fissile shale. Due to their size and shape, an interpretation as *Radiolaria* is permissible (McLachlan and Anderson, 1973), but in this case a replacement of the SiO_2 by carbonate, which could have destroyed the former internal structures, happened successively. *Radiolaria*, however, are pelagic algae and contradict the presence of wood and plant fragments, which indicate proximal marine conditions. Grill (1997) describes similar calcispheres, but with an internal, concentric structure. According to Grill these calcispheres are algal layers of *Dasycladacea*, which are tubular organism. Though all sections with nodules show circular forms, an oblique cut through a tubular body would leave elliptical forms. Thus the calcispheres at Zwartbas must be of a different origin and have not been sufficiently explained yet.

5 Tectonism

Tectonism in Zwartbas is dominated by two tectonic regimes: A compressional regime with folding and thrusting in the deposits of the Nama Group, and an extensional regime in the Karoo rocks. As the fault zones of both regimes possess a similar orientation, a reactivation of the faults of pre-Dwyka age during Dwyka time but with a reverse sense is considerable. Most of the features seen in the field, can be traced by the drainage pattern, which can be easily recognized on aerial photos (see Fig. 57).

Syn- and post-Nama tectonics

As the sediments of the Nama Group are generally undeformed in large areas of southern Namibia, the exposures at Zwartbas constitute a prominent exception. Tectonism here is related to a transpressional situation due to a northwestward subduction of the Kalahari plate underneath the Congo and the South American plate. Sinistral transpressive movement caused a marginal folding and thrusting of the sediments proximally onlapping on the Gariep mobile belt during one of the younger Damara events (Gresse et al., 1996; Gresse and Germs, 1993). Thus deposits on the western margin of the Nama basin were thrusted and folded eastwards, probably after the deposition ceased between 530 Ma and 496 Ma B.P. In reference to Allsopp et al. (1979) this deformation pred-dates an intrusion of a post-orogenic granite pluton in the Gariep Belt (Kuboos granite pluton, 525 ± 60 Ma).

A cliff-like wall about 1.5 to 1.7 km from the turn-off at the ostrich farm (outcrop # 9), 50 m north of the road to Nuwe Modderdrif displays the structural situation of the Nama rocks. From the west the limestone layers (Chapter 3.1.2) extend into the outcrop. The layers are bulged up, until they come upon a fault plane. The massive limestone in the central part does not reveal any structural information. East of the westward dipping fault plane calciclastite are upturned (Fig. 56). Their dip flattens out to the east. The sediments of the Nama Group represent a partly excised hinge of an overturned fold, which gave rise to a thrust fault. The highly vergent fold experienced a limb-break-through by eastward thrusting. West of the fault the dipping of the rocks outline a hinge line, which obviously plunges south. This is illustrated by an elliptical pattern of the variously coloured beds in an eroded plain of the aerial photograph (see Fig. 57). The half-wavelength of the antisyncline is about 300 m wide. Probably the structure constitutes a thrust fault with a drag fold, which bent with a high angle to the fault plane. Calcite filled tension gashes in the limestone furthermore indicate a north-northwest to south-southeast strike-slip component. This is consistent with the general southeastward thrusting of the Nama rocks described by Gresse and Germs (1993) and Gresse (1995). This folding of the Nama rocks must have happened syn-sedimentary, since the limestone conglomerate and breccia (Chapter 3.1.4) overlies the shale (Chapter 3.1.3) unconformably (see Fig. 10).

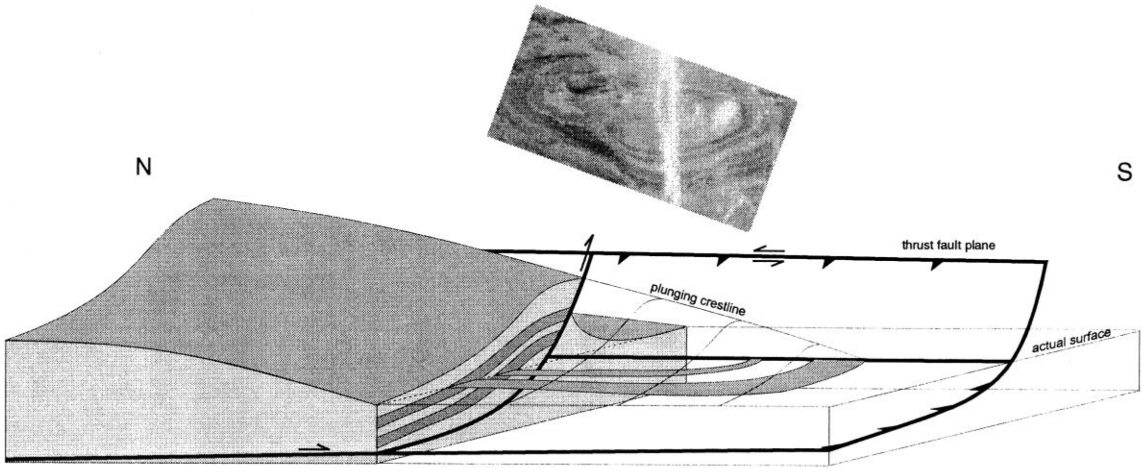


Figure 56
3D cross section of the plunging fold at outcrop # 9. The grey ribbons on the actual surface are slightly inclining limestone layers with different alteration colours. The same ribbons are seen on the small aerial photo.

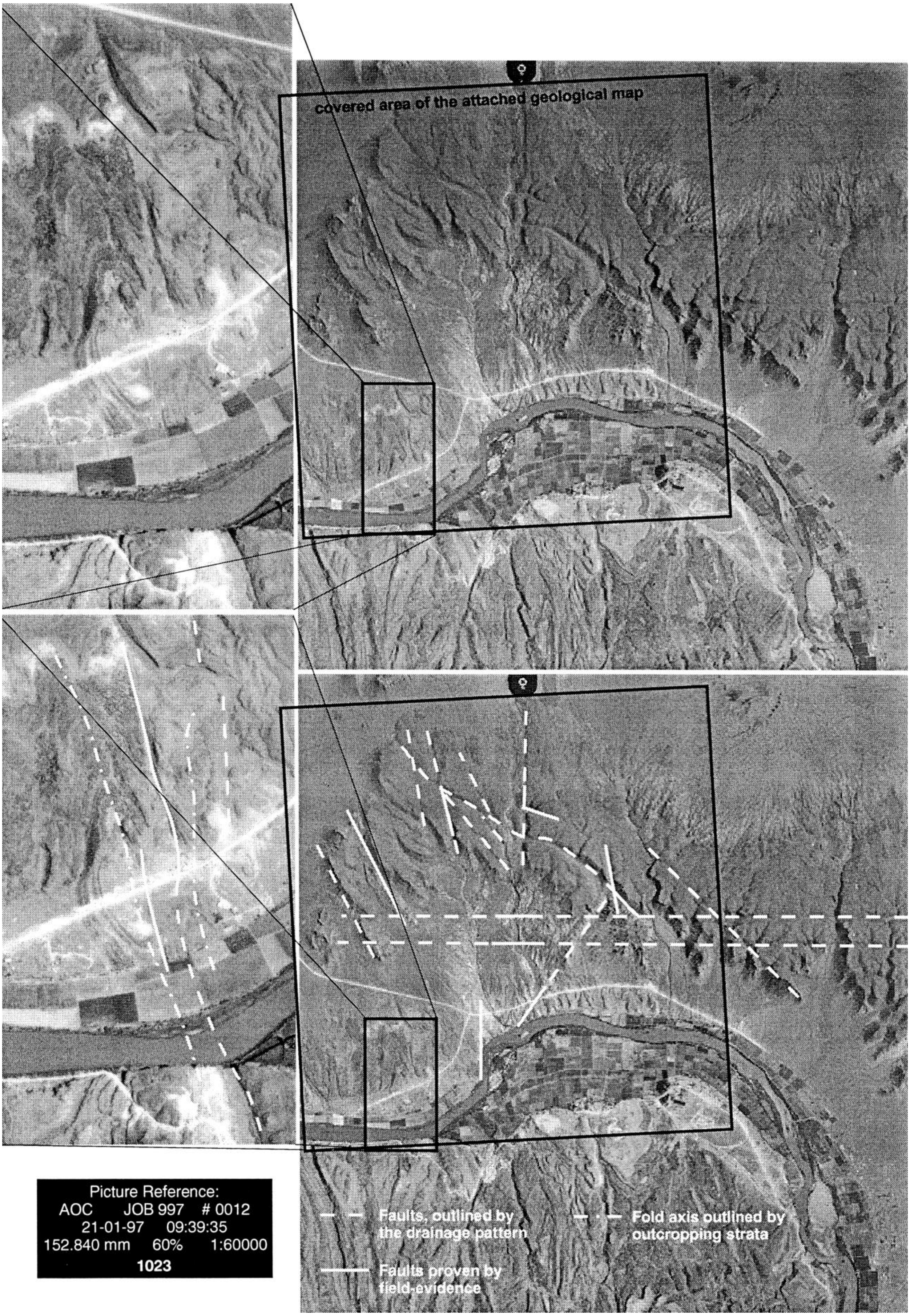


Figure 57
The collage of aerial photographs show faults which are outlined by the drainage or lithological pattern. Some of these faults were confirmed by field observations.

At Fossil Bend the western bank of the Orange River represents a flexed and faulted zone. The Nama shale is transformed in quartzite. The flexure axis of the quartzitic shale of the Nama Group coincides with the NW-SE trend of the Nama fold in the southwest of the study area (see below)

Syn- and post-Karoo tectonics

Tectonic activities through Karoo time have been mainly characterized by a stable or poorly extensional structural situation (Martin, 1981a). Two main orientations are present during the deposition of the Dwyka Group and Ecca Group shales (see Fig. 58a-e). NNE to SSW and WNW to ESE trending small scale faults disrupted the shale. At some localities evidence of syn-sedimentary faulting has been recognized. The Jurassic intrusion, however, only shows NNW-SSE trending extensional dislocations which sometimes extend into the shale. They are certainly post-sedimentary, as they dissect the dolerite (see chapter 3.2.3 and 3.4).

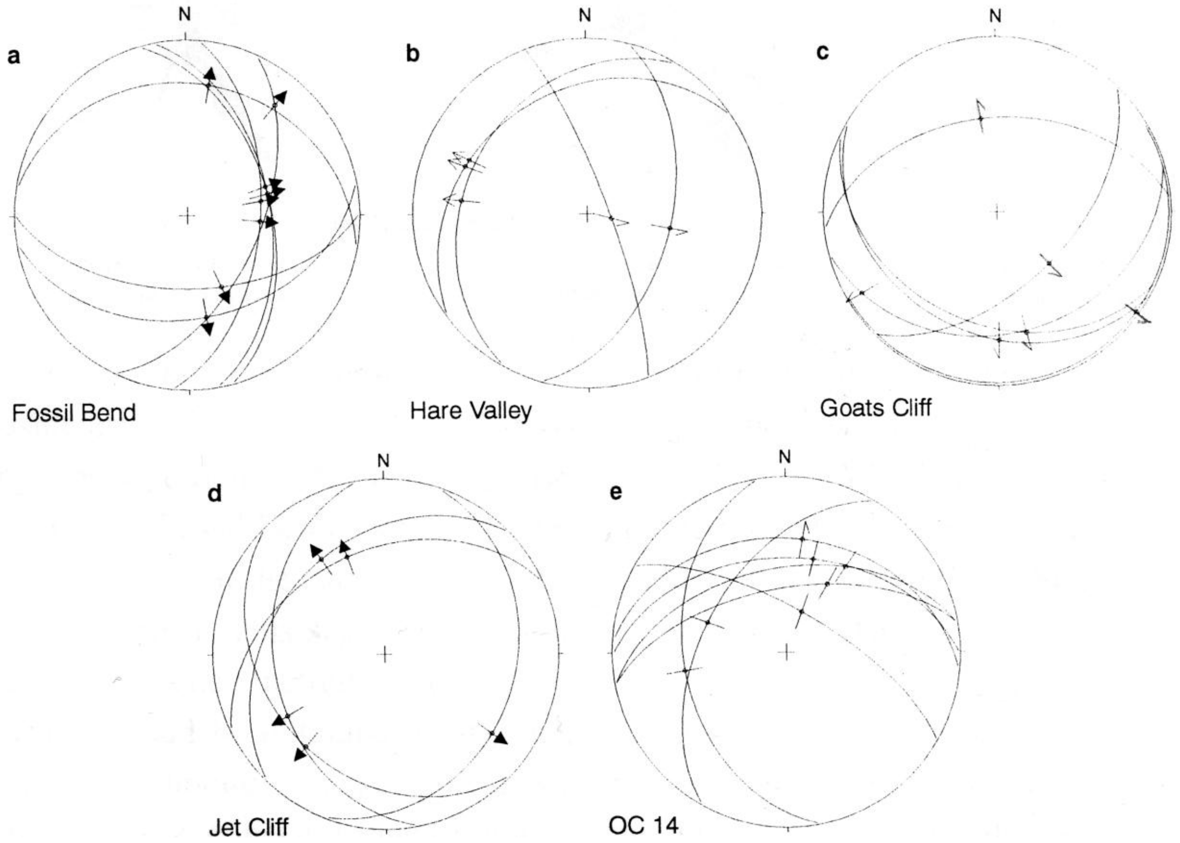


Figure 58
This set of stereographic plots visualizes the fault-planes and slip directions (arrows) of faults measured in Karoo rocks. They all show the extensional regime with exclusively normal faulting. There are two major directions: N-S and E-W striking faults.
a The plot describes the major displacement at Fossil Bend. The eastern block has been faulted down.
b Small scale faults in the Hare Valley strike NNE-SSW.
c and **d** show the N-S orientated extension at the Goats Cliff and the Jet Cliff.
e describes the E-W striking faulting at outcrop # 14.

At Fossil Bend the beds of the Dwyka Group incline in a high angle eastward into the river. Glacial grooves at the vertical wall of the undercut slope are covered with lodgment tillite and shale. The almost upright layers are part of a flexure with more than 5 m off-set. Eastwards the shale along the river shows a low flexed syncline, which passes into non-folded rocks. A large fault is trending northward along the Nama-Dwyka boundary through the flexure at the banks of the Orange River and separates the Nama rocks sharply from the Dwyka rocks. The eastern block has been faulted down (Fig. 58a). The hangingwall block constitutes the undercut slope at Fossil Bend. The straight river course south of Fossil Bend was produced by this fault. Further tectonic activities at outcrop # 15 and the deep incision of Owl Gorge and the disrupted dolerite at the head of Owl Gorge point to a northward extension of this fault zone. At outcrop # 15 an easterly inclined minor sill was probably displaced along a fault zone and is associated with a dolerite dyke (see Fig. 61). The inclining shales of the Ecca Group and the quartzitic shales in this area imply deformation and disruption. All these observations point to an extensive fault zone from the Orange River northward into the Ecca Group. The flexure at Fossil Bend differs in orientation from the fault. The joint analysis (Fig. 59) shows a typical pattern of fractures associated with flexures (Twiss and Moores, 1992). The joints in the outcrop are perpendicular to the bedding and constitute a typical joint pattern for a NW-SE-striking flexure axis. This flexure axis coincides with the fold axis of the large Nama fold (see above). This suggests either prevailing structural trends from Nama into Dwyka time or reactivation of the Nama structures in early Dwyka time. Since the fault extends into the Ecca and disrupted the dolerite, its activity is assumed to be post-Jurassic.

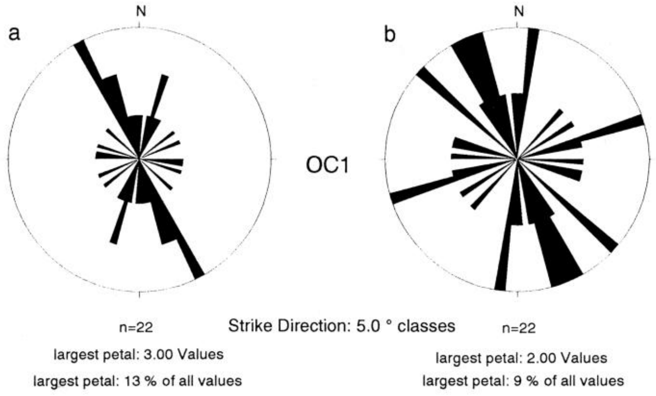


Figure 59
Rose diagrams of joint orientations on a flexure in Dwyka shales at Fossil Bend. The major striking direction comports with the field results of NW-SE striking flexing and faulting. **a** was measured on the upper, **b** on the lower limb of the flexure.

The flexure at Fossil Bend is supposed to be initialized during the deposition and constitutes an area of increased subsidence together with the NE-SW-trending fault passing through Provenance Camp. Evidence brings the variation in the distance between Tuff horizon VIII b and IX between Fossil Bend and Provenance Camp. Fossil Bend reveals 170 cm from the lower to the upper ash layer. At the east side of the canoe landing place at the camp the shale between the tuffs is only 95 cm thick. A fault passes the camp nearby into the river. This suggests syn-sedimentary faulting. An increased deposition rate on the subsiding block compensated the relief. Concretionary nodules at Fossil Bend sometimes show inordinate slickensides, which could be obtained by the flexing of the hosting shale. The nodules acted as rigid hinges. Eventually the flexing shale scraped slickensides on the hardened calcareous nodules. Therefore the concretions must have been formed prior to the deformation. Since the nodules were formed secondary, the rocks were deformed post-sedimentary.

A large E-W extending fault, clearly visible on the aerial photograph is seen at outcrop # 14 (Fig. 60). It is one of two parallel E-W trending faults, which extend almost throughout the entire study area, although only here the fault zone was found. The stereogram in Fig. 58e suggests a northward faulting.

Another interesting location of faulted sediments of the Dwyka Group is Puff Adder Valley. A view from the head of the valley (Fig. 61) shows different reference levels of the intrusional base on the eastern and western valley slope. The underlying shales are warped, upturned and eastward dipping at the eastern valley slope, while they are horizontally bedded on the western slope. As the cartoon illustrates, the dolerite branches into two separate minor sills. The eastern dolerite changed the stratigraphical level during its migration to a lower strata and developed the actual situation. Migrating southward, the western dolerite pushed to the east, while the eastern, stratigraphically elevated, moved to the west. The host rocks between both sills were compressed, flexed, partly folded and possibly thrusted. At the head of Owl Gorge the dolerite is highly disrupted. The rivers branching several times and the dolerite has been pedogenic transformed into calcrete in many places (see chapter 3.3 Calcrete).

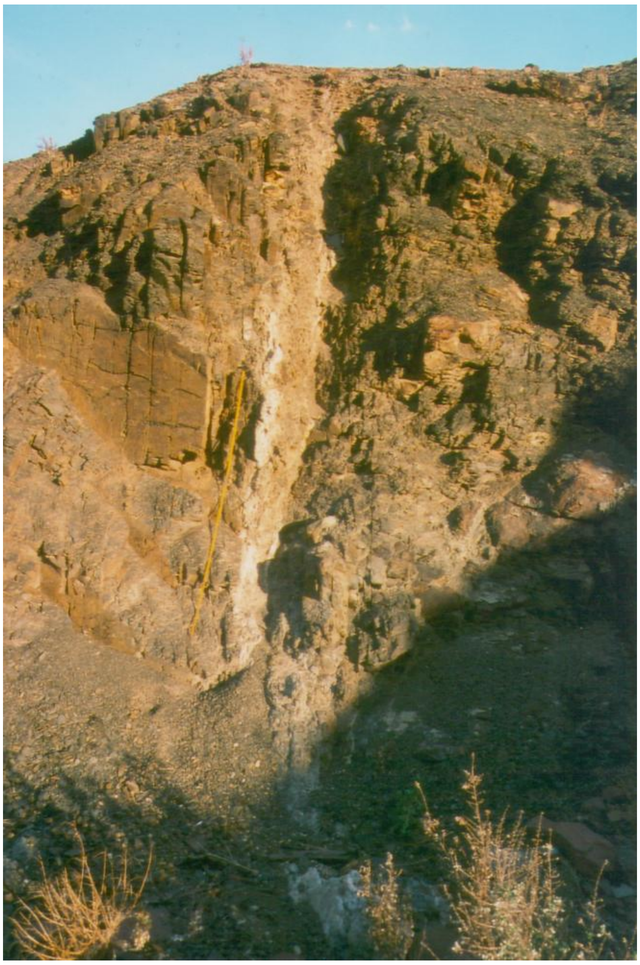


Figure 60
This photograph shows a big east-west striking fault. Calcite filled particular faults compose the 50 to 60 cm wide fault zone. The aerial photo (Fig. 57) outlines the fault by the drainage pattern.
Locality: Outcrop #14.

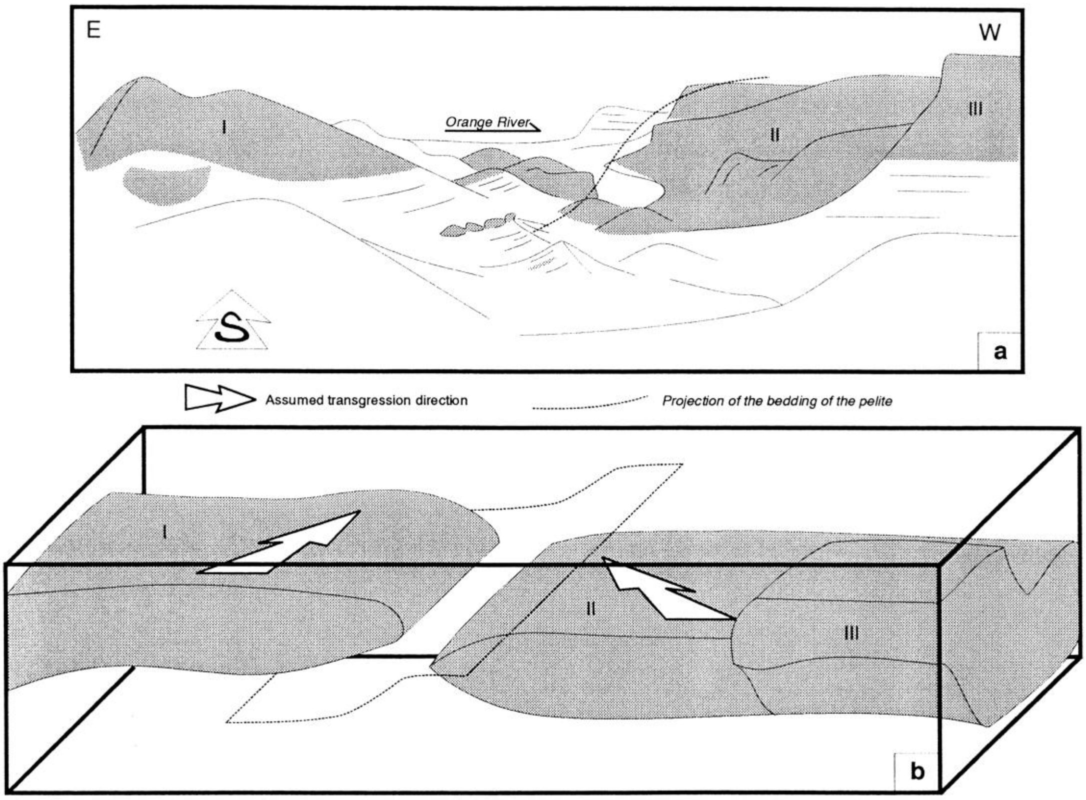


Figure 61
The drawing illustrates the shale-sill contact, which was influenced by tectonic activity and discordant transgression. This results in flexed shale beds outlined by the hypothetical bedding plane (dotted line).
Locality: Head of Puff Adder Valley.

6 Natural wealth and exploitation

A few small quarries provide the local residents with silty limestone plates for building. At several locations traces of small-scale mineral mining have been found. Mainly calcite has been knocked out of exposed vein, e.g. at outcrop # 15. Pits in the Orange River terraces are evidence of former diamond mining exploration and exploitation projects (western of Fossil Bend). None of them has had any economic significance within the study area. Moreover fluorite fragments were found in the debris on the valley floor at the head of Centipede Gorge, 20 m east of the waterfall and 50 m south of the place, where the NW-striking fault cuts in the dolerite capped plateau.

7 Ground water

Ground water has seldom been the subject of exploration in the study area. Since the river provides drinking water, efforts to drill wells have been rarely made. Some local people told of a bore hole, that was drilled above the cliffs close to Zwartbas several years ago. At about 20 m they reached water, which turned out to stink and had a bitter taste from a high sulphur content. This comports with the shale’s high content of organic material, shown by the dark colour of the mudstone and the occurrence of pyrite and other sulphur minerals principally in the Dwyka succession below tuff XV. The subsoil water dissolves soluble substances out of the ground-water-bearing shale, but does not get diluted by a significant recharge of uncontaminated water due to more or less irrelevant precipitation in the area. Thus a highly enriched solution of readily soluble substances, such as sulphur, accumulates in the aquifer. Despite the proximity to the Orange River, no or only minimal exchange seems to happen between the two water bodies. This implies that the drilling hit a confined aquifer, which explains the accumulation and contamination effect.

Only one permanent intermittent to perennial spring lies in the study area: Duifiefontein (northeasternmost corner of the study area, just beside the sharp curving 4x4 track: S 28°39.152'/ E 017°34.658'). The discharge of the spring is a subject to annual fluctuations, sometimes it dies. Discharging water is collected in a man-made headpool and is used to water cattle. Insufficient discharge can not provide enough water to form a streamlet in the dry season. The outlet lies in a N-E-striking valley, whose floor is formed by the top contact of the dolerite and the Ecca Group shale. This points to a conformance of the contact and the confining layer of the aquifer. As igneous rocks here are as normal intensely jointed, the impermeable layer seems to lie just above the dolerite. The water seems to seep through the well-jointed shale of the Ecca Group until it is restrained by a water-impermeable layer, maybe shale, which was baked and sealed by the intrusion. Thus overlying shale of the Ecca Group anyway serves as aquifer and pipes the infiltrated water to the spring. Due to little precipitation, ground-water recharge, flow and discharge is too small to play an important part in economy or ecology.

8 Conclusion

Though the Nama Group and Lower Karoo Supergroup stand stratigraphically about 260 Ma apart, they show a characteristic similarity of the sedimentary environment. In both groups glacio-marine conditions are indicated by dropstone bearing shale. But the diamictitic shale in the Nama Group could not be classified unambiguously. Further classification has to be implemented in the future. In addition the folding and thrusting of the Nama rocks complicated the classification of the other units. Insufficent literature hamper correlation of the studied layers with regional observations. The overlying Dwyka rocks represent a complete glacio-marine succession. It starts with a tillite above a scoured glacial floor, which is succeeded by a sequence of diamictite and shale. The classification of Karoo rocks is not contradictory to results of other authors and does not raise new questions, while the abundant occurrence of tuff beds is exceptional for southern Namibia. A subsequent diploma thesis will furthermore deal with the geochemism of the shale and the interspersed tuff beds and the plaeoenvironment in reference to the fossil findings.

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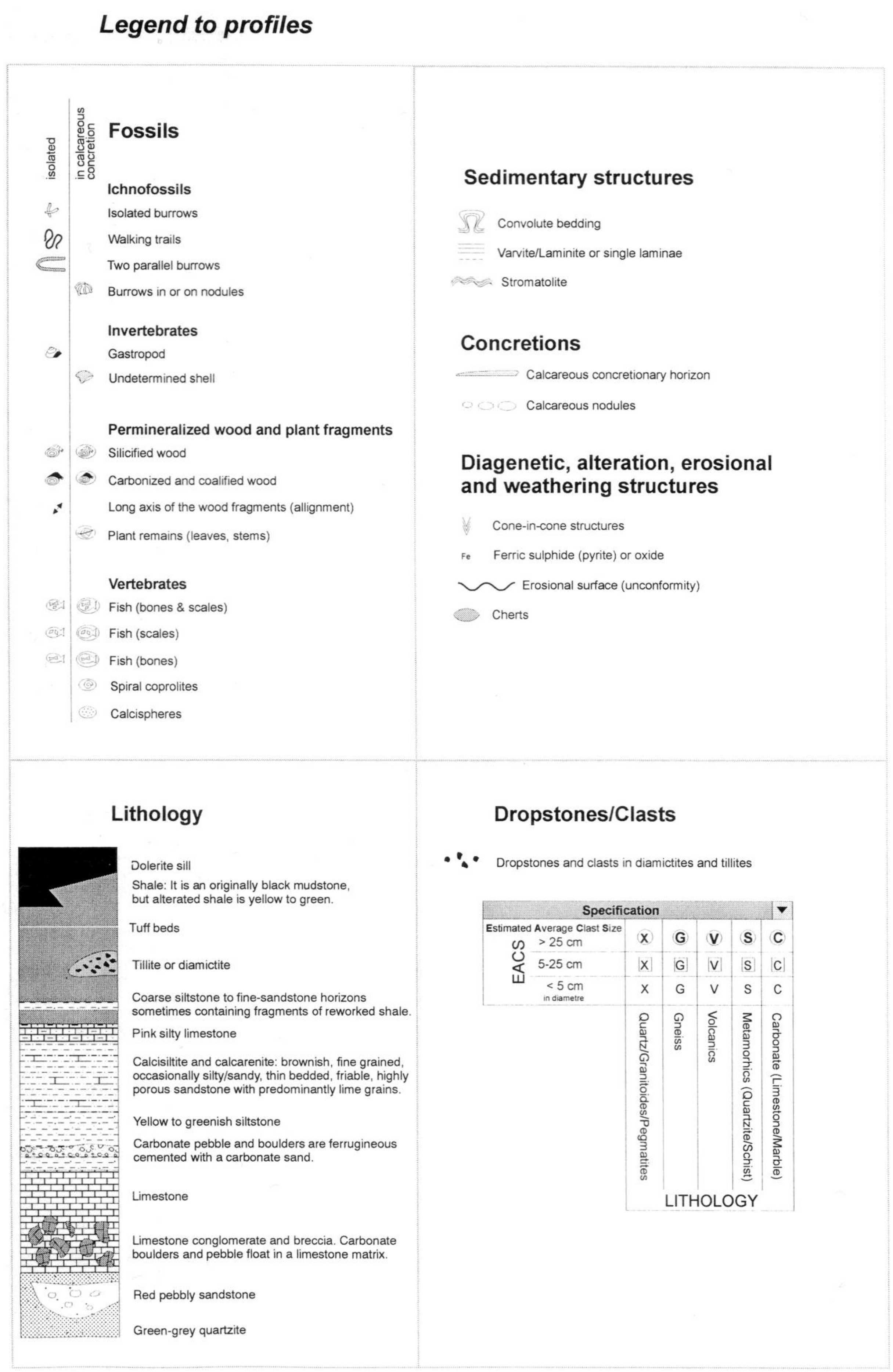
Appendix



Legend to profiles

Fossils

Ichnofossils

- Isolated burrows
- Walking trails
- Two parallel burrows
- Burrows in or on nodules

Invertebrates

- Gastropod
- Undetermined shell

Permineralized wood and plant fragments

- Silicified wood
- Carbonized and coalified wood
- Long axis of the wood fragments (allignment)
- Plant remains (leaves, stems)

Vertebrates

- Fish (bones & scales)
- Fish (scales)
- Fish (bones)
- Spiral coprolites
- Calcispheres

Sedimentary structures

- Convolute bedding
- Varvite/Laminite or single laminae
- Stromatolite

Concretions

- Calcareous concretionary horizon
- Calcareous nodules

Diagenetic, alteration, erosional and weathering structures

- Cone-in-cone structures
- Fe Ferric sulphide (pyrite) or oxide
- Erosional surface (unconformity)
- Cherts

Lithology

- Dolerite sill
- Shale: It is an originally black mudstone, but alterated shale is yellow to green.
- Tuff beds
- Tillite or diamictite
- Coarse siltstone to fine-sandstone horizons sometimes containing fragments of reworked shale.
- Pink silty limestone
- Calcisiltite and calcarenite: brownish, fine grained, occasionally silty/sandy, thin bedded, friable, highly porous sandstone with predominantly lime grains.
- Yellow to greenish siltstone
- Carbonate pebble and boulders are ferrugineous cemented with a carbonate sand.
- Limestone
- Limestone conglomerate and breccia. Carbonate boulders and pebble float in a limestone matrix.
- Red pebbly sandstone
- Green-grey quartzite

Dropstones/Clasts

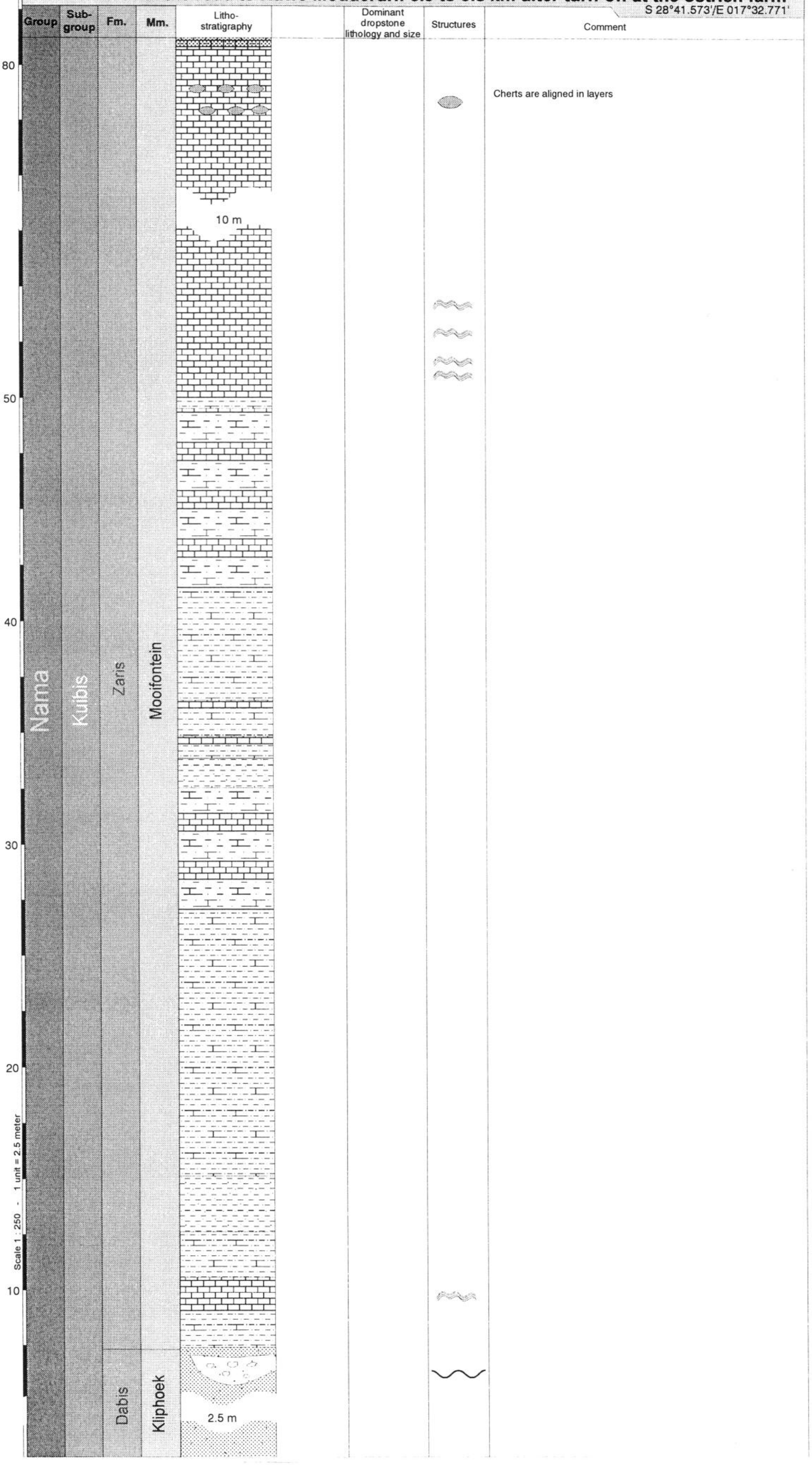
- Dropstones and clasts in diamictites and tillites

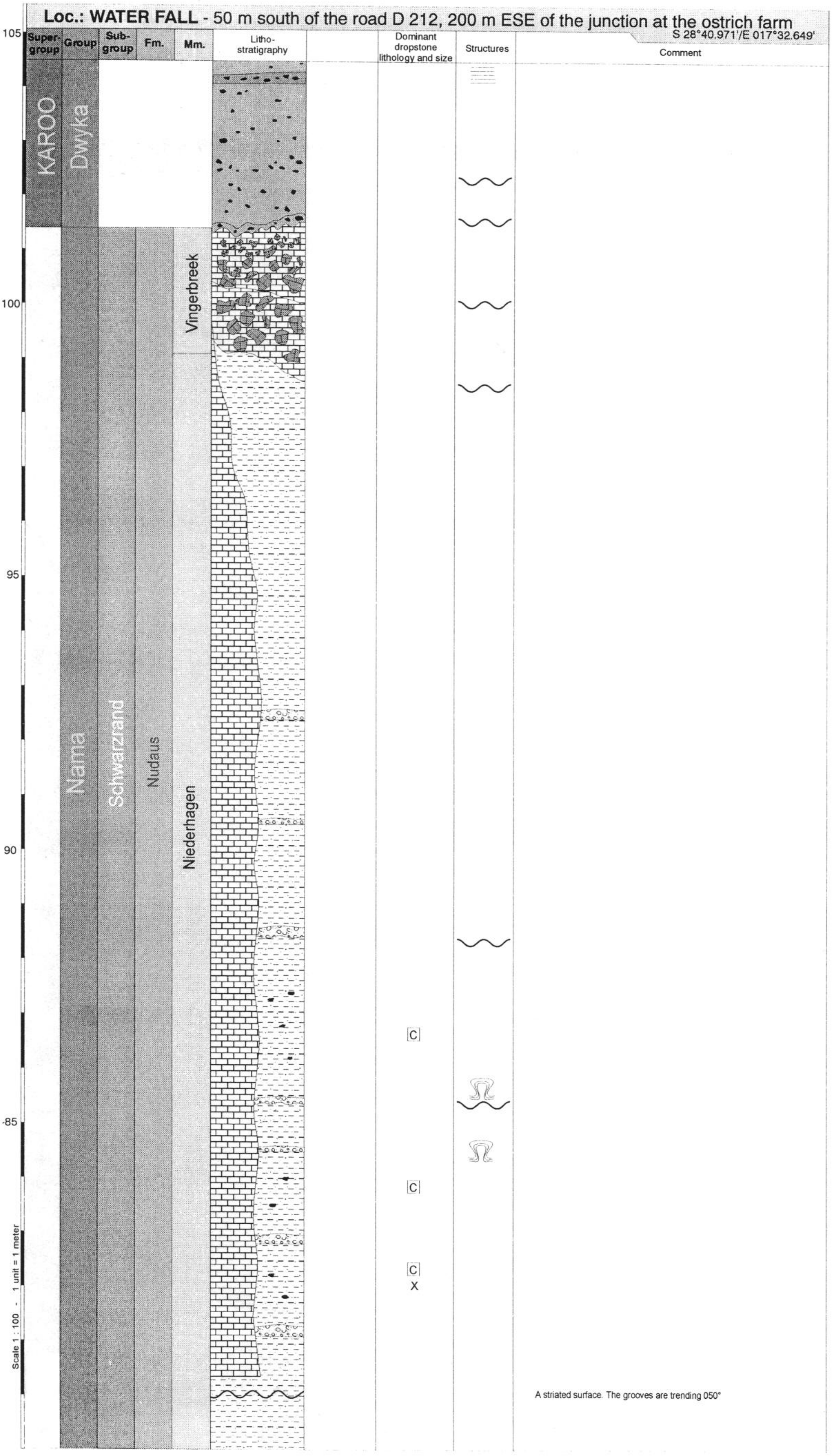
Specification ▼

Estimated Average Clast Size (EACS)	Quartz/Granitoides/Pegmatites	Gneiss	Volcanics	Metamorhics (Quartzite/Schist)	Carbonate (Limestone/Marble)
> 25 cm	ⓧ	Ⓖ	Ⓥ	Ⓢ	Ⓒ
5-25 cm	[X]	[G]	[V]	[S]	[C]
< 5 cm in diametre	X	G	V	S	C
	LITHOLOGY				

Loc.: North of the road to Nuwe Modderdrif 0.5 to 0.8 km after turn-off at the ostrich farm

S 28°41.573'/E 017°32.771'





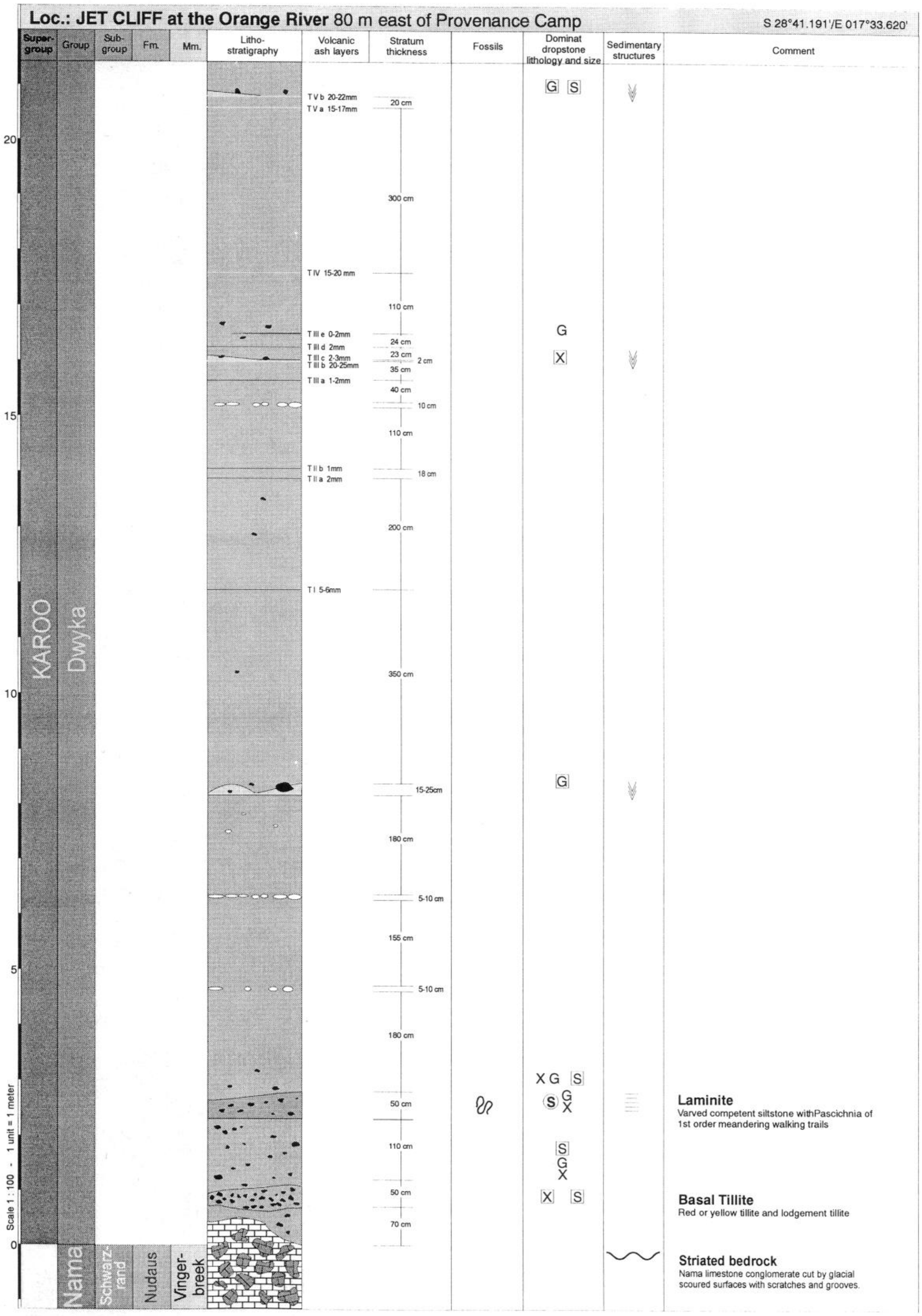
Loc.: WATER FALL - 50 m south of the road D 212, 200 m ESE of the junction at the ostrich farm

S 28°40.971'/E 017°32.649'

A striated surface. The grooves are trending 050°

Loc.: JET CLIFF at the Orange River 80 m east of Provenance Camp

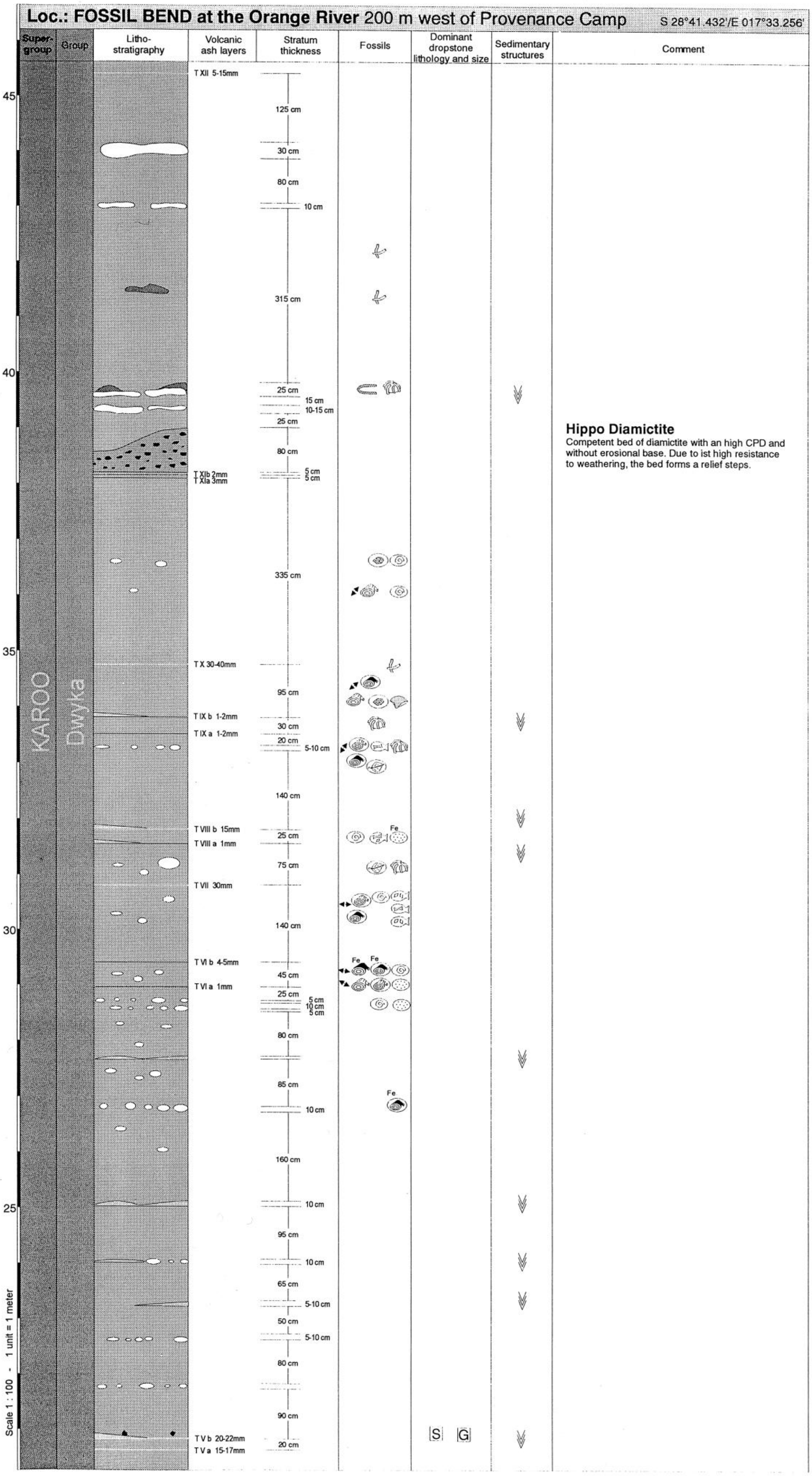
S 28°41.191'/E 017°33.620'



Laminite
Varved competent siltstone withPascichnia of 1st order meandering walking trails

Basal Tillite
Red or yellow tillite and lodgement tillite

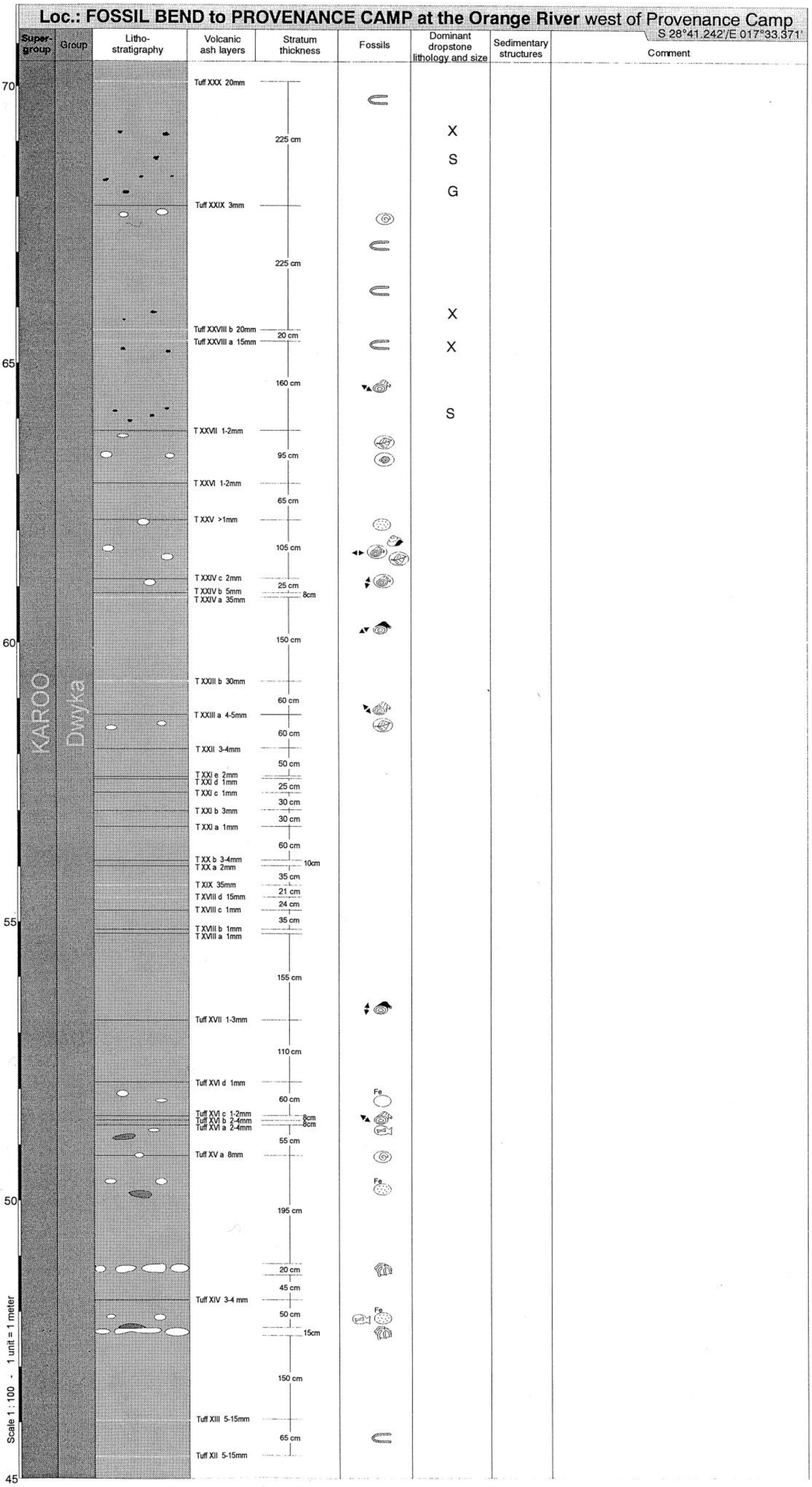
Striated bedrock
Nama limestone conglomerate cut by glacial scoured surfaces with scratches and grooves.

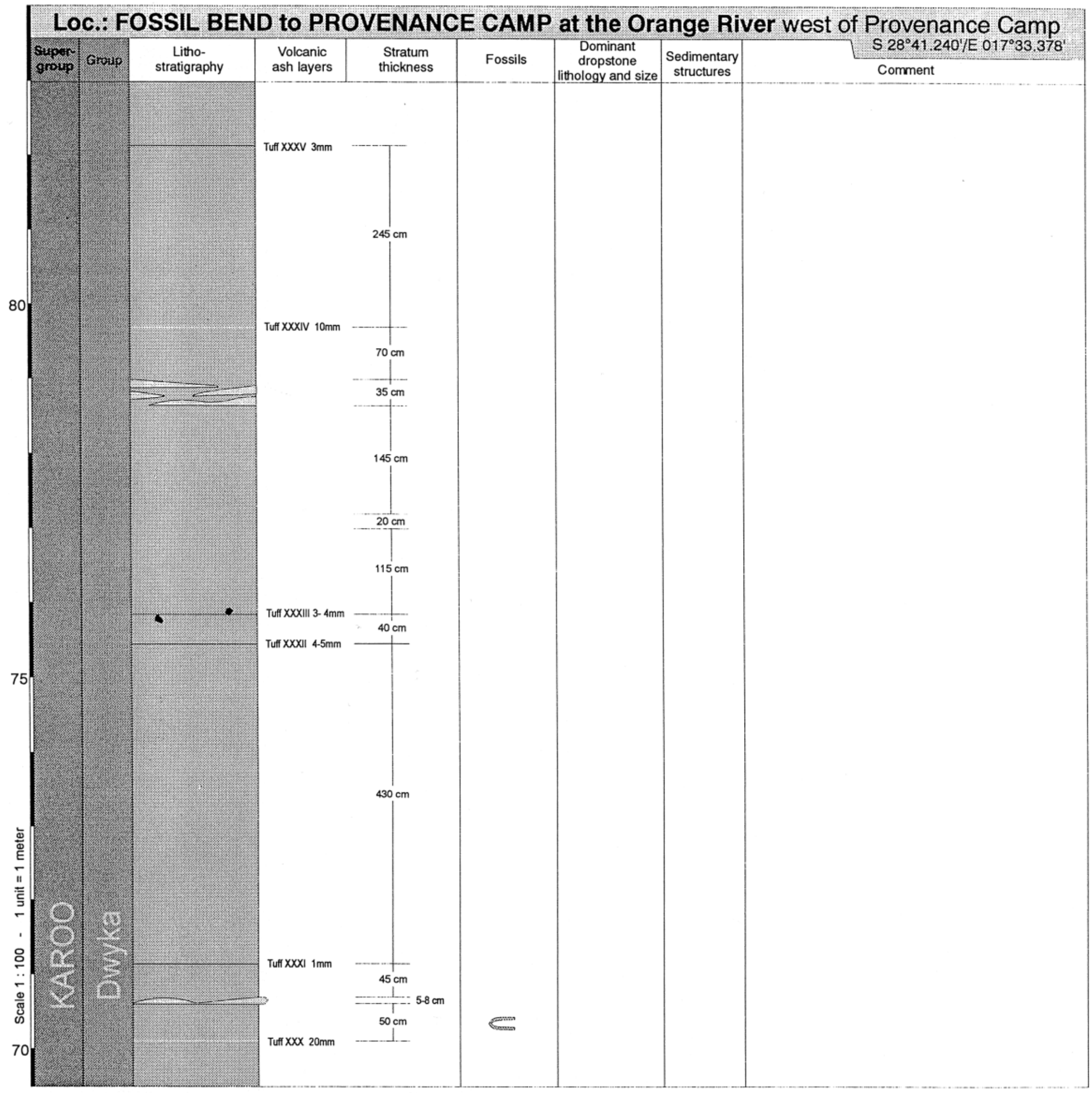


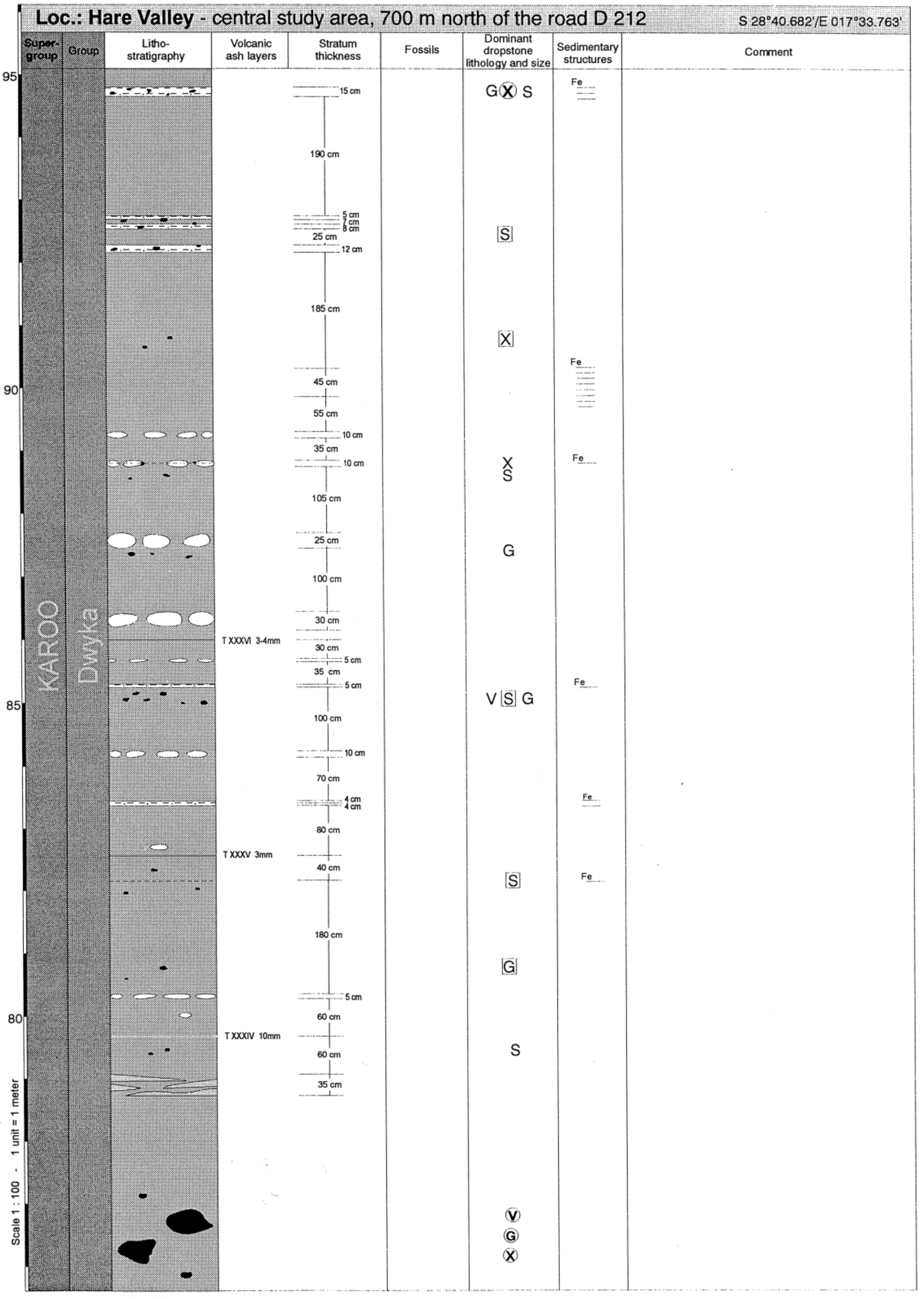
Hippo Diamictite

Competent bed of diamictite with an high CPD and without erosional base. Due to ist high resistance to weathering, the bed forms a relief steps.

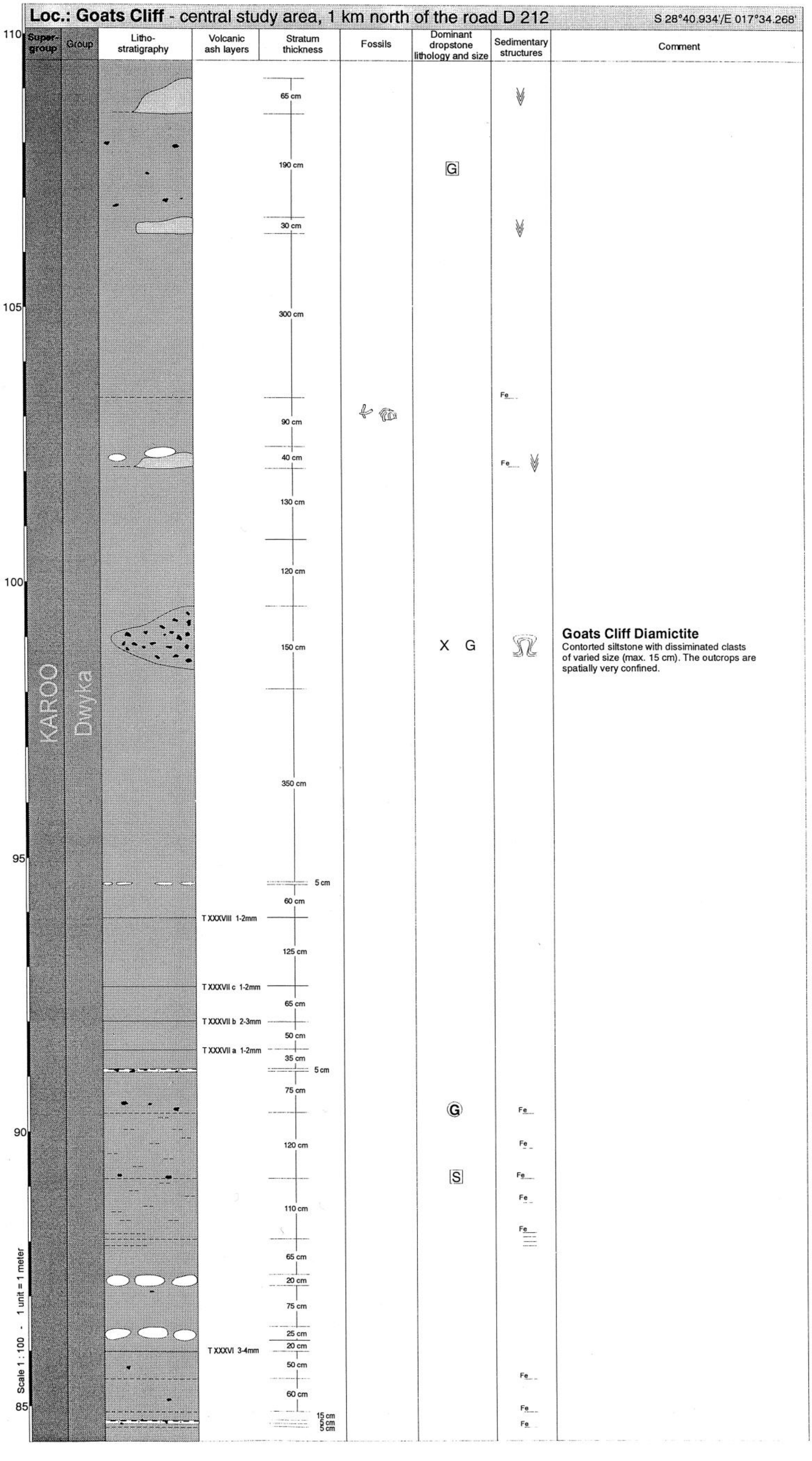
)


Loc.: FOSSIL BEND to PROVENANCE CAMP at the Orange River west of Provenance Camp
S 28°41.242'/E 017°33.371'
Super-group
Group
Litho-stratigraphy
Volcanic ash layers
Stratum thickness
Fossils
Dominant dropstone lithology and size
Sedimentary structures
Comment
70
65
60
55
50
45
KAROO
Dwyka
Scale 1 : 100 - 1 unit = 1 meter
Tuff XXX 20mm
225 cm
X
S
G
Tuff XXIX 3mm
225 cm
X
Tuff XXVIII b 20mm
20 cm
Tuff XXVIII a 15mm
X
160 cm
S
T XXVII 1-2mm
95 cm
T XXVI 1-2mm
65 cm
T XXV >1mm
105 cm
T XXIV c 2mm
25 cm
T XXIV b 5mm
8cm
T XXIV a 35mm
150 cm
T XXIII b 30mm
60 cm
T XXIII a 4-5mm
60 cm
T XXII 3-4mm
50 cm
T XXI e 2mm
T XXI d 1mm
25 cm
T XXI c 1mm
30 cm
T XXI b 3mm
30 cm
T XXI a 1mm
60 cm
T XX b 3-4mm
10cm
T XX a 2mm
35 cm
T XIX 35mm
21 cm
T XVIII d 15mm
24 cm
T XVIII c 1mm
35 cm
T XVIII b 1mm
T XVIII a 1mm
155 cm
Tuff XVII 1-3mm
110 cm
Tuff XVI d 1mm
Fe
60 cm
Tuff XVI c 1-2mm
8cm
Tuff XVI b 2-4mm
8cm
Tuff XVI a 2-4mm
55 cm
Tuff XV a 8mm
Fe
195 cm
20 cm
45 cm
Tuff XIV 3-4 mm
50 cm
Fe
15cm
150 cm
Tuff XIII 5-15mm
65 cm
Tuff XII 5-15mm

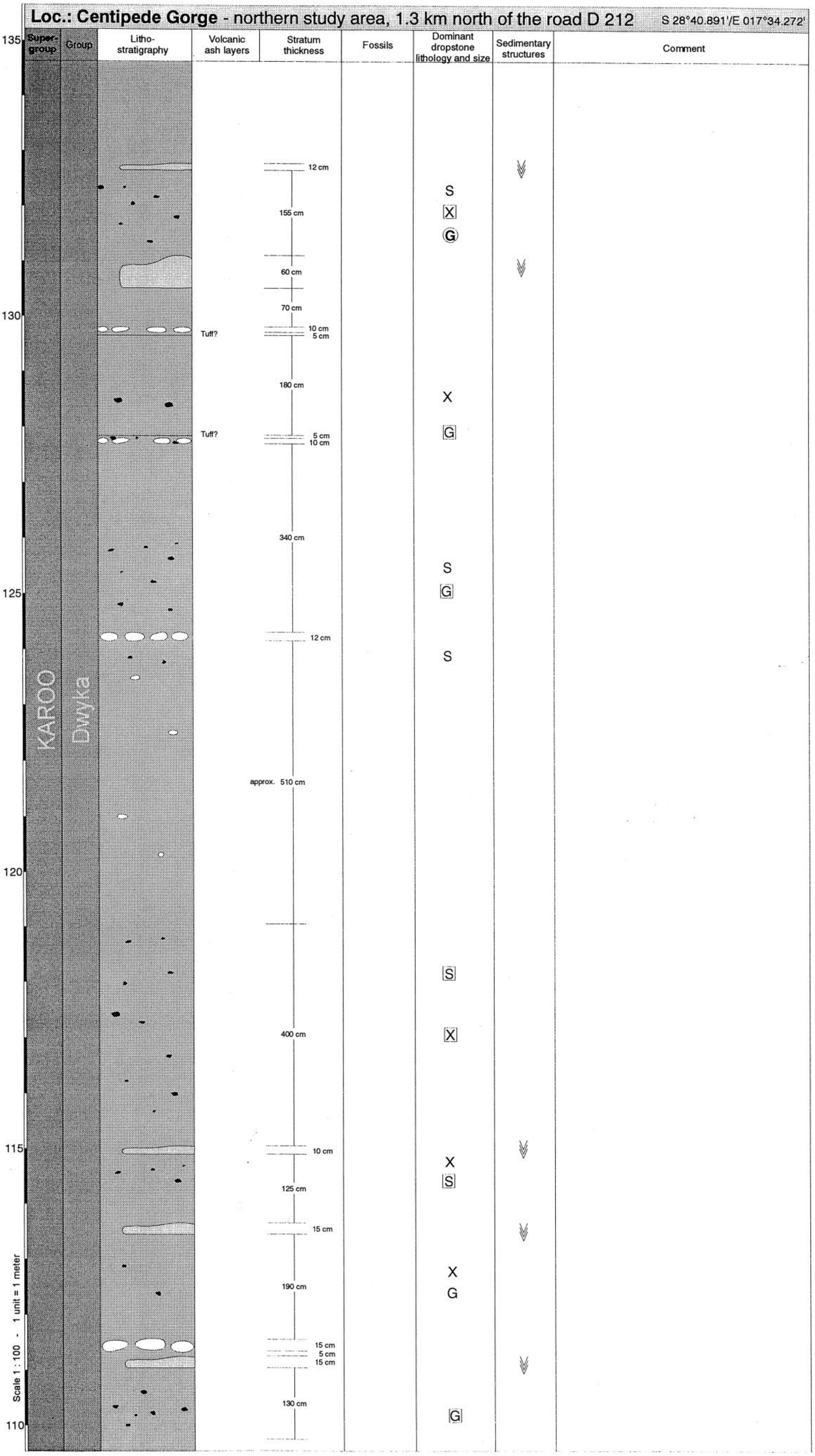

Loc.: FOSSIL BEND to PROVENANCE CAMP at the Orange River west of Provenance Camp
S 28°41.240'/E 017°33.378'
Super-group
Group
Litho-stratigraphy
Volcanic ash layers
Stratum thickness
Fossils
Dominant dropstone lithology and size
Sedimentary structures
Comment
KAROO
Dwyka
Scale 1 : 100 - 1 unit = 1 meter
80
75
70
Tuff XXXV 3mm
245 cm
Tuff XXXIV 10mm
70 cm
35 cm
145 cm
20 cm
115 cm
Tuff XXXIII 3- 4mm
40 cm
Tuff XXXII 4-5mm
430 cm
Tuff XXXI 1mm
45 cm
5-8 cm
50 cm
Tuff XXX 20mm

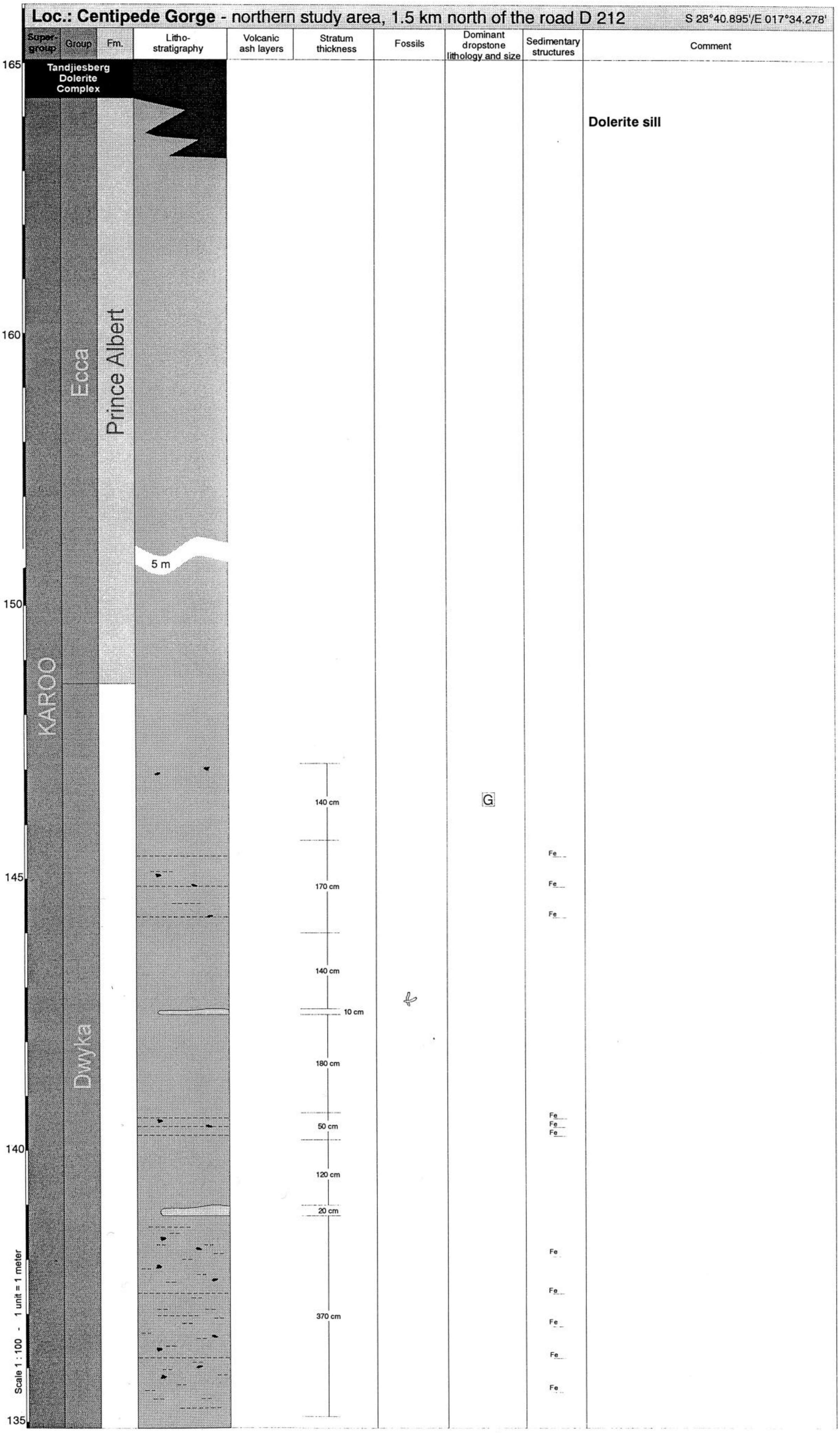

Loc.: Hare Valley - central study area, 700 m north of the road D 212
S 28°40.682'/E 017°33.763'
Super-group
Group
Litho-stratigraphy
Volcanic ash layers
Stratum thickness
Fossils
Dominant dropstone lithology and size
Sedimentary structures
Comment
95
90
85
80
KAROO
Dwyka
Scale 1 : 100 - 1 unit = 1 meter
15 cm
190 cm
5 cm
7 cm
8 cm
25 cm
12 cm
185 cm
45 cm
55 cm
10 cm
35 cm
10 cm
105 cm
25 cm
100 cm
30 cm
30 cm
5 cm
35 cm
5 cm
100 cm
10 cm
70 cm
4 cm
4 cm
80 cm
40 cm
180 cm
5 cm
60 cm
60 cm
35 cm
T XXXVI 3-4mm
T XXXV 3mm
T XXXIV 10mm
G X S
S
X
X
S
G
V S G
S
G
S
V
G
X
Fe
Fe
Fe
Fe
Fe
Fe

Loc.: Goats Cliff - central study area, 1 km north of the road D 212 S 28°40.934'/E 017°34.268'



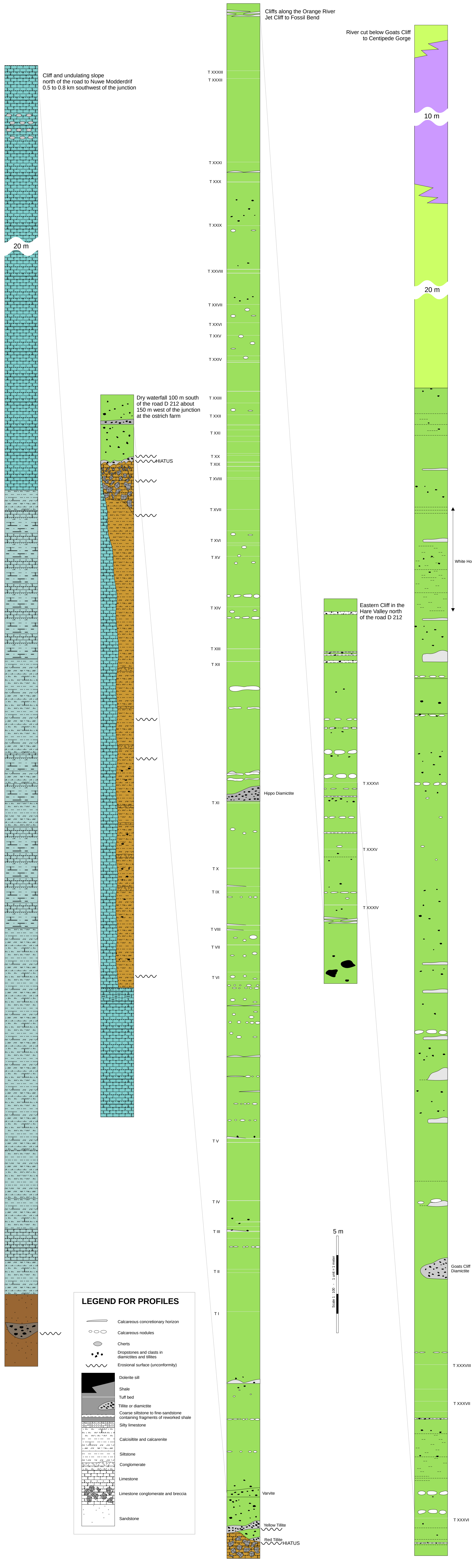
Goats Cliff Diamictite
Contorted siltstone with dissiminated clasts of varied size (max. 15 cm). The outcrops are spatially very confined.


Loc.: Centipede Gorge - northern study area, 1.3 km north of the road D 212 S 28°40.891'/E 017°34.272'


Loc.: Centipede Gorge - northern study area, 1.5 km north of the road D 212
S 28°40.895'/E 017°34.278'
Super-group
Group
Fm.
Litho-stratigraphy
Volcanic ash layers
Stratum thickness
Fossils
Dominant dropstone lithology and size
Sedimentary structures
Comment
165
160
150
145
140
135
Tandjiesberg Dolerite Complex
Dolerite sill
KAROO
Ecca
Prince Albert
Dwyka
5 m
140 cm
G
170 cm
Fe
Fe
Fe
140 cm
10 cm
180 cm
50 cm
Fe
Fe
Fe
120 cm
20 cm
370 cm
Fe
Fe
Fe
Fe
Fe
Scale 1 : 100 - 1 unit = 1 meter

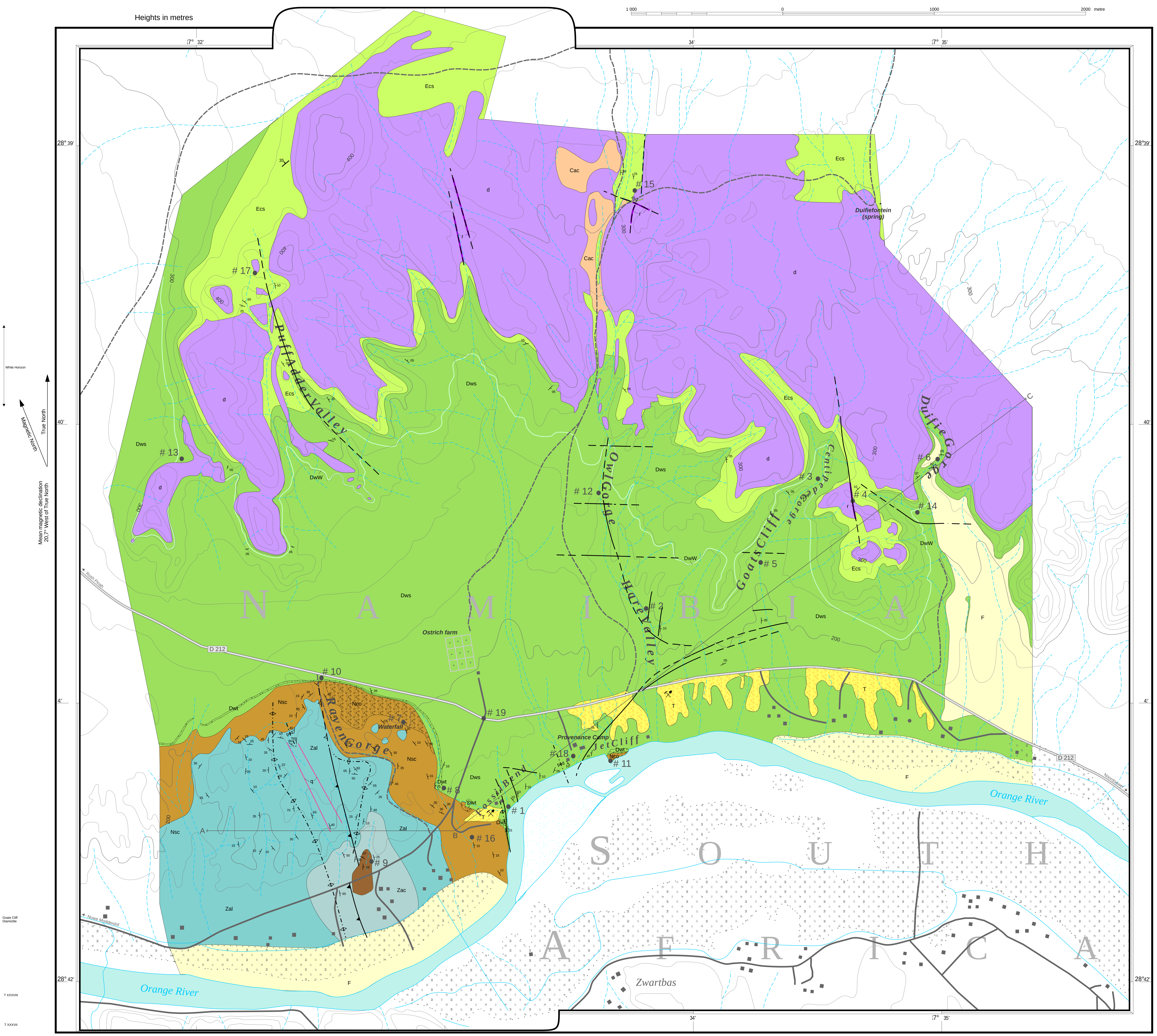
GEOLOGICAL MAP 1 : 10 000 OF THE NAMIBIAN BORDERLAND ALONG THE ORANGE RIVER AT ZWARTBAS

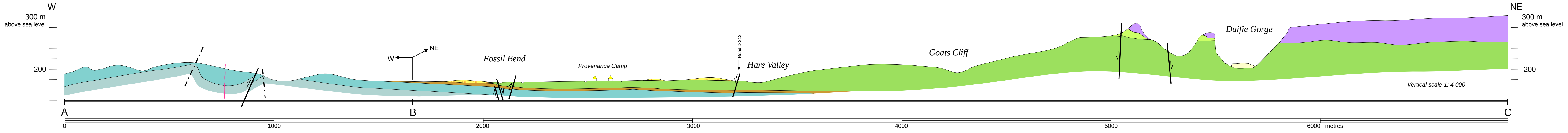
Noordoewer - Warmbad District - Karas Region - Namibia



LEGEND FOR PROFILES

- Calcareous concretionary horizon
- Calcareous nodules
- Cherts
- Dropstones and clasts in diamictites and tillites
- Erosional surface (unconformity)
- Dolerite sill
- Shale
- Tuff bed
- Tillite or diamictite
- Coarse siltstone to fine-sandstone containing fragments of reworked shale
- Silty limestone
- Calcisiltite and calcarenite
- Siltstone
- Conglomerate
- Limestone
- Limestone conglomerate and breccia
- Sandstone





MAP LEGEND

Kalahari Group and recent deposits (Cretaceous to present day)

F	Flood deposits; channel fills
T	River terraces
Cac	Calcrete and calcrete-cemented fluvial deposits

Karoo Supergroup

Ecca Group (Early Permian)

Ecs	Prince Albert Formation Shale

Dwyka Group (Late Carboniferous to early Permian)

DwW	White Horizon White weathering shale
Dws	Dwyka shale Shale, partly arenacous; diamictite (dropstones); conglomerate lenses and beds
Dwt	Dwyka tillite Diamictite

Nama Group (Late Proterozoic (Vendian))

Schwarzrand Subgroup

Nco	Nudaus Formation (Vingerbreek Member) Limestone conglomerate and breccia
Nsc	Nudaus Formation (Niederhagen Member) Quartzitic shale with a diamictitic base and intercalated conglomerate beds

Kuibis Subgroup

Zal Zaa	Zaris Formation (Mooifontein Member) Calcisiltite, calcarenite, siltite and silty limestone (Zaa) layered limestone and massive limestone (Zal)
Zac	Zaris Formation (Kliphoek Member) Red pebbly sandstone and green quartzitic sandstone

Karoo Supergroup

Intrusions (Jurassic; Post-Zaris)

r	Rhyolite dyke
d	Tandjiesberg Dolerite Complex Dolerite sill
q	Quartz vein

Normal faults
Dotted line: supposed fault;
arrow indicates strike-slip direction

Thrust fault
Dotted line: supposed thrust fault

Flexure and fold axis
crest trough

25 Bedding orientation
Long line is strike orientation; small line is dip direction, and angle of dip

Cross section
Surface line from point A to point B

8 Locality ID

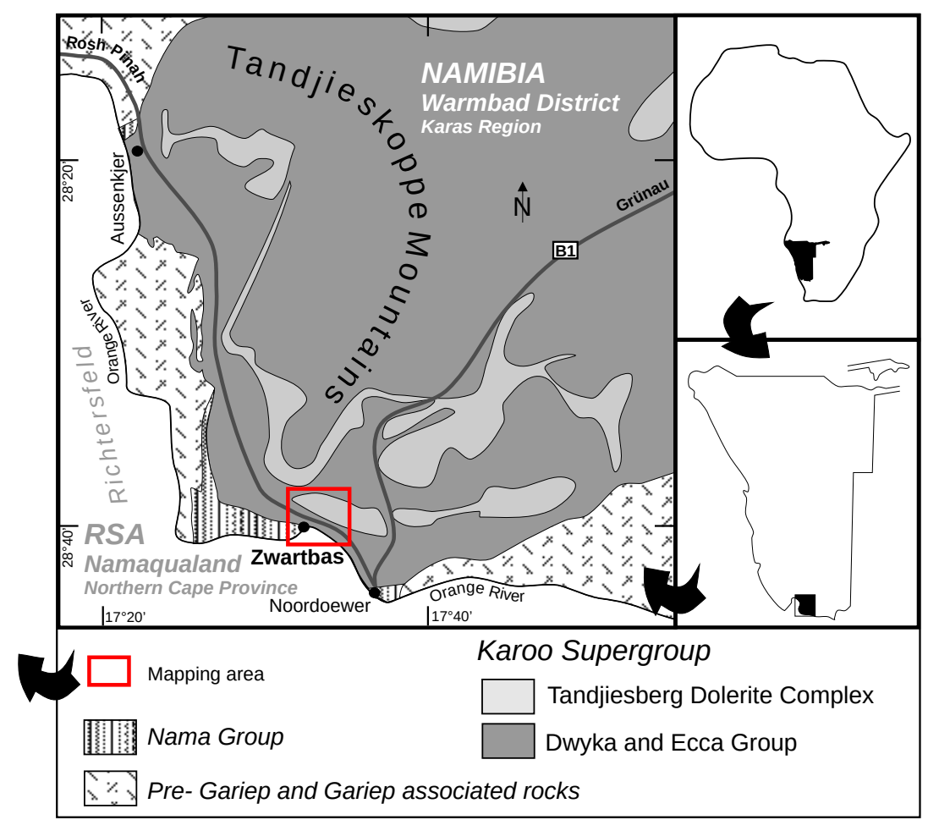
Mining Area

National road, farm road and 4x4 tracks

Farm buildings and houses

Cultivated land

Permanent streams and ephemeral rivers



Scale 1 : 10 000
Heights are in metres above sea level - contour interval 20 metres

Map source reference:
SOUTH AFRICA 1: 50 000 Sheet
2817 DA NOORDOEWER

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1999