VIRTUAL RECONSTRUCTION OF STRATIGRAPHY AND PAST LANDSCAPES IN THE WEST COAST FOSSIL PARK REGION

BY LELANDI ERASMUS

Thesis presented in partial fulfilment of the requirements for the degree of Master of Arts at the University of Stellenbosch.

Supervisor: Prof JH van der Merwe

April 2005

Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: ------------------------------

Date: ------------------------------

ABSTRACT

The West Coast Fossil Park near Langebaanweg in the Western Cape, South Africa, is known for its abundance of marine, freshwater and terrestrial fossils of Mio-Pliocene age. The fossil bearing deposits reflect the complex and varied depositional environments, which were influenced by the change in course of the Berg River and regressions and transgressions of sea-level. The fossil deposits at this site are world-renowned for their species richness and uniqueness and there was a need to gain an in-depth understanding of the events that gave rise to this situation. To understand these complexities, it was necessary to construct a composite model of the pre-history of the West Coast Fossil Park, incorporating topological, geological and palaeontological data. GIS provided the ideal platform to integrate data from such varied sources, using spatial correlation to interpret commonalities. Subsequently, a spatially explicit database of the present-day study area, from Dwarskersbos in the north to just north of Yzerfontein in the south, was constructed. The oldest geological formation, the basement layer, as well as three successive formations was reconstructed on a regional scale using borehole data. Interpolation of point data to regional surfaces was a dual process incorporating expert opinion and purpose-built tools within ESRI's ArcInfo and ArcMap 8.3. A similar reconstruction at a finer scale was done for the West Coast Fossil Park area using kriging as an interpolation method. These reconstructed geological layers can be used to predict the depth and location of fossil-bearing deposits. There is scope for further study and analysis to compare the accuracy of alternative interpolation methods, and combining it with field-based validation of modelled outputs.

OPSOMMING

Die Weskus Fossielpark naby Langebaanweg in die Wes-Kaap, Suid Afrika, is bekend vir sy oorvloed en verskeidenheid van mariene, varswater en terrestriële fossiele uit die Mio-Plioseen tydperk. Die fossieldraende afsettings weerspieël die komplekse omgewings waarin die afsettings plaasgevind het. Hierdie afsettings is beïnvloed deur die verandering in die loop van die Bergrivier en veranderinge in seevlak. Die fossielafsettings by Langebaanweg is wêreldbekend vir hul spesierykheid, en daar was ‘n behoefte om die omstandighede wat daartoe aanleiding gegee het, beter te verstaan. Topologiese, geologiese en paleontologiese data is gebruik om ‘n saamgestelde model van die oergeskiedenis van die Weskus Fossielpark te skep. Geografiese inligtingstelsels bied die ideale platform om data van verskillende dissiplines te integreer deur middel van die gemeenskaplike ruimtelike komponent. ‘n Ruimtelik-georiënteerde datastel van die studiegebied, wat strek van Dwarskersbos in die noorde tot net noord van Yzerfontein in die suide, is saamgestel deur huidige omgewingsdata te gebruik. Die oudste geologiese formasie, die basislaag, en die drie daaropvolgende formasies is geherkonstrueer op ‘n streeksskaal deur boorgatdata te interpoleer. Hierdie interpolasieproses het gebruik gemaak van spesialiskennis en –sagteware (ESRI ArcInfo en ArcMap 8.3). ‘n Soortgelyke rekonstruksie is gedoen op ‘n fyner skaal vir die Weskus Fossielpark area. Hierdie fynskaal analise het gebruik gemaak van kriging as ‘n interpolasietegniek. Ander fossieldraende afsettings kan moontlik opgespoor word deur hierdie fynskaal analise te interpreteer. Daar is ruimte vir verdere analise om alternatiewe interpolasietegnieke te vergelyk, en om die voorspellings in die veld te toets.

Acknowledgements

My thanks go firstly to my supervisor, Prof Hannes van der Merwe, for his support and patience during my years of study and thesis writing. Then also to Dr Dave Roberts, without whom this study would not be possible, a big thank you for explaining the complex geology of the Langebaanweg area, as well as interpreting data and commenting on the results.

Wolfgang Lück was of great help suggesting different methodologies that could be followed, as well as being the “helpdesk” during the early part of this study. Colleagues at the Council for Geoscience in Bellville patiently explained geological terms, and provided useful comments on the outputs of the interpolations.

My family supported me all the way in my years of study, and I thank them for encouraging and believing in me. Lastly, my sincere thanks go to my husband Barend, who provided invaluable discussions and the impetus to finish this study, and who shared the home stretch with me.

CONTENTS

Page

CHAPTER 1: UNDERSTANDING PALAEONTOLOGY THROUGH GEOLOGY 1

1.1 GEOLOGICAL SUCCESSIONS 1

1.2 SEA-LEVEL CHANGE 3

1.3 THE WEST COAST FOSSIL PARK PROBLEM 5

1.4 STUDY AIMS AND OBJECTIVES 6

1.5 THE STUDY AREA AND THE WCFP 6

1.6 DATA AND LITERATURE SOURCES 10

1.7 MODELLING AND MAPPING LANDSCAPE CHANGE 11

1.8 RESEARCH FRAMEWORK AND REPORT STRUCTURE 12

CHAPTER 2: SPATIAL PALAEONTOLOGY OF THE WEST COAST 14

2.1 SEA-LEVEL FLUCTUATION 14

2.2 FOSSIL OCCURRENCE AND TYPOLOGY IN THE WCFP 18

2.2.1 Relative dating of finds 18

2.2.2 The WCFP site and history 19

2.2.3 WCFP fossil record: megafauna 20

2.2.4 WCFP fossil record: microfauna, amphibians and avian fauna 21

2.2.5 WCFP fossil record: marine invertebrates 22

CHAPTER 3: MODELLING AND VISUALIZATION METHODOLOGY 23

3.1 GIS AND 3D VISUALIZATION OF SPACE 23

3.2 SPATIAL DATA MODELS 23

3.3 RECONSTRUCTION OF THE WCFP REGIONAL GEOLOGY IN GIS 25

3.3.1 Spatial data characteristics 25

3.3.2 Georeferencing raw maps 25

3.3.3 Contour interpolation methodology 27

3.3.4 Sequential mapping of formations 28

3.3.4.1 The GIS principle 28

3.3.4.2 Reconstruction of the Elandsfontyn Formation 30

3.3.4.3 Reconstruction of the Varswater Formation 32
3.3.4.4 Reconstruction of the Langebaan Formation 34
3.4 RECONSTRUCTION RESULTS OF THE WCFP GEOLOGY 36

CHAPTER 4: SPATIAL GEOLOGY OF THE WEST COAST AND WCFP 40
4.1 THE TOPOGRAPHY AND CLIMATE OF THE REGION 40
4.2 STRATIGRAPHY OF THE REGION 41
4.3 STRATIGRAPHICAL FORMATIONS AND THEIR OCCURRENCE PATTERN 42
4.4 THE WEST COAST FOSSIL PARK FORMATIONS 46
4.4.1 Occurrence of WCFP formations 46
4.4.2 The Varswater Formation 48
4.4.3 The Langebaan and Springfontein Formations 50

CHAPTER 5: SYNTHESIS 51
5.1 SUMMARY OF RESULTS 51
5.2 EVALUATION OF STUDY 52
5.3 RECOMMENDATIONS 54
5.4 FURTHER RESEARCH 55

REFERENCES 57

APPENDIX A: SPECIES CLASSIFICATION 62

APPENDIX B: GIS CARTOGRAPHIC BACKGROUND 69

FIGURES

Page

Figure 1.1 Cenozoic timescale with approximate ages in Ma (millions of years). 2
Figure 1.2 The study area 7
Figure 1.3 Covered excavation area in the WCFP 9
Figure 1.4 Fossil finds in their original formation inside the excavation structure 9
Figure 1.5 Research framework and methodology 13

Figure 2.1 Late Tertiary and Quaternary sea-level changes 14
Figure 2.2 A reconstruction of palaeo-shorelines during the Late Miocene and Early Pliocene 16
Figure 2.3 A reconstruction of palaeo-shorelines during the Middle and Late Pliocene 17

Figure 3.1 Steps followed to create the basement DEM of the study area and environs 28
Figure 3.2 Interpolated elevation and thickness of the basement and other formations 29
Figure 3.3 Procedure to reconstruct landscape after layer deposition 30
Figure 3.4 Steps followed to delineate and construct the elevation and extent of the Elandsfontyn Formation 31
Figure 3.5 Reconstruction of topography after the Elandsfontyn Formation was deposited 32
Figure 3.6 Steps followed to delineate and construct the elevation and extent of the Varswater Formation 33
Figure 3.7 Reconstructed landscape at the time of the Varswater deposition 34
Figure 3.8 Steps followed to construct the Langebaan Formation 35
Figure 3.9 Reconstruction of the landscape after the Langebaan Formation was deposited 36
Figure 3.10 Location of boreholes across the site of the WCFP 37

Figure 4.1 Stratigraphy of the study area 41
Figure 4.2 Spatial configuration of the basement layer and the Elandsfontyn Formation 43
Figure 4.3 Spatial configuration of the basement, Elandsfontyn, Varswater and Langebaan Formations 45
Figure 4.4 A reconstruction of the WCFP topography before mining activities commenced, showing the location of the geological profiles 47

Figure 4.5 Profile of geological formations and members along transect A 49
Figure 4.6 Profile of geological formations and members along transect B 49

Figure 5.1 A 3D rendition of the basement layer of the study area, viewed from the southwest 53

CHAPTER 1: UNDERSTANDING PALAEONTOLOGY THROUGH GEOLOGY

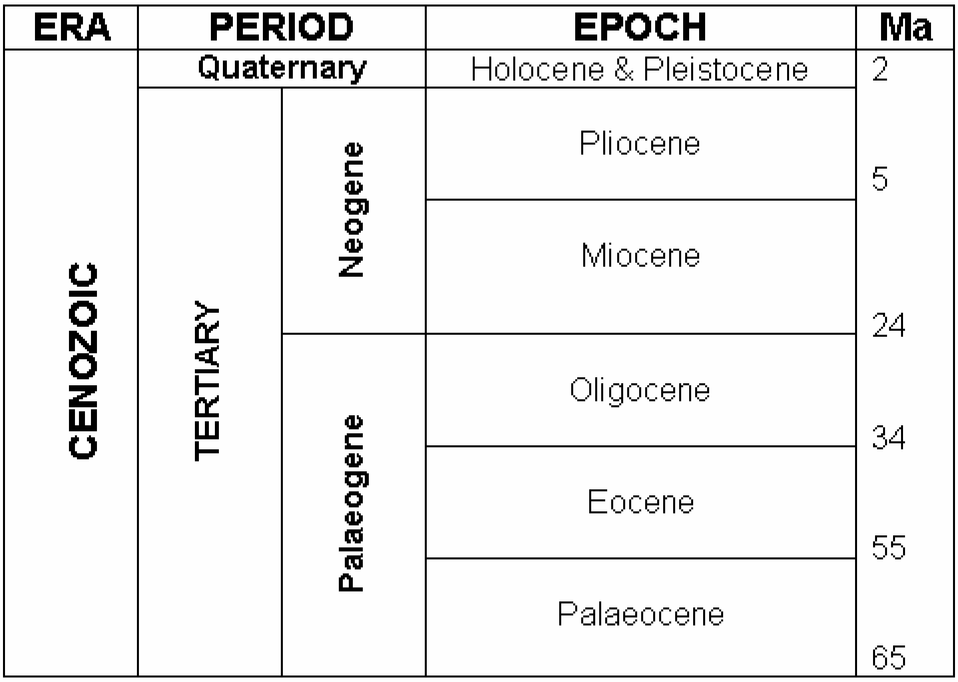
Palaeontology is inextricably linked with geology. As fossils are deposited and covered with sediment, they become part of the different geological layers as time passes. By examining the properties of geological layers, an idea can be formed of the climate and conditions of the landscape at the time of fossil deposition.

1.1 GEOLOGICAL SUCCESSIONS

The landscapes we observe today in South Africa, and indeed the whole world, represent only a fragment of all those that were evident throughout the long history of the earth. The shapes and forms of the landmass are the outcome of changes in climate and other natural forces, such as continental drift, volcanic activity, upheavals and subsiding during the continents' several-billion year history (Farb 1968). However, there is much that can be learned by studying the physical evidence for past landscapes in the landforms and geological formations that exist today.

The earth's history as deduced from rocks and fossils is complex, with parts missing at various places over the globe. After numerous surveys and expeditions, experiments and research on the structure and age of geological strata, using e.g. radioisotope decay and indicator fossils, scientists have been able to piece together a geological time scale in which a sequence of time periods has been described. Each period is characterized by its fossils, as well as by indications in the rocks of the physical events that took place while these rocks were being formed (Rubidge & Brink 1986). By studying the fossil record, we can see how environmental conditions changed from one epoch to another, and also how plants and animals evolved over time. The principle of succession can be explained as follows: geological formations are deposited on top of each other, and that means that one can deduce age from the stratigraphic sequence of different layers; with older material occurring in the deepest layers, and younger material in the upper ones. It is thus possible to date fossil finds relative to the stratigraphic sequence in which they were found. According to Deacon & Deacon (1999: 12), "composite sequences involving more than one deposit may be constructed by correlation, or matching strata according to common items of content such as artefacts or fossils".

Geological time is divided into eons, eras, periods and epochs. Of interest for this study is the Cenozoic era (see Figure 1.1), which ranged from about 65 million years ago up to the present. The Cenozoic is divided in two main sub-divisions, namely the Tertiary and the Quaternary. Most of the Cenozoic consists of the Tertiary, the period of time between 65 million years ago to 2 million years ago.



ERA	PERIOD		EPOCH	Ma
CENOZOIC	Quaternary		Holocene & Pleistocene	2
	TERTIARY	Neogene	Pliocene	5
			Miocene	24
		Palaeogene	Oligocene	34
			Eocene	55
			Palaeocene	65

Source: South African Committee for Stratigraphy (2004)
(revised from original and not to scale)

Figure 1.1 Cenozoic timescale with approximate ages in Ma (millions of years)

During the last part of this period, a fortuitous set of circumstances led to the preservation of the remains of animals from a diverse freshwater, marine and terrestrial fauna at a locality now known as the West Coast Fossil Park (WCFP), near Langebaanweg in the south-western part of the Western Cape Province of South Africa. The formation and preservation of fossils is a chance affair, dependent on the rapid burial of organic remains in a suitable substrate, soil conditions conducive to fossil formation, and subsequent exposure by excavation or natural erosion (Clegg & Mackean 1994; Deacon & Deacon 1999). Even if circumstances lead to successful fossil formation, such fossils are usually either marine, aquatic or terrestrial in origin. However, at the WCFP, the shifting of the palaeo - Berg River, as well as changing sea-levels, were factors that contributed to the deposition of fossils originating in three different habitats in one locality, and elevates this site to that of a fossil find of global importance. The WCFP, recognized as one of the most prolific sources of late Tertiary vertebrate fossils in the world, has an internationally renowned fossil fauna, e.g. of the larger mammals the only bear known in sub-Saharan Africa, a wolverine, short-necked giraffids and five species of hyaena once occurred here.

The late Tertiary is the period of geological time between 24 and 2 million years ago, and comprises the Miocene and Pliocene epochs. The above-mentioned fauna (about five million years old) suggests a Mio-Pliocene age for the deposit. Deacon & Deacon (1999) refer to this latter part of the Tertiary as the Neogene, comprising the Miocene and Pliocene epochs. Most of the deposits overlying the bedrock in the vicinity of Langebaanweg date from these epochs, and it is the Pliocene element that includes the most important of the phosphate ore-bodies, as well as the largest assemblage of fossils recovered to date (Hendey 1982). Authors differ as to the exact time spans assigned to each of these periods, and the standardized version of the South African Committee for Stratigraphy (SACS) is used here.

Geological papers on the Langebaanweg area consulted for this thesis included those by Dingle, Lord & Hendey (1979), Hendey (1970a; 1976b; 1981a; 1982), Roberts (2000; in press –a; in press -b) and Tankard (1974b; 1976). Unfortunately some of these authors failed to reach consensus on the main issues of naming the layers and members they comprise, and of the dating of the different formations (Hendey 1976b; Tankard 1974b; 1976), which make interpretation of other results difficult and often problematical. Rogers (1980) gives a clear description of previous investigations and published work available on these issues. The most recent publications, e.g. Roberts (2000; in press –a; in press -b) are followed here for sequence nomenclature.

1.2 SEA-LEVEL CHANGE

Changing sea-levels were one of the major influences in the deposition of Tertiary sediments along the southern African coastline (Hendey 1982). These fluctuations were brought about by changes in elevation of the earth’s crust, resulting in either a change in the volume of ocean basins, or in vertical movement of the coastline. Changing climates may also have contributed to sea-level change by thermal expansion of ocean water and ice cap melt. Evidence of ancient shorelines can therefore give us an indication of the sequence and magnitude of sea-level change over geological time (Hendey 1982).

Up until 1975, there was no consensus on the rate, magnitude and sequence of global sea-level changes. In 1975, the American oil company, EXXON, released a definitive study on the subject. This study recognized ‘cycles of relative sea-level change’. Such a cycle would typically be characterised by a relatively quick period of sea-level rise (called a transgression), followed by a period during which the sea-level remained constant (called a stillstand). Similarly, drop in sea-level (called regressions) happened over relatively short time spans, also followed by stillstands. Hendey (1982) gives a short description of the transgressions and regressions in sea-level during the past 24 million years, which will be discussed in more detail in Chapter 3.

Changes in sea-level along the southern African coast tracks global sea-level changes closely, with the result that the Langebaanweg deposits can be related to the geological time-scale and to significant geological events that occurred elsewhere in the world (Hendey 1982).

Langebaanweg’s local geological succession, being so close to the coast, has been considerably influenced by past changes in sea-level. The succession itself provides some evidence of the nature and timing of these changes, but it is also necessary to look at regional and global evidence. The local record of sea-level movements is complemented and supplemented by evidence from further afield; in this regard Hendey (1981b) gives an account of correlations and differences between the two regions of the west coast of South Africa. They are the southwestern Cape coast between False Bay and the Olifants River, and the Namaqualand coast between the Olifants and Orange Rivers.

There is unfortunately not complete consensus on the exact location of the ancient shorelines when comparing the two regions. Uncertainty stems from the lack of good exposures, but the sea-level history of the two regions is nonetheless linked by vertebrate and invertebrate fossils (Pether 1986). Confusion arose because of the more complex geology of the southwestern Cape coast where the record is poorer and also more difficult to interpret.

Hendey (1981b) gives a comprehensive summary of different views and evidence in the literature on the sequence and magnitudes of southern African sea-level changes, but such detail falls outside the scope of this study. It is here accepted that there is evidence for significant changes and for the purposes of this study they will be simplified to four distinct events.

Four well-defined late Cenozoic shorelines can be distinguished in the Langebaan area, and they are referred to by their approximate elevations of 90m, 50m, 30m and 20m (relative to current sea-level). According to Hendey (1981b: 11) “it has generally been assumed that there is a direct correlation between the age and the elevation of these shorelines, the oldest being the highest”. However, evidence from the Langebaanweg record proves that this is not always necessarily the case. In this area a 30m shoreline is the oldest, followed in descending order of age by the 90m, 50m, a younger 30m and 20m shorelines. There is good evidence for a younger (Plio-Pleistocene) 30m shoreline and an older (Miocene) one (Roberts & Brink 2002). Local geology plays an important part in providing evidence of the actual or likely age of these shorelines. By comparing the geology and different sea-level stands, much can be learned about the fossils at the time of deposition.

1.3 THE WEST COAST FOSSIL PARK PROBLEM

Fossils (from the Latin *fossilium* meaning ‘a dug up thing’) have been objects of human interest since the earliest times. Palaeontology - the study of fossils - (from the Greek *palaeos*, meaning ‘ancient’ and *on*, meaning ‘being’) can be regarded as having begun with the work of Leonardo da Vinci (1452 - 1519), who refuted many old superstitions, for example that fossils have healing properties (Kershaw 1983). Fossils are the preserved remains of animals and plant tissues in sedimentary rocks, which get impregnated by silica and mineral salts and harden into “stone”. They are indispensable guides to past animal and plant assemblages. As documents of organisms living aeons ago, fossils provide a window to the past. The WCFP may hold the key to our understanding of the local stratigraphy over the past 5 million years.

The mining in the Langebaanweg area had its advantages and disadvantages: if there had been no mining activities, there is no guarantee that, and when, the fossil finds would have been made. The downside of the mining activities is, however, that a lot of the geological evidence has been removed, which makes it difficult to place the geological context. Early research does not show consensus on the relative ages of fossils and geological formations (Hendey 1969; 1981b; Tankard 1976). Although there has been some work since (Roberts 2000), a more in-depth knowledge of the spatial extent of formations will inform geologists as to which processes (i.e. sea-level change) could have been responsible for which deposits. These processes may inform researchers on what type of fossils to expect in any particular formation. There is therefore a need for a spatially explicit framework to reconstruct geological formations from borehole data and using expert opinion so that fossil finds can be interpreted in the correct temporal and spatial context.

1.4 STUDY AIMS AND OBJECTIVES

The aim of this study is to spatially reconstruct the palaeo-geomorphological environments of the WCFP by virtual geomorphological modelling of the key stratigraphic units, accounting for surface topography during fluctuating sea-levels and consequent fossil deposition over the past five million years, and providing computerized means to communicate findings.

The research objectives were the following:

- ◊ To establish a GIS database for the present surface of the study region by means of a 20m Digital Elevation Model (DEM) and incorporating inter alia topography, drainage, and infrastructure data;
- ◊ To establish a spatial distribution GIS database for the full area coverage/occurrence of each current stratigraphic unit on a regional scale, and in greater detail for the Fossil Park area, as a separate overlay;
- ◊ To establish a palaeo-surface geomorphological reconstruction for each major (landscape defining) sea-level stand during the past 15 million years;
- ◊ To synchronize key fossil occurrences with key stratigraphic units and to capture appropriate imagery.

1.5 THE STUDY AREA AND THE WCFP

The WCFP (approximately 32° 58’S, 18° 09’E) is situated on the R45, 120 km north of Cape Town in the Saldanha Bay - St Helena Bay region of the Western Cape Province. The area is topographically fairly homogeneous at low elevation, with mostly calcareous sandy soils, occasionally broken by granite hills. Frequent strong winds, nutrient-poor soils and low rainfall (ca 300mm p a) have resulted in a bleak environment (Hendey 1982). Fresh surface water does not occur in the immediate vicinity of Langebaan, except for small ephemeral ponds during winter. The major part of this region is drained by the Berg River, which is also the largest river in the southwestern Cape. For orientation purposes the major spatial characteristics of the study area are displayed in Figure 1.2. It shows the major settlements, infrastructure and natural features.

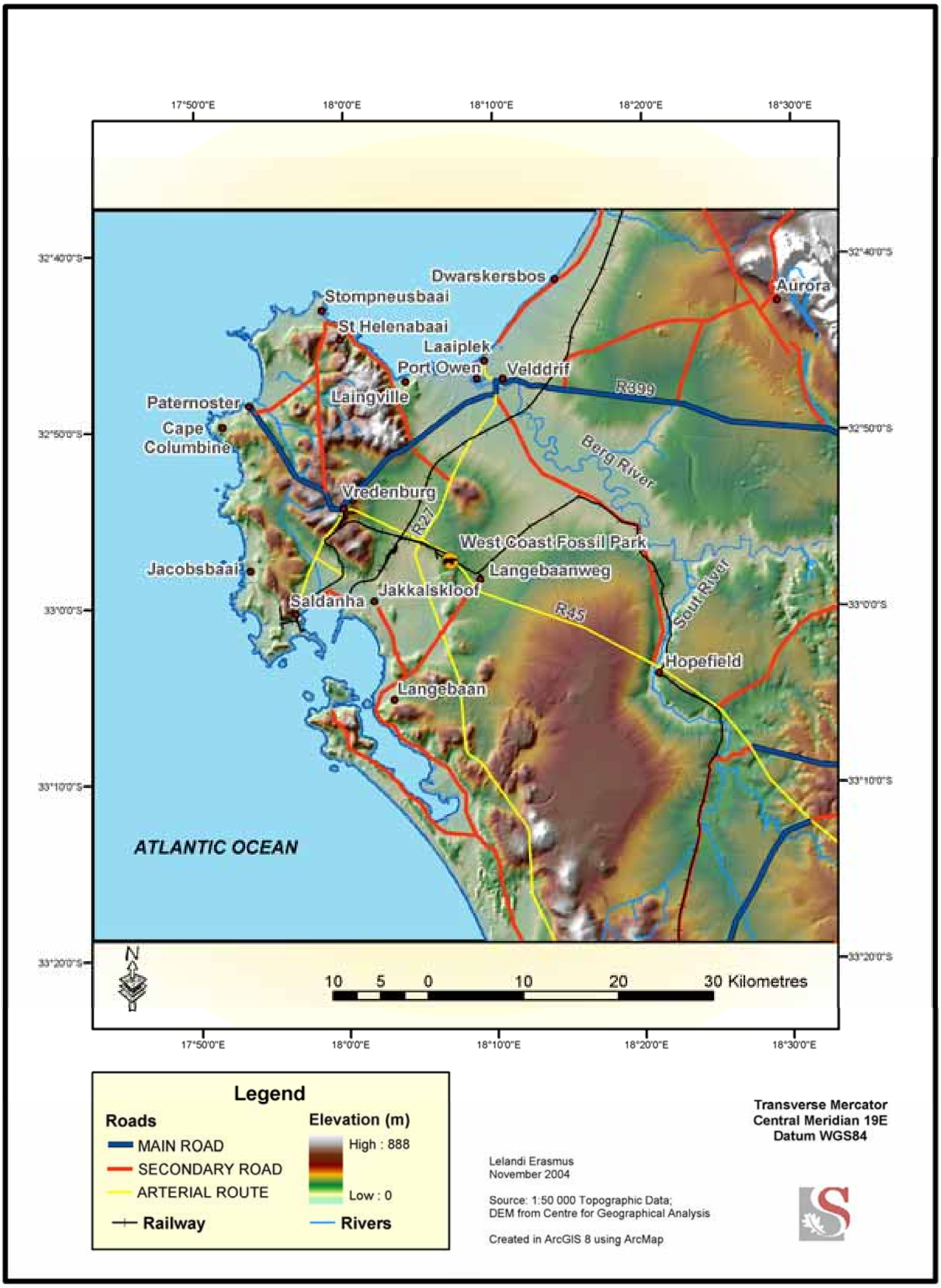


Figure 1.2 The study area

The background of the study area map is a shaded Digital Elevation Model (DEM) overlaying a hillshade of the same extent. The criteria used for delineating the exact area shown, are i.a the location of the WCFP as well as the phosphate mines on surrounding farms; the Elandsfontyn fossil site (not shown on this map); the Berg River as well as the palaeo-Berg River course; the coastal areas and Langebaan lagoon which forms an important part of the discussion on past sea-level changes.

The natural vegetation of the area is classified as ‘coastal fynbos’, with annuals being present, but no indigenous trees. Anthropogenic land-use change in the form of agriculture has resulted in very little remaining natural habitat. The only localised exceptions are areas where water and associated nutrients result in abundant bird life, such as the Berg River estuary and the Langebaan lagoon (Hendey 1982). No larger mammals survive, although smaller ones such as insectivores, bats, rodents, small carnivores and small antelope are not uncommon.

The original fossils were found in 1958 during mining operations in the CHEMFOS Ltd phosphate mine on the farm Langeberg (and subsequently on the nearby farm Varswater) near Langebaanweg (Hendey 1982). Phosphate has been mined in two areas, one being an opencast mine immediately west of the Langebaanweg railway station, known as Baard’s Quarry. Large quantities of fossils were uncovered here, but unfortunately most were unidentifiable fragments (Hendey 1978). The farm Varswater, about two kilometres further west, yielded few fossils. Mining was started in 1965 on the New Varswater Mine (‘E’ Quarry), which proved to be the source of the vast majority of fossils from this area.

When mining stopped in 1995, the South African Museum, together with SAMANCOR (African Metals Corporation), recognized the potential for developing the site as a fossil park (www.museums.org.za/wcfp), and consequently a 14 ha fossil-rich area within the mine property was declared a National Monument in 1996. The WCFP is managed by Iziko Museum of Cape Town in partnership with BHP Billiton. Photographs of the “dig” or excavation site at the WCFP, and the in-situ display of fossils inside the covered area are provided as Figures 1.3 and 1.4.

Not only is the WCFP, and more specifically the fossils found there, the source of many scientific papers, but the Park is also an important educational, research and eco-tourism facility. Employment opportunities were created for the local population when SAMANCOR provided funds for mine rehabilitation. The local residents were employed to clear alien plant invaders that had choked the old mines, after which indigenous vegetation was re-introduced. Through refurbishing the old mine buildings, more jobs were created. Many residents are still employed at the Park as guides, fossil sorters and caterers (Roberts 2002).

Figure 1.3 Covered excavation area in the WCFP

Figure 1.4 Fossil finds in their original formation inside the excavation structure

1.6 DATA AND LITERATURE SOURCES

Dr Dave Roberts from the Council for Geoscience, who initiated the study, was of great help, supplying and interpreting the borehole data, discussing the geology of the region, guiding field trips and making literature available. Mr Alan Woodford of Earthdata International (now SRK Consulting) provided a borehole database, a 1:125 000 scale geological map of the area in digital format, as well as catchment data. The Centre for Geographical Analysis, University of Stellenbosch, provided digital 1:50 000 topographic data (originally Chief Directorate: Surveys and Mapping), a Landsat image as well as a 20m digital elevation model (DEM). Dr Pippa Haarhoff of the WCFP advised on palaeontological aspects, and provided useful insights in the working, prospects and problems of the Park. The staff at the Council for Geoscience's Bellville office explained and discussed the complex geology of the region, and commented on the outputs of the borehole data interpolations.

Many published papers were consulted, ranging from geology and palaeontology to geography, in order to understand the complexities mentioned earlier. Journal articles form the main body of the literature consulted, with most of them being fairly dated. Research output on the fossils and geology of the WCFP peaked in 1969 to 1982, as evidenced by the largely descriptive articles by Hendey (1970a; 1970b; 1973; 1975; 1976a; 1976b; 1978; 1981a; 1981b; 1982), Kensley (1977) and Olson & Eller (1989). A few individuals conducted most of this research a few years after the discovery of the site. The reasons behind this lack of interest in intervening years are unknown. Geographical literature as such forms a smaller part of the references used, although most articles about the fossils, geology, climate and sea-level changes at the fossil site have a short description of the Langebaanweg area (Hendey 1982; Coetzee & Rogers 1982). Studies on the geological aspects are often integrated with geomorphology and topography.

Some of the literature consulted for this thesis are too technical - and specific - for use here. For example, anatomical descriptions of a number of the fossils found (Denys 1998; Harris 1976; Hendey 1977; Maglio & Hendey 1970; Simpson 1976; Singer & Hooijer 1958), while providing background, is beyond the objectives of this research. The different geological and geomorphological processes (Birch 1977; Tankard 1974a) provide more process background. Several authors go into much more detail than would be needed, for example the paper by Partridge (1969) on fluvial features and climatic change during the Quaternary period in South Africa.

Much emphasis is placed here on literature regarding the fossils and their (relative) ages, as the fossil discoveries provided the main impetus for the current research effort. In order to spatially reconstruct the palaeo-geomorphological environments, it is necessary to understand the conditions at the time of deposition. Hendey (1970a; 1970b; 1973; 1975; 1976a; 1976b; 1978; 1981a; 1981b; 1982) covers most aspects of the fossil-related part of the present research problem, namely the fossils themselves, sea-level changes and the geology of the area.

1.7 MODELLING AND MAPPING LANDSCAPE CHANGE

As mentioned earlier, the geological history of the fossil-bearing deposits at Langebaanweg over the past five million years is complex, involving repeated rises and falls in sea-level (Roberts in press -b). This resulted in a range of sedimentary settings surrounding shifting riverbeds and -courses, marshes, estuaries and marine shorelines. Comprehending and communicating this complexity coherently and enabling informed further excavation activity in the area necessitates the construction of a spatial model reconstructing the geomorphological development of the region.

A Geographic Information System (GIS) is the ideal spatial modelling instrument. It is essentially a digital database and a set of functions and procedures to capture, analyse, query and manipulate spatially-related data. Such a database can easily and continually be updated as more information becomes available and/or as interpretation of the area is refined (Holland 1997). Visual presentation of the spatial and temporal distribution of a phenomenon often provides clues to the process(es) that generated the phenomenon (Vitek, Giardino & Fitzgerald 1996). A GIS is therefore a most suitable tool to capture, analyse, manipulate and also present these processes by means of maps. Comparisons of the different locations of fossil finds can be made; this need not be only in two dimensions, but can also be looked at from other perspectives as well. Where there is only limited information available, as is the case in this study where a lot of the geological evidence in the Langebaanweg area has been removed due to mining activity, a GIS can interpolate between points and give an estimate of what the values could have been. Such interpolations are based on continuous data, i.e thicknesses of geological layers. Science, or more particularly a GIS, can help in suggesting areas in which to search for fossils of the appropriate age. There is also a continuing effort to fill the gaps in the present record, by using advanced techniques like satellite images of earth structures so as to indicate likely locations (Deacon & Deacon 1999).

Mapping and interpolation techniques and the methodology followed are covered in Chapter 2, as well as the software used to perform all the analysis.

1.8 RESEARCH FRAMEWORK AND REPORT STRUCTURE

The flow diagram in Figure 1.5 illustrates the broader methodology followed in this study. The problem definition and research proposal guided a literature review. The data that was needed to complete the aims and objectives were identified and collected. Various data sources were utilised as shown before. A key research component was field visits to the WCFP to acquire study area images, and also to interview the WCFP staff. Analyses were conducted in ArcInfo, ArcGIS 8.3, ERMapper and ERDAS Imagine. Outputs from these analyses formed the basis of the final report, where the results and implications are discussed in detail.

In Chapter 2 the report focusses on the fossils and interprets their location relative to relict coastlines and palaeo-landscapes. GIS and spatial modelling is an integral part of the methodology followed to investigate these palaeo-landscapes, and Chapter 3 then provides an in-depth treatment of the usefulness of GIS in reconstructing sea-level changes and geological formations. In Chapter 4 the report examines general links between palaeontology and geology and then focusses on the geology and stratigraphy of the West Coast region of the southwest Cape. In this latter section it is demonstrated that an understanding of geological formations is vital to an in-depth analysis of fossils in this area. In the final chapter findings are synthesized and recommendations made for future studies of this nature. An appendix with the fossil finds database and GIS commands used to construct the different geological surfaces are attached.

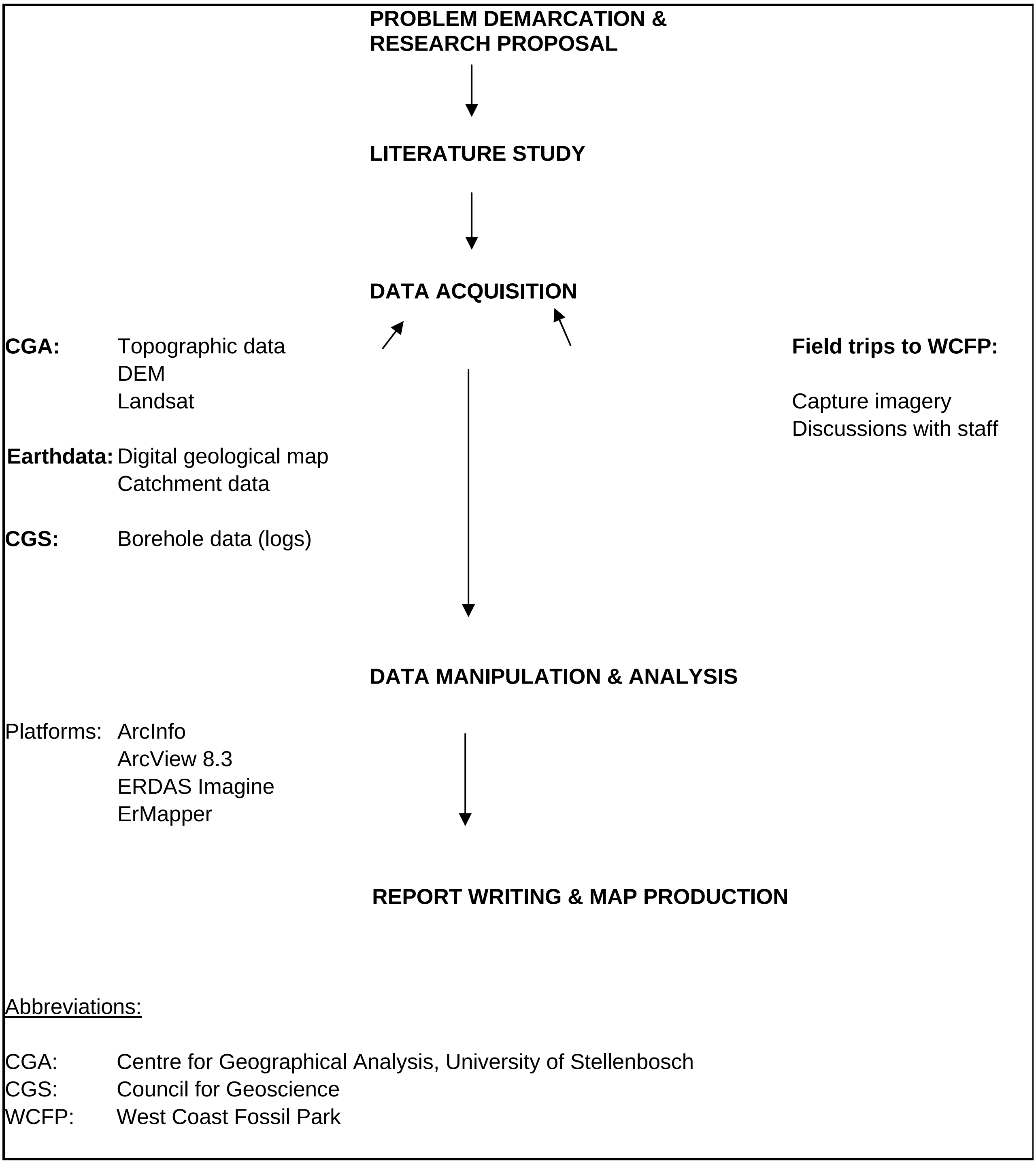


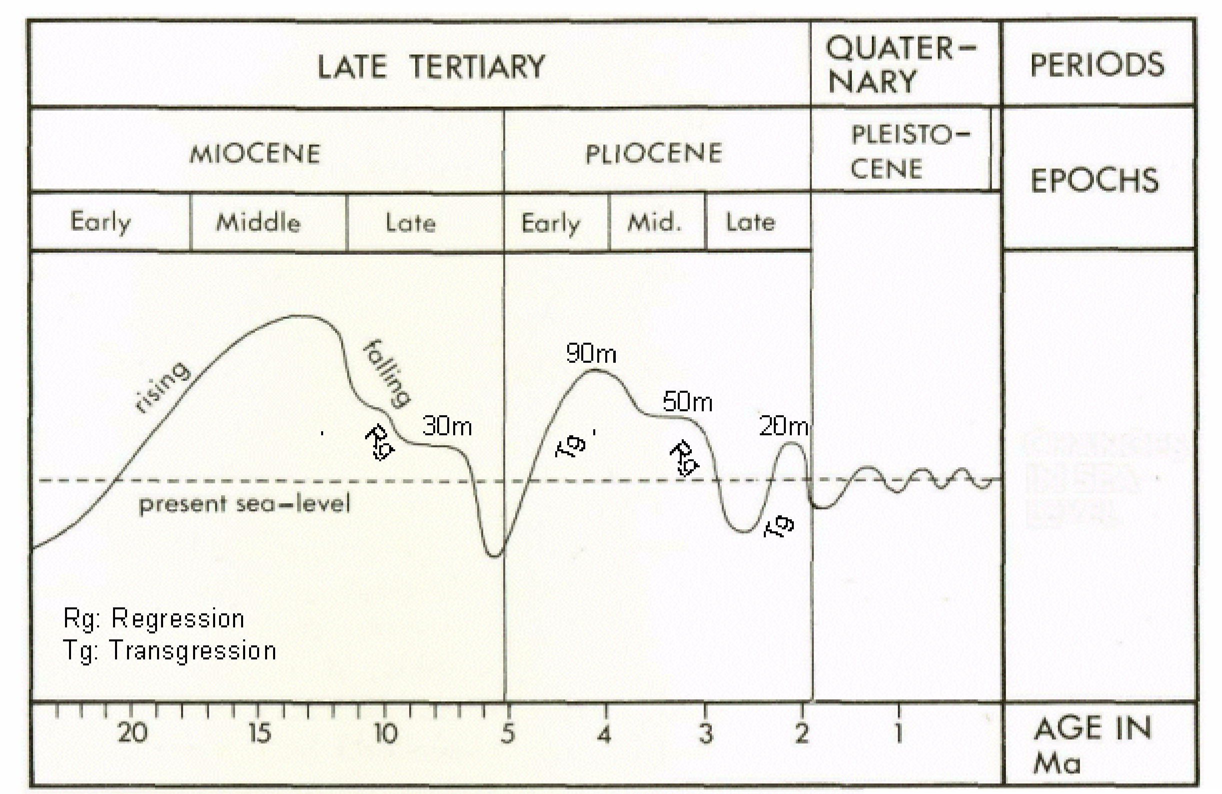
Figure 1.5 Research framework and methodology

CHAPTER 2: SPATIAL PALAEONTOLOGY OF THE WEST COAST

Changing sea-levels had a pronounced impact on the timing and type of fossil deposition in the study area, as the shoreline retreated landwards and seawards in the course of a few million years.

2.1 SEA-LEVEL FLUCTUATION

As mentioned in Chapter 1, there were four significant sea-level stands during the late Cenozoic. Figure 2.1 shows the fluctuating sea-levels, and concomitant transgressions and regressions of the shorelines during the past 24 million years (Ma): this will be explained below.



(Source: Hendey 1982 p6)

Figure 2.1 Late Tertiary and Quaternary sea-level changes

The challenge is to relate these sea-level fluctuations to specific time periods, and the accompanying geological formations. In general, sea-level changes along the west coast of South Africa conformed to global changes (Vaili & Hardenbol, in Hendey 1981b). More specifically, there was a major transgression (retreat landwards of the shoreline as the sea-level rose) in the

Neogene, which started in the early to middle Miocene, to be followed by a subsequent drop in sea-level and regression seawards of the shoreline in the middle to late Miocene. This regression is associated with the 30m (above present) palaeo-shoreline. Erosion of deposits formed during previous transgressions took place during this regression. These deposits consisted primarily of phosphatic sandstone, and wave action reduced this sandstone to gravel. This gravel forms the basal unit of the Varswater formation. During this period, most of the present-day low-lying areas along the coast and river valleys were inundated, with the WCFP on the palaeo-coast (Figure 2.2). After this regression, there was a subsequent transgression during the early Pliocene, evidenced by the 90m shoreline as its maximum. Most of the study area was flooded, with hilltops remaining as islands (Figure 2.2). During the early stages of this transgression, the Berg River entered the sea near present-day Langebaan, and was responsible for most of the sediments making up the 2nd and 3rd members of the Varswater formation. As the sea-level rose, the Berg River's course shifted northwards, assisted by the formation of a sand bar in the estuary, and its contributions to sediments at the WCFP became less towards the end of this transgression (Hendey 1981b).

Subsequent regression during the late Pliocene resulted in the 50m shoreline. This regression truncated the fossil record at the WCFP by removing much of the topmost layer. During this period, the Langebaan lagoon and the Berg River valley were connected, and the WCFP was in shallow coastal water (Figure 2.3). There is also evidence for a 20m shoreline. However, this represents either a second, lower sea-level that stayed constant for long enough to create a recognisable shoreline, or it represents a subsequent early Pleistocene transgression. The 20m shoreline approximates the present-day shoreline, with the WCFP situated some distance from the coast. Towards the end of the Pleistocene the Berg River was very close to its present position and made no significant contribution to the formation deposition at the WCFP.

Figures 2.2 and 2.3 show a reconstruction of the palaeo-coastlines along the West Coast for the four recognised phases of sea-level change that can be identified (Hendey 1981b). These reconstructions are based on a present-day digital elevation model (DEM), and as such they have their limitations. First, for this analysis no information on the actual inland topography at the time of sea-level change exists and the depicted topography should not be interpreted as such. Second, the current course of the Berg River distorts the modelled coastline, but in the absence of data on the appearance of the current Berg River valley in those ancient times, interpretation has to be limited to the palaeo-Berg River valley, which ended in the Langebaan lagoon.

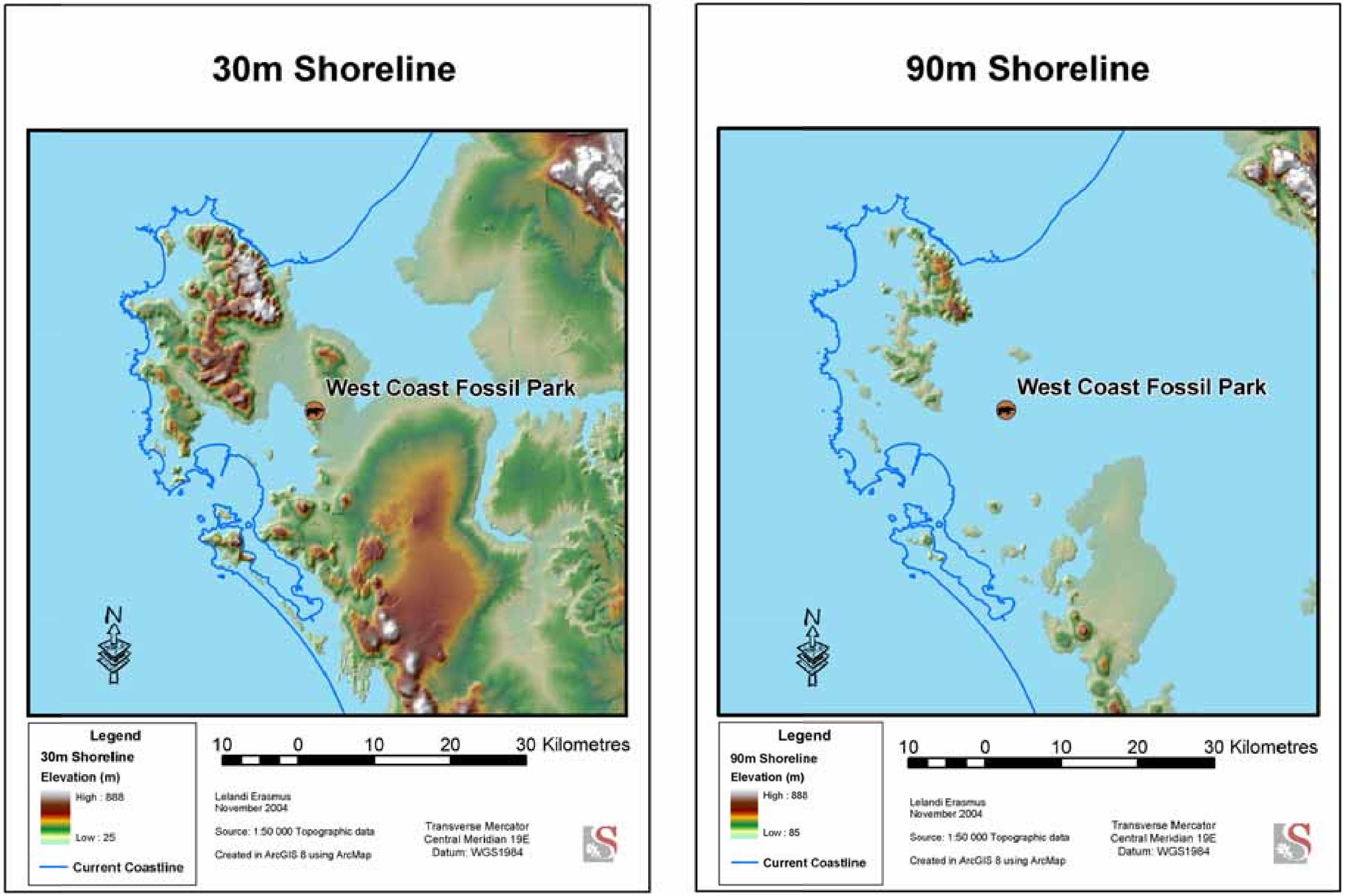


Figure 2.2 A reconstruction of palaeo-shorelines during the Late Miocene and Early Pliocene

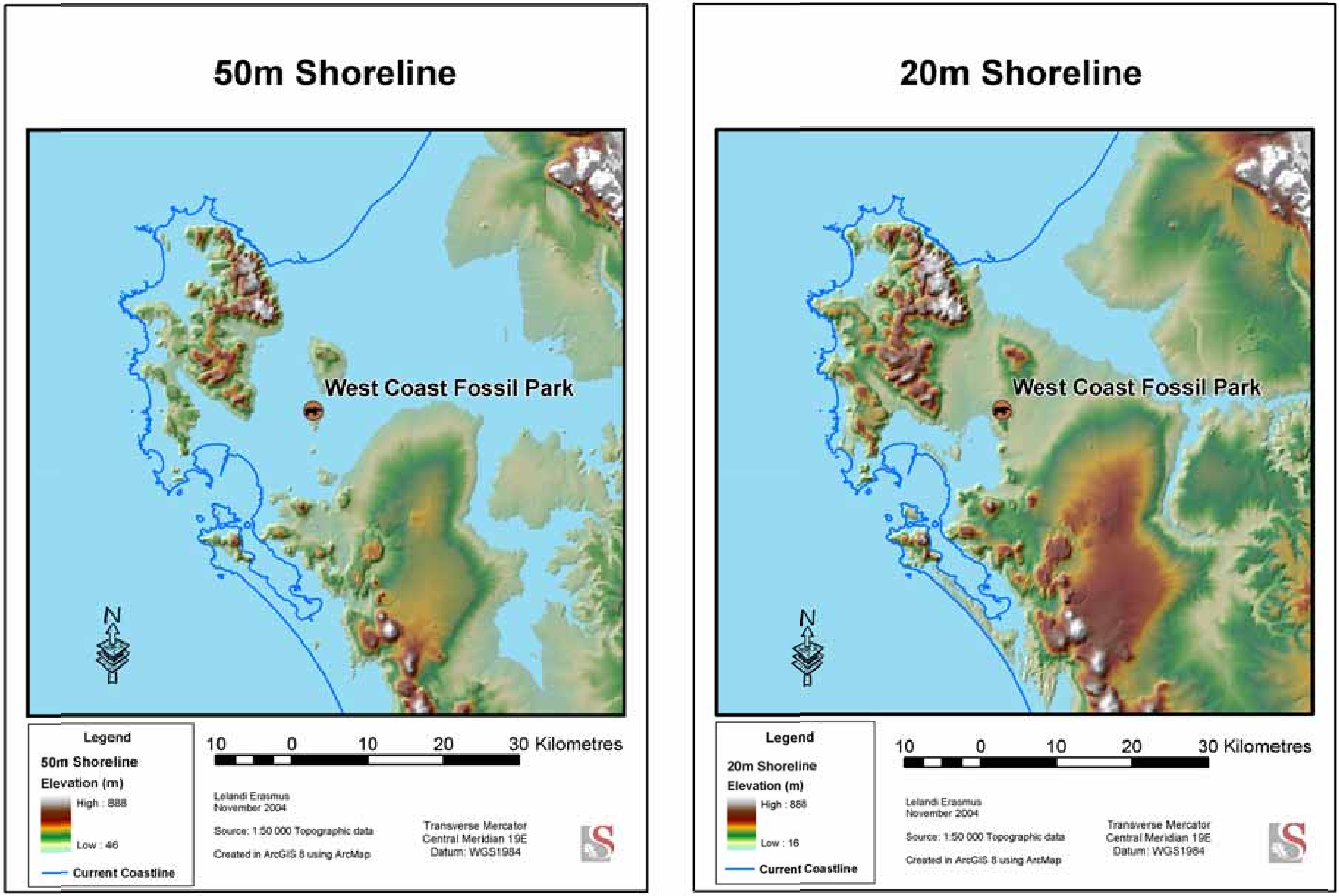


Figure 2.3 A reconstruction of palaeo-shorelines during the Middle and Late Pliocene

However, the modelled coastline still represents a plausible explanation of those palaeo-shores. Of particular interest are not the exact shape of the coastline, but rather the periods of shoreline transgression and regression across the Langebaanweg fossil site, providing ample opportunity for the deposition of marine fossils.

The reconstruction of the above-mentioned shorelines was done in ArcMap with the Spatial Analyst extension, using a present day 20m DEM. Elevation values were selected for each of the four sea-level stands, for example all values of 30m and above were selected for the 30m shoreline (*in Raster Calculator: dem >= 30*). The result was a grid with the two cell values zero or one. Zero represents all values of cells not selected, and one will be the selected cell value. The next step was to convert this grid to polygons (Spatial Analyst: *convert raster to feature*); then select cells with the grid code value of one, and export this so that only one polygon remains. The resulting polygon does not have any elevation values at that moment; therefore it must be converted back to a grid (Spatial Analyst: *convert feature to raster*). The last step in Raster Calculator is to multiply the grid values (*dem * 30m grid*). This procedure was done for all four shoreline reconstructions.

2.2 FOSSIL OCCURRENCE AND TYPOLOGY IN THE WCFP

Fossils were found in different members of geological formations in the WCFP area, and the age of these fossils relies on knowledge of the relative ages of the different sediments.

2.2.1 Relative dating of finds

The succession of life on earth, starting more than 3000 million years ago, is a fascinating and complex story (Rubidge & Brink 1986), with higher forms of life having a history dating back at least 500 million years (Clegg & Mackean 1994; Hendey 1982). The only direct evidence of the course of life from earliest times comes from the fossil record. Through extrapolating and comparison with living organisms and their environment, past environments can be reconstructed. The age of fossils is usually calculated from comparison with other finds and sites, or through geophysical dating methods such as radioisotopes, C^{14} or potassium-argon (Clegg & Mackean 1994). Relative dating of some of the Langebaanweg fossils has been based on comparisons of some mammals with their counterparts in East Africa (Harris 1976; Hendey 1969; 1976a; Klein 1981). On this basis, it is believed that the Langebaanweg deposits bearing the main body of higher vertebrate remains in the WCFP could be four to five million years old.

It is also possible to estimate the age of some vertebrates at the time of death, and to construct age (and mortality) profiles, by using dental crown heights. The mortality profiles suggest probable causes of death, which are closely related to the environment of the time (Klein 1981). Climates prevailing at the time of fossil deposition can be deduced from palynological (pollen) sources (Coetzee & Rogers 1982) and the fauna itself. However, in spite of all these sources of information, the fossil record is far from complete as a record of past animal life, since the most successful fossilization is of hard parts. Soft-bodied animals rarely survive as fossils (Kershaw 1983).

2.2.2 The WCFP site and history

At Langebaanweg, palaeontologists have met with a set of circumstances that has made it possible to discover, and recover, a very rich source of fossils (Hendey 1982). The Langebaanweg deposits are of particular interest because they are the only ones of major importance in sub-Saharan Africa where the remains of marine, fresh-water and terrestrial animals occur together (Hendey 1975). The WCFP is one of the richest fossil sites in the world, with fossils dating back 5 million years. The Langebaanweg site is 14 km wide, and according to Smith (1998), it is impossible to walk anywhere on the site without treading on fossils. The top layer of the site has examples of early Pleistocene stone tools, such as hand axes; left behind by human ancestors who lived on the banks of the tropical forest that 500 000 years to 1 million years ago typified the now semi-arid Langebaan area. The WCFP is also littered with thousands of 2 million year old land snails which have not evolved further since the Miocene period some 24 to 5 million years ago, and which look the same as modern land snails (Smith 1998).

Since 1958, when Singer & Hooijer (1958) recorded the first discoveries from the quarries of the African Metals Corporation, tens of thousands of vertebrate specimens have been recovered from these Pliocene phosphate deposits near Langebaanweg. At least 60 mammalian species, as well as a full complement of birds and cold-blooded vertebrates, have been recognized (Hendey 1970a; 1970b). Appendix A gives an overview of fossils found at the WCFP and surroundings. The fossil finds are so numerous that it will be impossible to list all the fossils found at the WCFP; instead only some fossils that were the first of their kind ever found in Southern Africa (or Africa) will be mentioned, as well as fossils that contributed significantly to our knowledge of palaeo-ecology.

2.2.3 WCFP fossil record: megafauna

One such fossil is the Langebaanweg seal, which is represented by a large number of specimens. It is important in that it provides the first good evidence of the antiquity and ancestry of the monachine seals in the Southern Hemisphere (Hendey 1972b; Hendey & Repenning 1972).

Another first is the genus *Stegolophodon*, found in Baard's Quarry, 2km north of present-day Langebaanweg, on the farm Langeberg in a phosphate deposit. The fossil molar fragment from this extinct elephant-like animal provides the first evidence for the occurrence of this genus in Southern Africa (Singer & Hooijer 1958). Other *Stegolophodon* fossils have been found in India, North Africa and Borneo. The African elephant (*Loxodonta africana*) and *Stegolophodon* shared a common ancestor ca 38 million years ago (*Palaeomastodon*)[1].

Despite the richness and diversity of the early Pliocene vertebrate assemblage at Langebaanweg, **primate** remains are exceedingly rare (Klein 1977). The only identified primate specimens recovered so far are two teeth from a vervet monkey-like ancestor (a cercopithecid). The deposits wherein the teeth were found are an element of the Langeberg Quartzose Sand Member of the Varswater formation, which was laid down during the early Pliocene (about 5 million years ago). These teeth thus form the earliest record of the order Primates in South Africa (Grine & Hendey 1981).

One of the more unusual mammals that provide insight into the palaeo-climate and vegetation of the Pliocene is a hitherto unknown boselaphine. Boselaphini are bush or open woodland antelopes, and it is only recently that members of the Boselaphini have become known in Africa. The Langebaanweg finds are their most southerly record; the only two living forms are found on the Indian subcontinent (Gentry 1974).

Pecarichoerus africanus, a new species found at Langebaanweg, is the first fossil peccary to be described from Africa. It is also the most recent record of the peccary family in the Old World. Peccaries and true pigs belong to the same superfamily, but they are, however, from different

---

[1] In the light of later material discovered, Maglio & Hendey (1970) argues that *Stegolophodon* should now be regarded as belonging to a primitive *Mammuthus subplanifrons*.

families. The Langebaanweg peccary is unique in that it is not identical to any previously described fossil species (Hendey 1976a).

In palaeontology it is common practice to use mammalian fauna from different sources for dating purposes, and comparative studies with East African sites have enables scientists to date fossils from Langebaanweg. However, the fossil-bearing deposits at Langebaanweg have also made a significant contribution to our knowledge of **carnivore** evolution, by interpreting the ancestral nature of fossil species relative to other fossil sites at Makapansgat and elsewhere. The carnivore fossils from Langebaanweg are unique in that they are mostly extinct, ancestral species with little or no relation to extant species; often the nearest extant relatives are Eurasian (Hendey 1974). Details of specific fossil finds are listed in Appendix A. Klein (1977) emphasizes the general archaic nature of the deposits at Langebaanweg. Many of the forms are now extinct in Africa, and the only extant relatives are Asian or European in origin (i.e. bear, wolverine, peccary, racoon, Eurasian hyaena, boselaphine antelope).

2.2.4 WCFP fossil record: microfauna, amphibians and avian fauna

Vertebrate microfauna (such as rodents, hares, bats, shrews, mole rats and golden moles) receive less attention than typical megafauna in the fossil history and fossil descriptions are typically biased in this regard. Microfauna fossil finds from Langebaanweg ‘E’ Quarry go a long way towards correcting this bias and gives us insight into the more primitive lineages of species that still exist today. Twenty-one genera from nine families, belonging to the bat, insectivore, rodent and hare families were found, with many of these genera still persisting today (Pocock 1976). Not only do these finds fill an important gap in our knowledge of the Pliocene fossil history of African myomorphs, but it also sheds light on the relative age of similar fossil genera found at other Plio-Pleistocene hominid sites, in particular the correct systematic position of the rat subfamily Otomyinae (Pocock 1976).

The **amphibian** fossil diversity at Langebaanweg is as rich and varied as that of any of the other taxa found here, and is definitely the richest site of its kind in Africa, and possibly in the world (Van Dijk 2003). These fossils are found in the Varswater Formation’s upper members, and represent amphibians from a wide variety of habitats upstream (river banks, fast-flowing currents, ephemeral pools, trees, rock pools, marshes and vleis) of the palaeo-Berg River mouth. There are four anuran families, and possibly six, represented by seven genera (Van Dijk 2003). Currently, the lizard fauna is being investigated by Van der Worm (2004: pers com).

Langebaanweg is also the richest pre-Pleistocene **avian** fossil deposit worldwide; at least 10 000 bones of 61 different taxa (marine, freshwater or terrestrial) were recovered (Rich 1980). All fossil taxa have extant relatives in the area except for the parrots, where the closest relative occurs in the northwestern extreme of the Northern Cape province, some 800km to the north. Most of the fossils seem to have been transported there after death, and only a few water bird representatives are considered to have had their habitat in the immediate vicinity of the current fossil find (Rich 1980). Another extant marine bird which lacked a fossil record, was the jackass penguin. Several late Cenozoic specimens have in recent years been excavated near Langebaanweg, and one species, originally named *Spheniscus predemersus*, is the first fossil penguin to be described from Africa. According to Simpson (1971) it was closely related and possibly ancestral to the living species, *Spheniscus demersus* (African black-footed or jackass penguin), of southern and southwestern Africa[2].

2.2.5 WCFP fossil record: marine invertebrates

Not only is Langebaanweg well known for its mammal fossil record, but also for **marine invertebrates**. Identification of these fossils is difficult, due to the fact that in many cases molluscs are only identified by soft tissue structures, which are not typically preserved as part of the fossil. In many cases only internal casts and external impressions are preserved. Although Kensley (1972; 1977) focused on molluscs, sharks, bony fish and whale fossils are also present, as well as non-marine deposits where most of the well-known terrestrial fossils were recovered (Kensley 1972). In total, 22 fossil molluscs have been described, consisting of sand and rock-dwelling species. This supports the conclusion that the upper-Pliocene coastline consisted of both rock and sand elements (Kensley 1972).

It is clear that the WCFP experienced a complex and unique depositional environment, resulting in an exceptional variety of fossils. Knowledge about the spatial extent of geological formations, which will be discussed in the next chapter, may guide future fossil excavations.

---

[2] However, additional specimens from the Pliocene of Langebaanweg indicated that *Spheniscus predemersus* (Simpson 1971), was incorrectly referred to *Spheniscus*, and the species is now placed in a new genus, *Inguza* (Simpson 1976).

CHAPTER 3: MODELLING AND VISUALIZATION METHODOLOGY

Information on geological formations is typically gathered at point localities, and for the purposes of this study, the entire spatial extent of each formation is needed. GIS provides the ideal platform within which to conduct such spatial modelling.

3.1 GIS AND 3D VISUALIZATION OF SPACE

Traditionally, geographic information systems depict spatially explicit data in a two-dimensional plane. This tradition probably stems from the fact that GIS has its historical origin in analog maps, which, with the advent of GIS, were eventually transformed to digital format. The digital nature of the data allowed manipulation which was previously too time-consuming or expensive to contemplate (Jones 1999), and the science of spatial analysis and statistics developed rapidly.

Increases in computing power and graphical display technology allow modern GIS software packages to incorporate a third dimension in spatial analysis (Jones 1999). This third dimension typically represents elevation in classic digital elevation models, but it can also be used to depict rainfall intensity, temperature, or in the current study, depths and thicknesses of geological formations. In conventional modern GIS software, this third dimension is represented by a colour gradient in a two-dimensional (2D) plane; however, ArcGIS has a three-dimensional (3D) visualisation tool called ArcScene, and it allows interactive manipulation of the data along all three axes. There are few, if any, truly three-dimensional GIS software packages on the market. Most of the current packages have a visualisation tool, but it has limited functionality as far as spatial analysis is concerned. Due to this limitation of the available software, the present research objectives were better served by conventional spatial analysis.

3.2 SPATIAL DATA MODELS

Before any spatial analysis can be done, a conscious decision has to be made on the data model that will be used. Although many data models exist, this discussion will be limited to vector and raster data, since these are the appropriate data models for this study.

Spatial data in vector format can be represented by features such as points, lines or polygons (Burrough 1998). Vector data usually appear realistic and is an intuitive analogue to traditional paper maps. Vector data have the additional advantage that it is visually pleasing, easy to relate to, have a fine resolution and high spatial accuracy, and simple vector files use less storage space. However, the data structure of vector data is inherently complex, and therefore any involved analysis requires considerable computing power. Topology is the key to spatial vector analysis, and it can be described as the characteristic of the data that defines the size, position and proximity of vector features relative to each other. It follows that for any complex vector shape, the topology will also be complex, with subsequent costs in computing power.

The alternative to the vector data model is the raster, or grid, data model. In a raster, spatial data is assigned to a rectangular array of even-sized square cells (Jones 1999). Cells contain floating point, integers or binary values, and are considered to be homogeneous with respect to the assigned value. Cells do not correspond to observed spatial entities, and as such the size of the cell relative to the extent of the study area determines the finest useful level of detail that can be depicted. Although the raster data model is more parsimonious when it comes to storage space, fine resolution raster data of a large area still require substantial storage space. At high resolutions, raster data may approximate vector data quite well, but it remains a generalisation, and as such locational precision is limited to the size of a single cell in the raster. According to Jones (1999: 37), “the raster data model is advantageous for representing the spatial distribution of phenomena, particularly natural features, that may be imprecisely defined”. That is exactly the case with the borehole data that consist of isolated sample points and interpreted boundaries.

For this study, vector point data of borehole localities were used as a primary data source. Each borehole represented a point of which the feature class contained attributes pertaining to the depth and/or thickness of geological layers at that particular point. However, this means that one only has complete information of the structure of the geological layers at that particular point. Obviously, it is not feasible to collect landscape level data by sinking a borehole every few metres. The crux of the problem is that the three-dimensional structure of the subterranean formations of interest is not completely known, and never will be if one has to rely on physical sampling of the entire landscape. A transparent and repeatable method is needed to interpolate the point data to a continuous surface that encompasses the entire landscape, and that provides information about geological structure in unsampled locations. This extrapolation process is typically a statistical process, but it can also utilize expert knowledge if such expertise exists, and is accessible. It is vital to recognise throughout that these interpolated values for formations should be interpreted as probabilities of occurrence rather than absolute values, by virtue of inherent uncertainties in the modelling process.

3.3 RECONSTRUCTION OF THE WCFP REGIONAL GEOLOGY IN GIS

There are many different types of spatial interpolation techniques, but the nature of the data that is available and the answers that are sought determine the methodologies that are appropriate.

3.3.1 Spatial data characteristics

The interpolation of borehole data was done at two scales for this study: a coarser regional analysis to show regional geological formations, and a finer scale analysis at the site of the WCFP, to show the sequence of deposition of the individual members of the geological formations of interest. Regional borehole data were made available by Dr Dave Roberts of the Council for Geoscience and Mr Allan Woodford of SRK Consulting. This data contains information about the occurrence of current stratigraphic units - both the formations and the different members. The regional analysis focused on formations, and not their respective members. This borehole data contained information about drill depth, elevation, latitude, longitude and other information about the formations and different members of the region.

Dr Dave Roberts, an expert on the geology of the Cenozoic in Southern Africa, interpreted this regional borehole data for use in the current study, and drafted contours of the thicknesses (isopachs) of the formations, as well as their spatial extent. These maps were in analog format and no cartographic projection information was attached to them, so the first step was to scan, georeference and then digitize the contours onscreen.

3.3.2 Georeferencing raw maps

Scanned maps usually do not contain information as to where the area represented on the map fits on the surface of the earth; thus it needs to be aligned (or georeferenced) to a map coordinate system. It was decided to use a Transverse Mercator projection (central meridian 19E) with the WGS84 datum. Transverse Mercator (also known as Gauss Krüger) is a cylindrical projection with a central meridian placed in the centre of the region of interest. This centering minimizes distortion of all properties in the region of interest. It works well for a relatively small area such as the Fossil

Park and the West Coast as shapes are maintained (larger shapes are increasingly distorted away from the central meridian). A datum provides a frame of reference for measuring locations on the surface of the earth and defines the origin and orientation of latitude and longitude lines. WGS84 is the standard datum used in South Africa and was employed here.

The process of georeferencing entails identifying known features on the scanned map and assigning them real world coordinates. This is done by adding ground control points that link the raster (scanned map) to known positions (in x, y coordinates) on existing spatial data. In this case a (georeferenced) satellite image of the target area was used. Control points can be placed on any feature that is visible or recognizable in the existing data as well as on the scanned map, such as road or river intersections, coastlines, rock outcrops or the corner of a field or building. The number of control points used depends on the method to transform the raster to map coordinates. It is, however, not always the case of more is better – control points should be evenly distributed over the entire raster, rather than concentrating on one small area. A good start is to have one control point in every corner of the raster. The number of control points is determined by the root mean square error, which gives an indication of the difference between georeferenced features on the map and their real spatial location. When enough control points have been identified, the raster can be transformed or warped to map real-world coordinates. Warping uses a mathematical transformation to determine the correct map coordinate location for every cell in the raster. The mathematical transformations usually take the form of a first, second or third order polynomial (DeMers 2002), each with a specific minimum number of ground control points required. The georeferencing was done using either Erdas Imagine or ERMapper.

The georeferenced scanned map does present spatially explicit data, but it contains information on all the spatial features in one layer. Before any spatial analysis can be done, these features need to be separated into distinct polygon, line and point features. In order to convert the features on the scanned map into digital format, they must be digitised. This was done onscreen using ESRI's ArcMap. Many errors can occur during digitising, for example arcs (the technical term for lines in a GIS) that overshoot or undershoot or arcs that cross each other. These errors can be corrected by cleaning the data in ArcInfo – in which case the data must be in coverage format. This conversion from shapefile to coverage was done using ArcInfo. The contours could now be used to interpolate a surface depicting elevation above sea-level or thickness of the different formations.

3.3.3 Contour interpolation methodology

The ArcInfo module most suitable for this kind of real-world contour analysis is TOPOGRID. Using an interpolation method, the TOPOGRID command generates a hydrologically correct DEM from elevation and stream data (ESRI 1999 in Schaetzl et al 2000). No hydrology data were available from the time of formation deposition, and none were used. The resolution or pixel size of all the output digital elevation models (DEM) was 100m square, or 1 ha. Originally, the term DEM was used to refer to elevation only, but it has since evolved to a more general term of reference for all spatially explicit surfaces. The following commands were used to construct the basement layer (elevation values were used, derived from borehole logs):

```
Topogrid: topogrid base100 100
        : boundary coast_cov
        : contour base_cov id
        : datatype contours
        : enforce off
        : margin 100
        : end
```

To provide a boundary as the cut-off point for interpolation, the coastline formed part of it, and the extent was ruled by the available borehole data. The result of this interpolation was a surface (grid) that shows the elevation of the basement layer: positive values are above current sea-level, and negative values below sea-level. Figure 4.2 maps the basement layer with a legend explaining the height categories. Figure 3.1 below diagrammatically represents the steps followed in reconstructing the basement layer of the study area and vicinity, starting from a scanned map to an interpolated DEM of the relevant member’s ‘topography’.

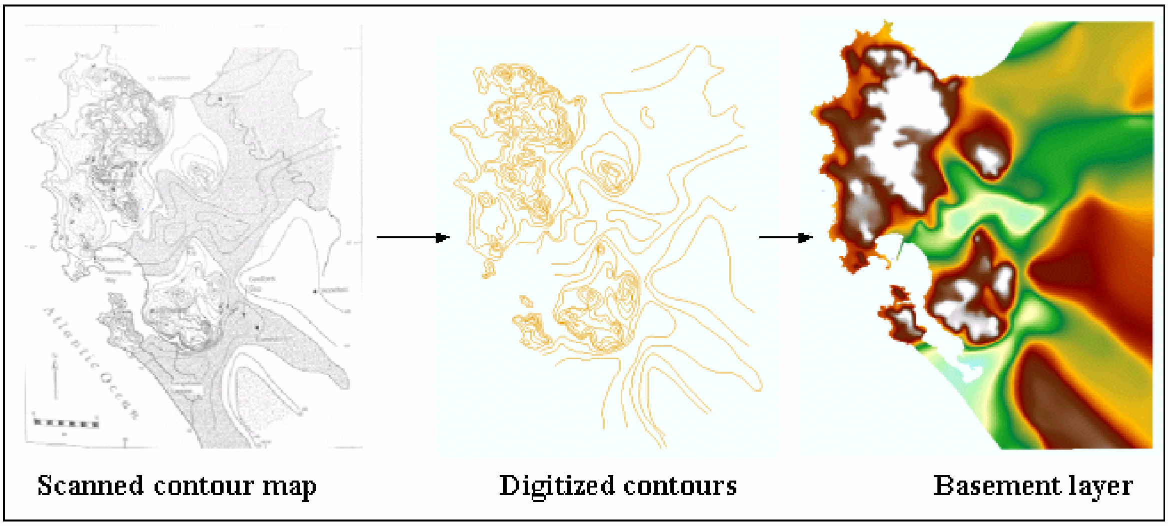


Figure 3.1 Steps followed to create the basement DEM of the study area and environs

3.3.4 Sequential mapping of formations

3.3.4.1 The GIS principle

The same commands as above were used to construct surfaces (DEM's) for each of the three significant geological formations (Elandsfontyn, Varswater and Langebaan). Figure 3.2 below shows the basement layer and the three formations after the steps in the previous section were followed. The darker shades in the basement layer represent the lower elevations, and the lighter shades the higher elevations. In the other three formation layers, the darker colours show the lower thickness values, and the lighter colours the higher thickness values. The basement layer depicts elevation relative to present sea-level; bearing in mind that it is the oldest (deepest) geological layer of interest for this study. The elevation values for this layer are negative where it is below sea-level (typically deep under the present surface), or positive, where it is above sea-level. These positive values may indicate rock-outcroppings, where the shallower (younger) layers have weathered away. The other three formations depict formation thickness, and by adding them in sequence to the basement elevation, a composite picture of the geological formations in the area is constructed. Refer to Figures 4.2 and 4.3 for a geological interpretation of the above-mentioned layers.

Basement layer

Elandsfontyn Formation

Varswater Formation

Langebaan Formation

Figure 3.2 Interpolated elevation and thickness of the basement and other formations

The area of interest is an artificial boundary to all these geological formations and the inland edge of the extent was dictated by the limitations of the interpolation procedure. It would be useful to know the elevation of each formation where it occurs, and since the sequence and thickness of layers above the basement layer is known, the elevation of each layer can easily be calculated. However, not all formations occur over the entire extent, with the result that there will be locations where a particular formation is “missing”. The first step to account for such areas is to delineate the extent of each formation. This was done by drawing an analysis mask using the outermost contour line, and closing it to form a polygon. A value of one was given to the area inside the mask, and a value of zero was given to everything that falls outside the mask. In so doing a Boolean constraint mask was formed for each formation and these could be used for building elevation DEMs for each formation respectively. Figure 3.3 illustrates the principles followed to reconstruct the landscape after the deposition of each geological layer.

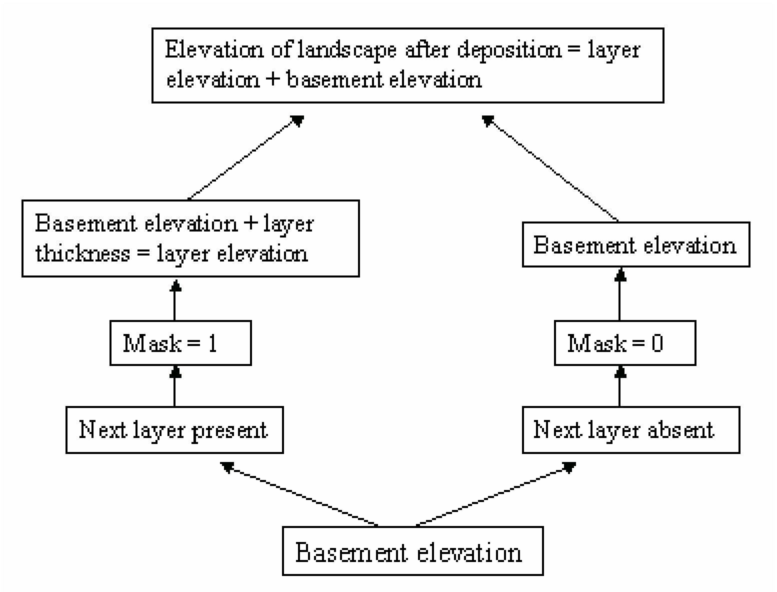


Figure 3.3 Procedure to reconstruct landscape after layer deposition

3.3.4.2 Reconstruction of the Elandsfontyn Formation

The ‘mask’ shapefile mentioned in the previous paragraph was converted to coverage, and then converted to a grid in ArcInfo. The following command was used to do the conversion, using the Elandsfontyn Formation as an example:

```
Arc: polygrid base_efm base_efmask code
   : cellsize 100
```

(where base_efm = coverage mask and base_efmask is the output grid)

This process defined the extent of the Elandsfontyn Formation. This formation rests on the basement layer, therefore, by using the extent as a spatial constraint and by adding the thickness values (in metres) to the elevation of the basement layer, the elevation of the Elandsfontyn Formation can be calculated. This was done in ArcInfo using the GRID module:

```
Grid: if (base_efmask == 1) base_ef100 = base100 + ef100
    : endif
```

It means that where the mask has a value of 1, the Elandsfontyn layer's thickness values are added to the elevation of the basement, and everything outside the formation's boundary (value of zero) will be ignored. Figure 3.4 shows the different steps followed and the actual layers used.

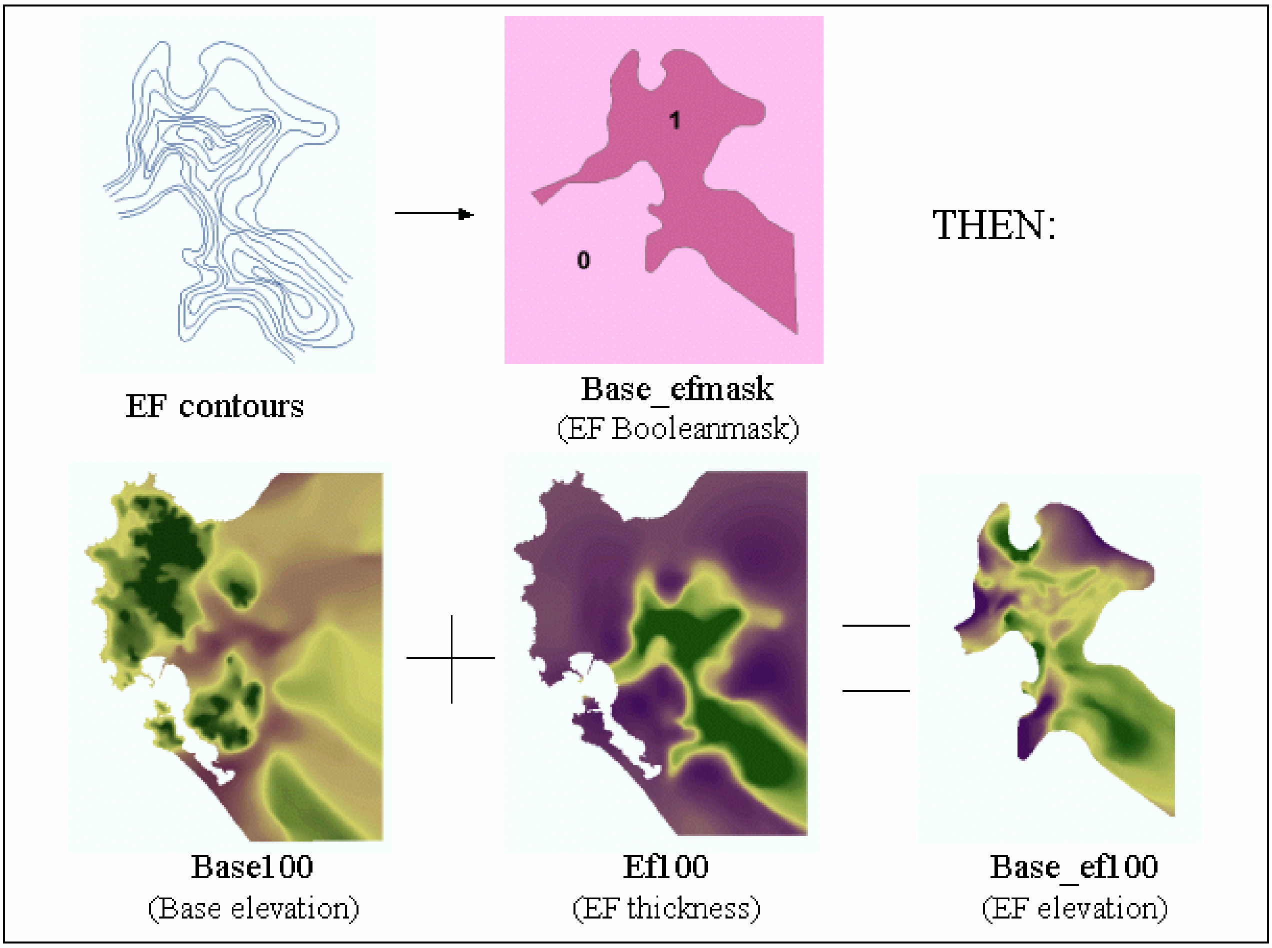


Figure 3.4 Steps followed to delineate and construct the elevation and extent of the Elandsfontyn Formation

This extent-corrected elevation surface for the Elandsfontyn Formation could now be added to the basement layer, and doing that successively for all subsequent formations gave a reconstruction of the landscape after every deposition. The following commands were used in ArcInfo Grid for the Elandsfontyn layer:

```
Grid: base_efall = con (base_efmask == 1, (base100 + ef100), base100)
```

This means that where the mask's value is equal to one (the extent of the Elandsfontyn Formation), the thickness values of the EF is added to the basement layer's elevation values, otherwise where the value is not one, the basement values are used. Figure 3.5 below shows the different layers used.

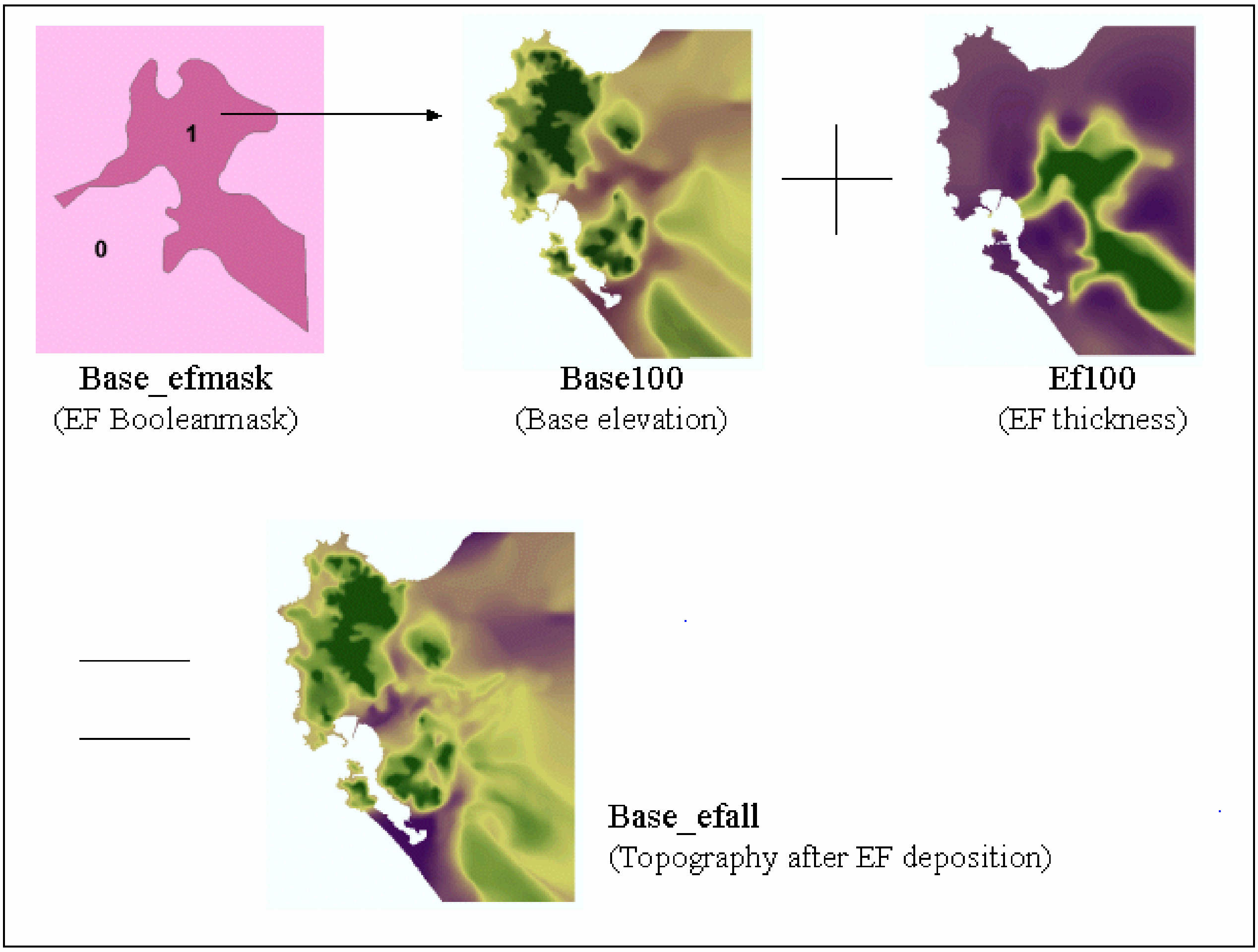


Figure 3.5 Reconstruction of topography after the Elandsfontyn Formation was deposited

3.3.4.3 Reconstruction of the Varswater Formation

The commands used to reconstruct the other two formations (Varswater and Langebaan) were essentially the same. The first step was to define the extent and elevation of each individual formation, and then add that layer to the elevation surface of the underlying deposits. To show the extent and elevation of the Varswater Formation, the following command were used:

```
Grid: if (vars_mask ==1) base_ef_vars = base_efall + vars100
      : endif
```

This means that where the Varswater Formation occurs, the value of the mask is one. In these areas where the value of the mask is one, the new value is the thickness of the Varswater Formation plus the elevation of the underlying deposits, which is the basement plus the Elandsfontyn Formation. Values outside the mask are ignored. See Figure 3.6 below for a diagrammatic representation.

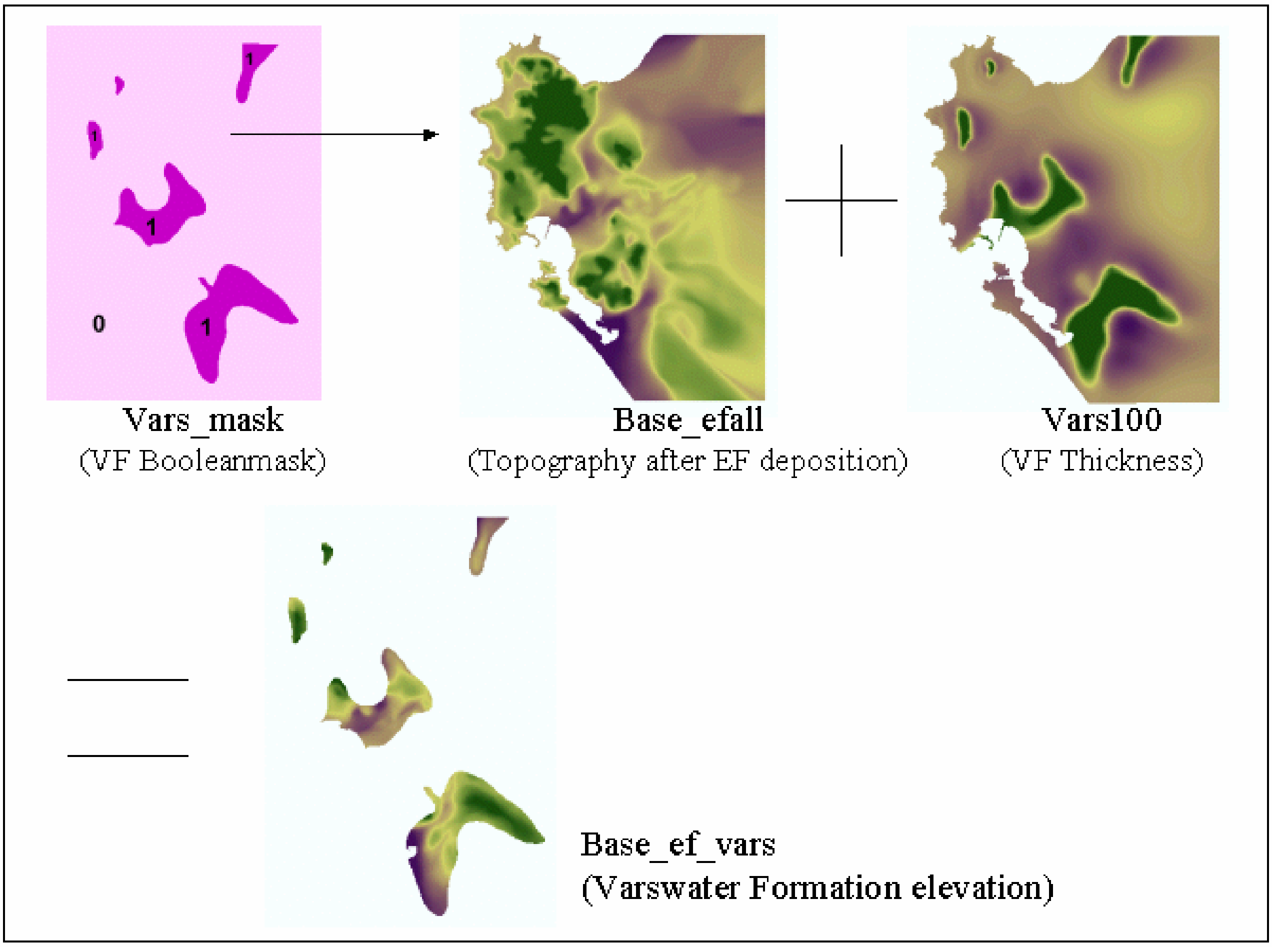


Figure 3.6 Steps followed to delineate and construct the elevation and extent of the Varswater Formation

Now the Varswater Formation is ready to be added to the basement and EF layers. The commands are similar as when the EF was added to the basement:

```
Grid: if (vars_mask == 1) all3 = base_efall +vars100
    : else if (vars_mask == 0) all3 = base_efall
    : endif
```

The diagram below shows the layers used in the reconstruction of the landscape after the deposition of the Varswater Formation:

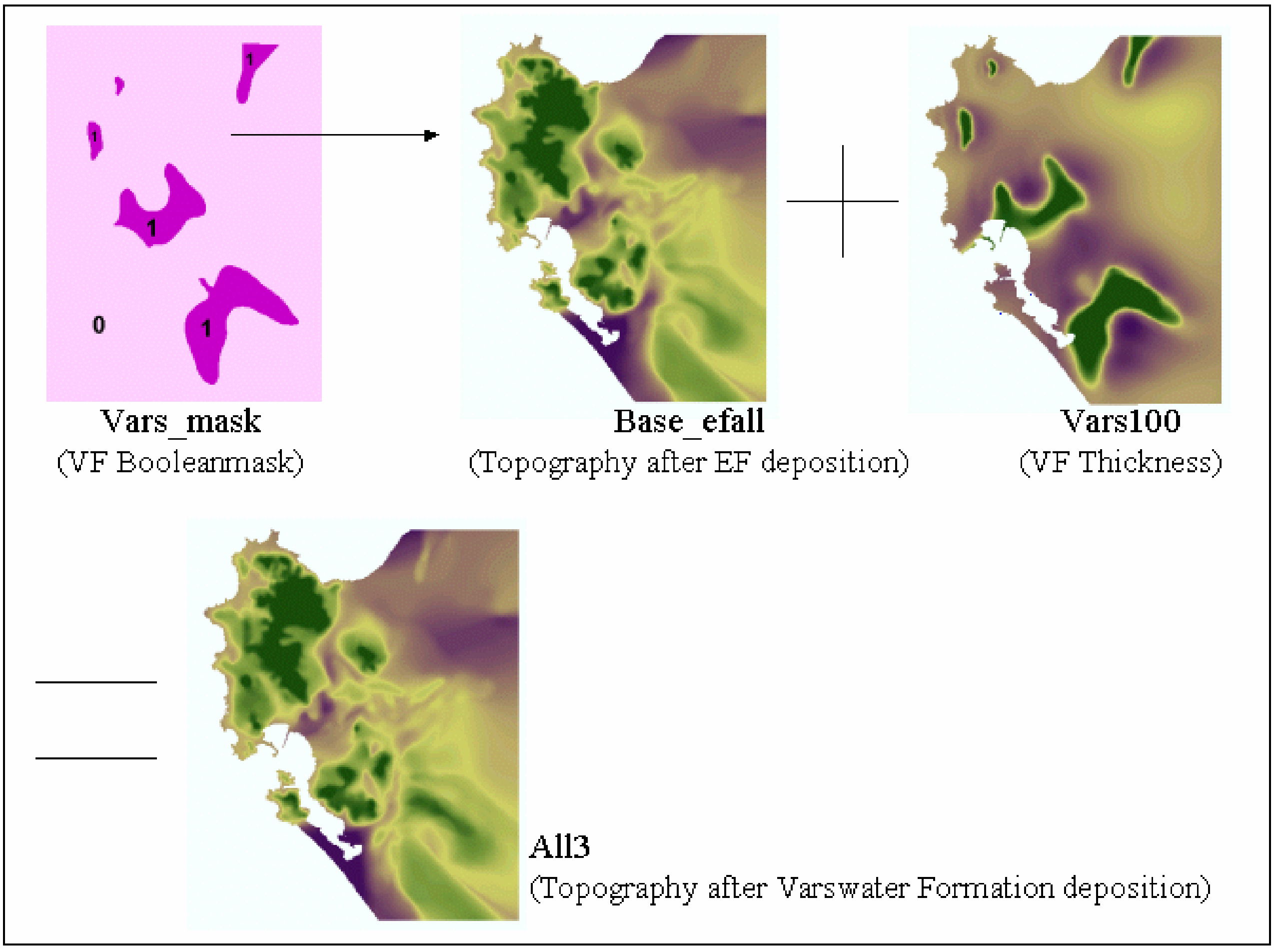


Figure 3.7 Reconstructed landscape at the time of the Varswater deposition

The landscape as seen above is a reconstruction of how the Langebaanweg area could have looked when the Varswater Formation was deposited.

3.3.4.4 Reconstruction of the Langebaan Formation

The last formation to be modelled was the Langebaan Formation. Again, the same commands were used to show the extent and elevation of the formation in isolation, with the result depicted in Figure 3.8:

```
Grid: if (lang_mask == 1) all_lang100 = all3 + lang100
      : endif
```

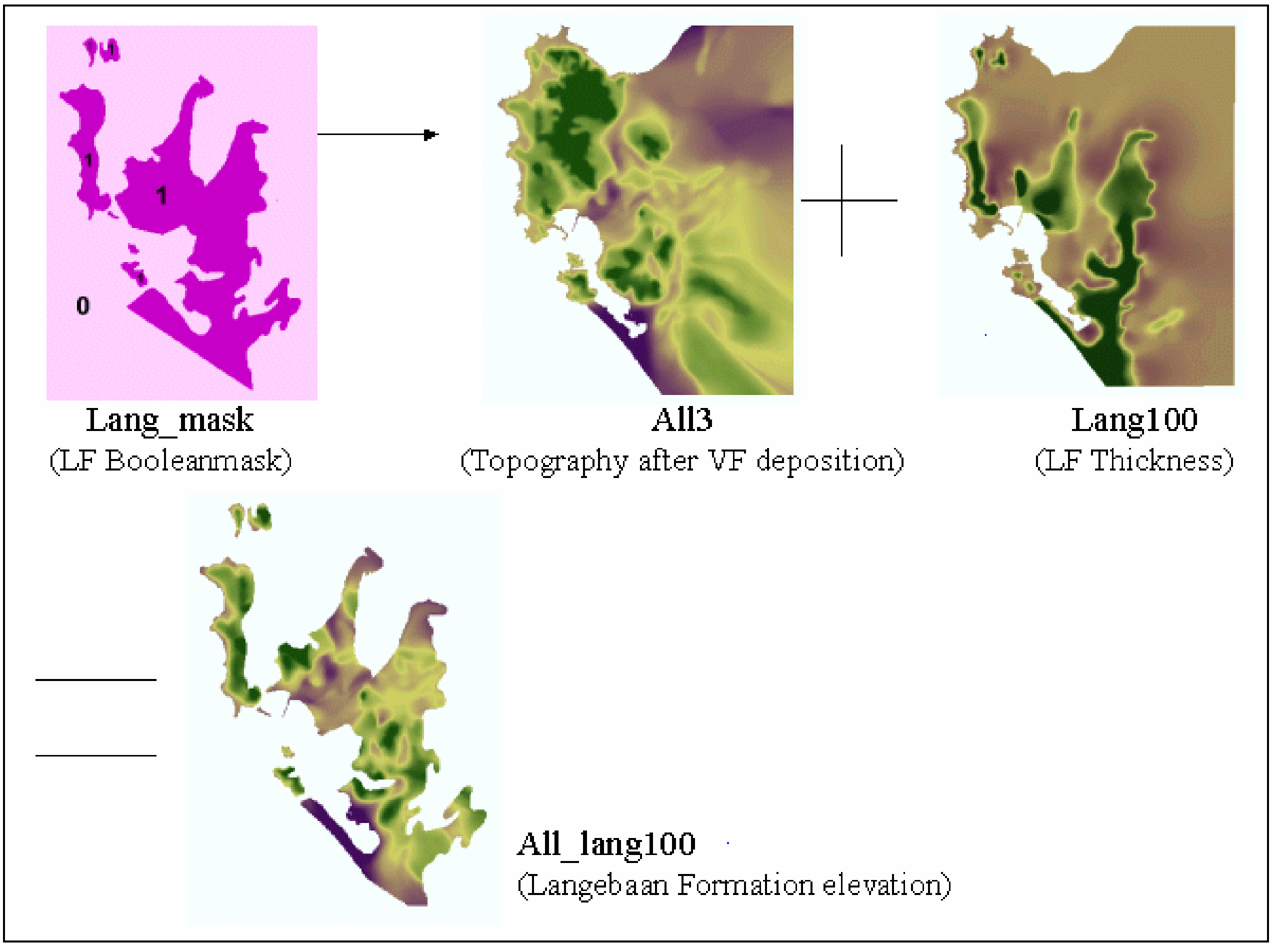


Figure 3.8 Steps followed to construct the Langebaan Formation

The extent of the Langebaan Formation is now visible. This last layer was then added to the underlying layers, so that the landscape at the time of the Langebaanweg deposit could be shown (Figure 3.9). These commands were used, all in ArcInfo's Grid module:

```
Grid: if (lang_mask == 1) all4 = all3 + lang100
    : else if (lang_mask == 0) all4 = all3
    : endif
```

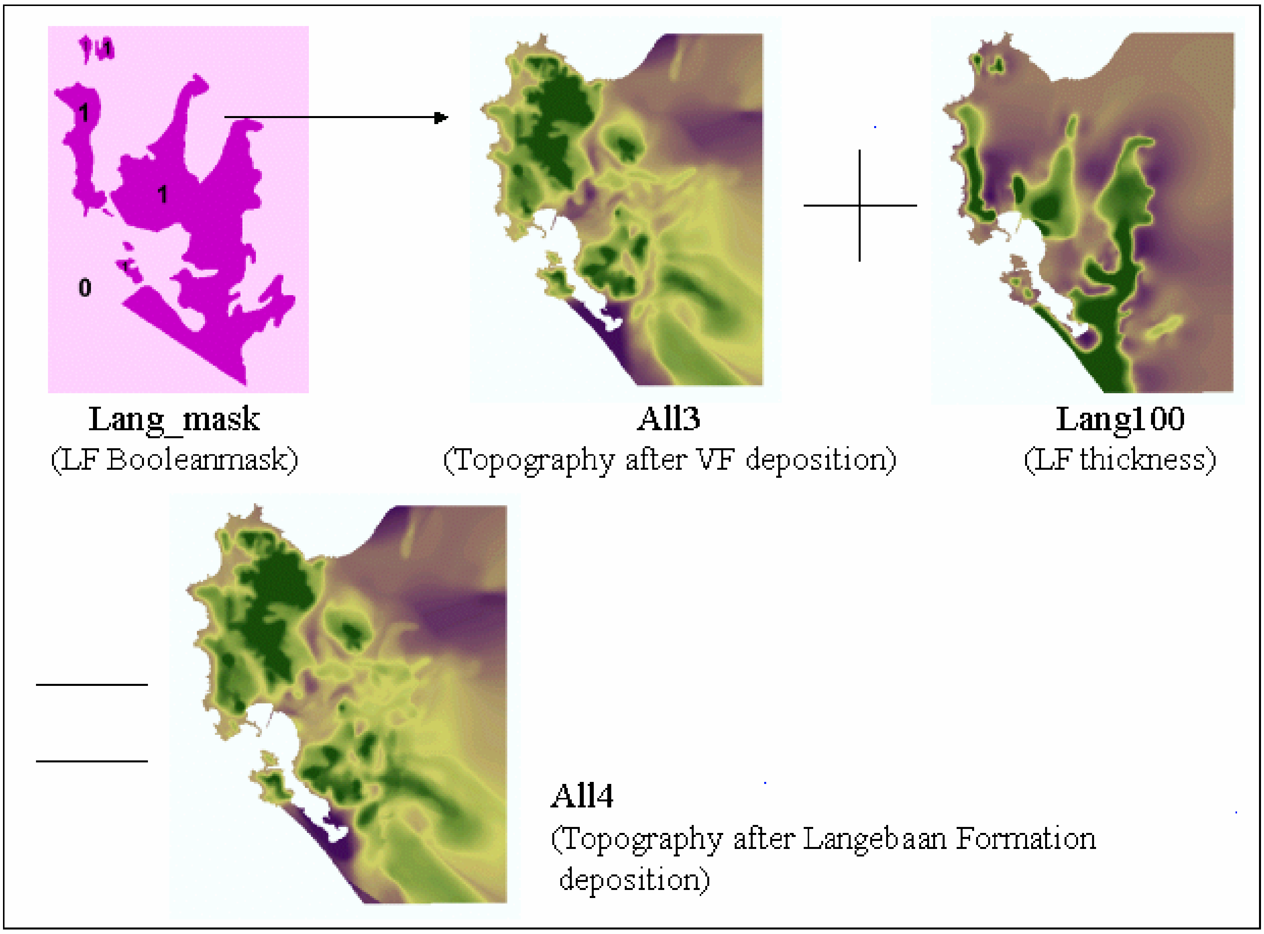


Figure 3.9 Reconstruction of the landscape after the Langebaan Formation was deposited

The layer named “all4” is a representation of the landscape a few million years ago after the Langebaan Formation was deposited. Appendix B lists all the commands used that are mentioned above.

3.4 RECONSTRUCTION RESULTS OF THE WCFP GEOLOGY

The methodology followed to reconstruct the more detailed geology of the Fossil Park area itself is similar in that borehole data form the primary source of information. Dr Dave Roberts from the Council for Geoscience made borehole data from the WCFP area available. Once again, there was a need to interpolate point feature data to a landscape level. Expert knowledge proved to be sufficient for this interpolation at the regional scale, but the need for a fine scale answer necessitated a different approach. These boreholes from which the data was used, were arranged in a mostly regular grid every 150m (Figure 3.10) in the WCFP.

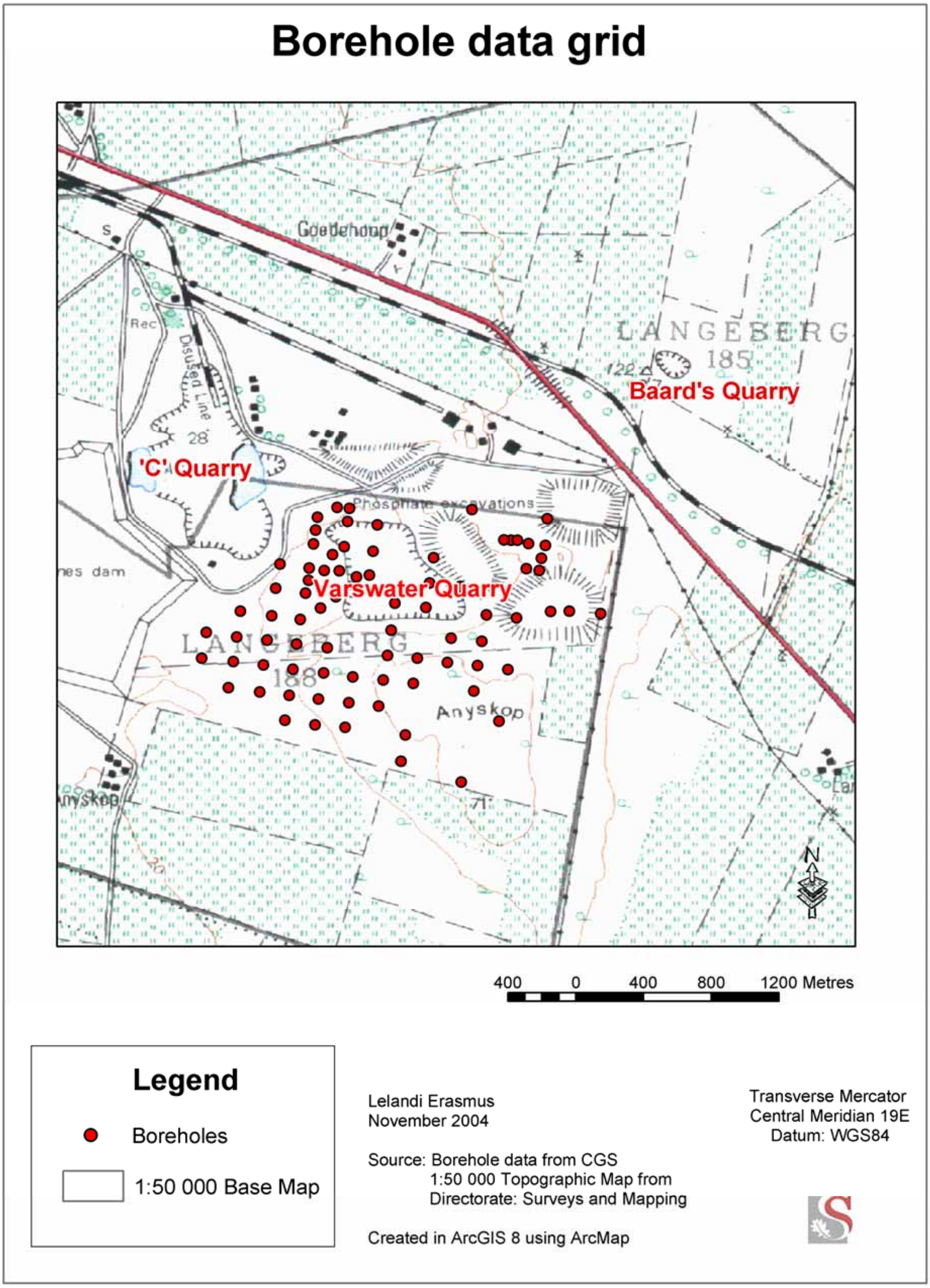


Figure 3.10 Location of boreholes across the site of the WCFP

This regular grid, as well as the need for information on geological formations at a finer scale, guided the decision to use kriging as an interpolation method. Kriging is a well-established method to interpolate spatial surfaces from point data (Cressie 1993; Ripley 1981; Kaluzny et al 1998). It originated as an application in mining and is especially well suited to geological applications. The basis for kriging is a graph called a variogram, which shows the level of spatial autocorrelation between any two spatially explicit measurements. Tobler’s first law stating that everything is related to everything else, but that objects that are close to each other are more related than those that are far away from each other, sums up spatial autocorrelation. Variograms show the difference between any two points as a function of the distance between the two points (DeMers 2002). Variograms are typically constructed using statistical software, where pairwise comparisons of the differences between all points at all distances are calculated. The mean difference (γ) for all pairs separated by each of the distance classes is then plotted as a function of distance (Cressie 1993). A variogram that is empirically constructed from data shows the relationship between the values of points as a function of distance, and therefore it can be used to interpolate values between sampled points. However, such an empirical variogram typically contains some noise. A model variogram is then fitted to the data, and the model variogram with the best fit is then used to do the interpolation, and this process illustrates the principles of kriging (Cressie 1993).

Empirical and model variograms were constructed using the borehole data, and model variogram fit was assessed qualitatively. Model variograms were fitted using either Gaussian, exponential or spherical curves. Variogram parameters (the nugget, range and sill) were derived from the modelled variogram and used as inputs into ordinary kriging. Variogram fitting was done using the statistical software SPLUS and the kriging was done in ArcGIS Spatial Analyst.

Each borehole contained information on collar elevation (in metres), which is effectively the elevation above mean sea-level, where the drilling of the borehole started. The other values were all thickness data for the different formations, also in metres. The collar elevation and thicknesses were kriged to form continuous surfaces.

The regional analysis was based on knowledge about the elevation of the deepest geological layer of interest. For this finer scale analysis, the basement elevation was unknown, and the regional basement values were considered to be too coarse. Therefore, the collar elevation was used as a reference point and the thickness of each layer was subtracted in turn, to arrive at an elevation surface for every formation of interest. During the subtraction procedure, the extent of each layer had to be taken into account, in a similar fashion as the regional analyses.

At the time of these analyses, it was not possible to gain access to ArcInfo, and the analyses were conducted using Spatial Analyst’s Raster Calculator. This is an example of the command used to construct an elevation surface (called collar_sf) for the Springfontein Formation, which is the uppermost formation:

```
Con ([sf > 0.3, ([collar_elev] – [sf]), [collar_elev])
```

This means that where the Springfontein Formation (SF) is more than 0.3 metres thick (its minimum), the grid must take on the values of the collar elevation minus the SF; in all other places it must take on the values of the collar elevation. It was done this way because there were null values in the data, since the SF does not occur everywhere where there is a collar elevation. This new grid is in fact the bottom part of the SF, or one can say it is the upper part of the Langebaan Formation (LF), which underlies the SF. The same technique was used to construct surfaces for all the different members and formations, namely the Springfontein Formation, Langebaan Formation, Muishond Fontein Pelletal Phosphorite Member, Langeberg Quartzose Sand Member, Konings Vlei Gravel Member, Langeenheid Clay Member and Elandsfontyn Formation.

When these raster images are compared to those of the regional geology, it is quite obvious that they are not as smooth. Burrough (1998:185) argues that “often we prefer to model them by smooth surfaces rather than a proper representation of reality because the former are computationally convenient”. It does not help to increase the resolution of the grid when the sample data points are few. In this case the sample points were not so few and high resolution grids were made.

In Chapter 4 the results of the regional and fine-scale geological reconstructions are shown and discussed in more detail with regards to their relevance to fossil deposition.

CHAPTER 4: SPATIAL GEOLOGY OF THE WEST COAST AND WCFP

The topography as we see it today is the result of the deposition of the geological formations modelled in the previous chapter.

4.1 THE TOPOGRAPHY AND CLIMATE OF THE REGION

The southwest coast region, between Yzerfontein and the Berg River, is economically rich in carbonate and aluminium phosphate deposits (Rogers 1980). It is also very rich palaeontologically, containing Mio- and Pliocene fossils from different habitats. This area is part of the Sandveld, which Tankard (1974b: 266) calls “the coastal lowlands”. The principal rivers draining the Sandveld are the Berg River and the Sout River. Granite hills are prominent along the coast. On the basis of available borehole data, and the important link with fossils of the Langebaanweg area, it has been decided to reconstruct the geology by focussing on the Varswater Formation (which is the most fossil-rich), and the formations immediately above and below it (Langebaan and Elandsfontyn respectively) to provide context. The Elandsfontyn Formation rests on neo-Proterozoic bedrock (Siesser & Dingle 1981 in Roberts 2000), which will also be geologically reconstructed because it forms the basic layer onto and into which all tertiary deposits and the topography were formed.

Rogers (1980:36) explains that “a combination of bedrock depressions below sea-level, major marine transgressions and strong dune-building resulted in sediment thicknesses often exceeding 100m”, which can be subdivided into the different formations mentioned above.

The climate of the southwestern coast of Southern Africa has changed over the years, and is manifested in the geomorphology, depositional environments and fossils of the time. Some of the molluscs fossilized near Velddrif can still be found in the area today; other depositional environments like the estuarine-lagoonal units contain species that today live in tropical waters to the north (Tankard 1976). Sub-tropical flora such as the *Palmae* palynomorphs were found in the region, and a forest with adjacent grasslands are also suggested by fossil fauna and flora (Roberts in press –b). During the Pliocene the climate changed to a cooler and drier one, as can be seen in the macchia flora that developed.

4.2 STRATIGRAPHY OF THE REGION

The South African Committee for Stratigraphy (SACS) explains stratigraphy as "the subdivision of rock strata into mappable, named units", a subdiscipline of geology that is necessary for geological research and the production of geological maps (SACS 2004). The lithostratigraphic units can be explained as follows: there are several Groups (Malmesbury Group, Cape Granite suite, Sandveld Group etc.) that comprise the different formations. Of great importance in this study is the Cenozoic Sandveld Group, which is rich in fossils including trace fossils, microfossils, invertebrates and vertebrates. The Sandveld Group stretches from Cape Hangklip in the southeast to Elands Bay in the northwest. The Sandveld Group overlies pre-Mesozoic basement rocks (sediments from the Malmesbury Group and granites from the Cape Granite Suite), and ranges in age from Miocene to Holocene (Roberts 2000, in press –a). A series of marine regressions and transgressions during the Neogene and Quaternary were manifested in the depositions of the Sandveld Group: it consists of Neogene and Quaternary fluvial, aeolian and shallow marine strata, which are mainly sands (Roberts in press –a). Figure 4.1 lists the more important fossil-bearing units of the study area that will be discussed in detail. The naming of the formations and members is according to Roberts (in press –a; in press -b), who coined the formal Member names for subunits informally defined by Tankard (1974b).

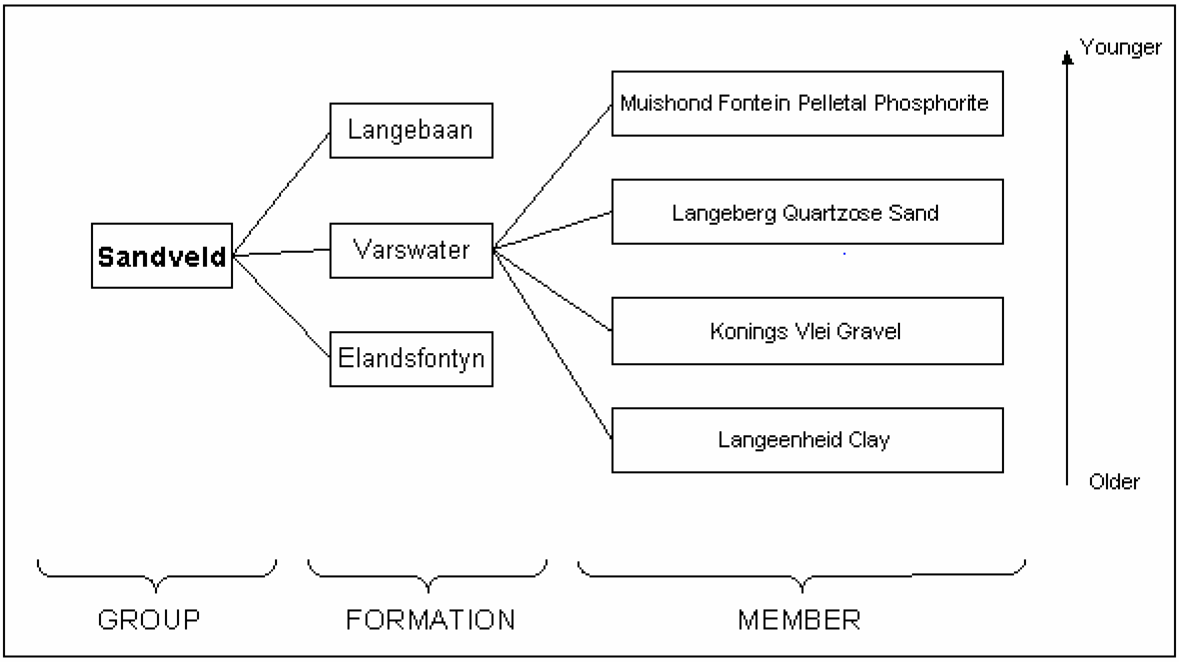


Figure 4.1 Stratigraphy of the study area

The Sandveld Group comprises the Elandsfontyn, Prospect Hill, Varswater, Velddrif, Langebaan, Springfontein and Witzand Formations. The Varswater Formation is the primary fossil-bearing formation, and the Elandsfontyn and Langebaan Formations provide spatial and temporal context to interpret the age and distribution of fossils. Some fossils have also been found in the Langebaan Formation. Therefore only the Elandsfontyn, Varswater and Langebaan Formations will be discussed in a regional context. The main body of the Varswater Formation contains vertebrate fossils of Mio-Pliocene aspect (Hendey 1981b). Formations are then divided into sub-units called Members. The sub-units of the Varswater Formation all occur widely in the Saldanha region and have therefore been accorded formal Member status. They are: Langeenheid Clay, Konings Vlei Gravel (formerly called Gravel Member or GM), Langeberg Quartzose Sand (formerly called Quartzose Sand Member or QSM) and the Muishond Fontein Pelletal Phosphorite Member (formerly called Pelletal Phosphorite Member or PPM).

As mentioned in Chapter 1, some of the authors of papers on geological studies of the West Coast region failed to reach consensus on naming the layers and members they comprise, and of dating of the different formations. The most recent literature, e.g. by Roberts (2000, in press) are followed here.

4.3 STRATIGRAPHICAL FORMATIONS AND THEIR OCCURRENCE PATTERN

The **Elandsfontyn Formation** was recognized and named by Rogers (1980). It is of middle to late Miocene age, and is fluvial in origin (Rogers 1980). Borehole data and core descriptions were used to define the Elandsfontyn Formation, since it is nowhere exposed above ground (Roberts 2000). It rests on bedrock and is thickest (~70m) east of the Langebaan Lagoon. Roberts (2000: 35) states that the formation is comprised of “upward fining sequences consisting of angular, fine- to coarse-grained, quartzose sand, gravelly in part, with variable proportions of sandy clay, clay, carbonaceous clay, and lignite”. These deposits are typical of meandering river sedimentation. The Elandsfontyn Formation is non-phosphatic. According to Hendey (1981a: 35), “the only recorded fossils from this unit in the Langebaanweg area are plant remains” which “indicate a forested environment which is consistent with a local vegetation of Miocene age”.

Figure 4.2 shows the reconstructed basement layer as well as the extent of the Elandsfontyn Formation, which overlay the basement.

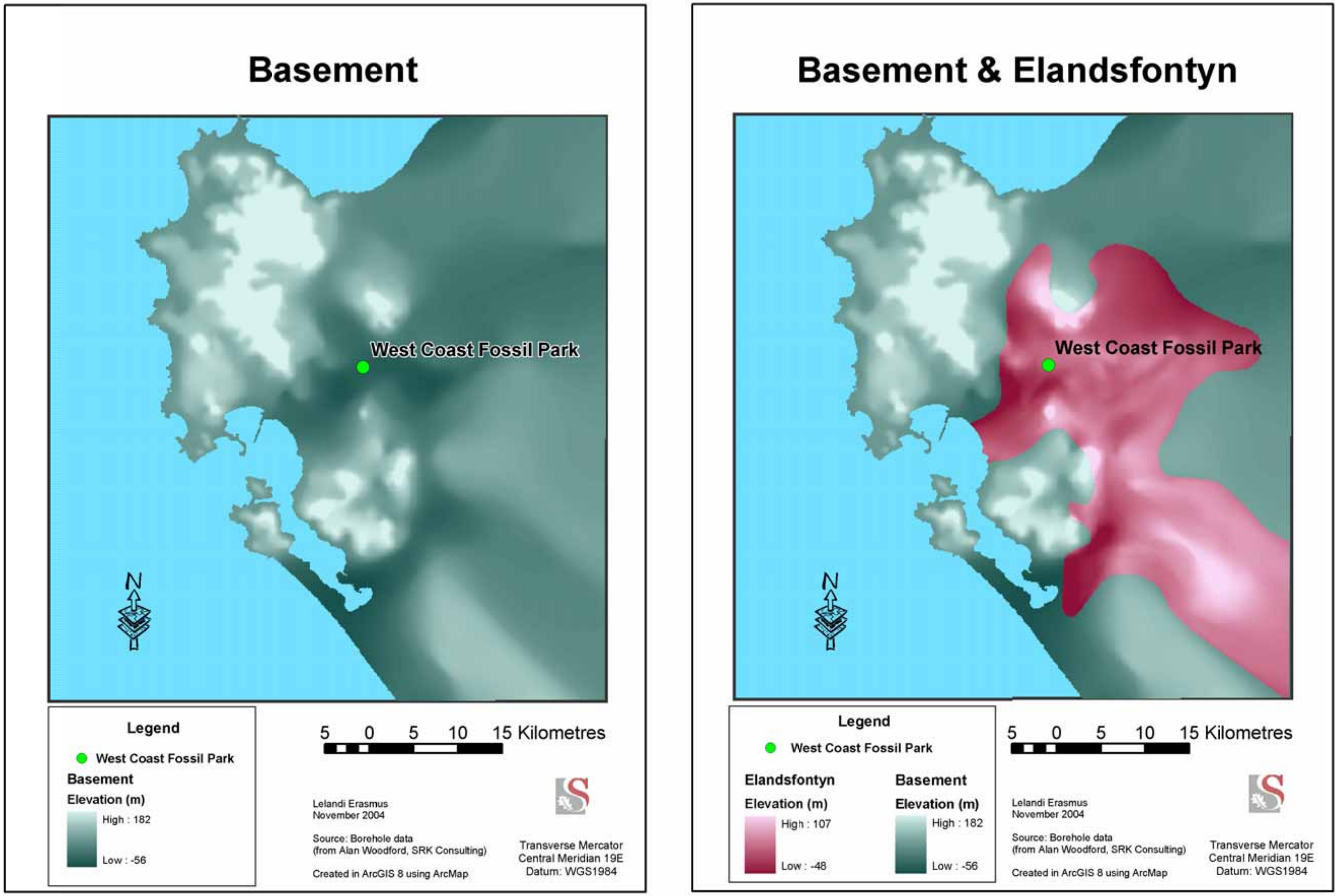


Figure 4.2 Spatial configuration of the basement layer and the Elandsfontyn Formation

The basement maintains topographical prominence (>150m) in the granite outcrops in the western coastal margin. The Elandsfontyn layer reaches the sea in the northern and southern approaches to the Langebaan Lagoon, where it occurs well below current sea level.

Hendey (1974) named the **Varswater Formation** after the Varswater Quarry at Langebaanweg as indicated in Figure 3.10. The Varswater Quarry, also referred to as 'E' Quarry, is situated in the WCFP. The Varswater Formation is up to 60m thick in places (Timmerman 1988 in Roberts 2000), and overlies the Elandsfontyn Formation and neo-Proterozoic bedrock (Rogers 1980) in several isolated occurrences. The Varswater Formation, regarded as a product of the Mio-Pliocene transgression that is correlated with the 90m sea-level stand (Rogers 1980), is marine to estuarine in origin (Tankard 1974b) and consists of phosphatic sediments. It is well developed and exposed at the Varswater Quarry as a result of the mining activities, which yielded not only phosphate but also a rich late Tertiary fossil fauna. This succession is of Mio-Pliocene age, and is overlain by Quaternary units of the Springfontyn, Velddrif and Langebaan Formations (Rogers 1980), which consists of aeolian sands and calcretes (Dingle, Lord & Hendey 1979).

The **Langebaan Formation**, depicted in Figure 4.3, accepted but not yet formally approved by SACS (Roberts 2000), is aeolian in origin (Rogers 1980) and occurs over an extensive area. Du Toit (1917 in Rogers 1980) first called it "Dorcasia Limestone", and then Wybergh (1919 in Rogers 1980) called it "Coastal Limestones". Visser and Schoch (1973 in Rogers 1980) proposed the name "Langebaan Limestone", and Tankard (1976) formally proposed a Langebaan Limestone Member, which was raised in status to the Langebaan Formation (Roberts 2000). It rests on the Varswater Formation, and is overlain by the Witzand Formation in places. The Langebaan Formation was, according to Tankard (1976:113), "probably accumulated during the last glacial lowering of sea-level when vast tracts of unvegetated sand lay exposed on the emerging sea floor".

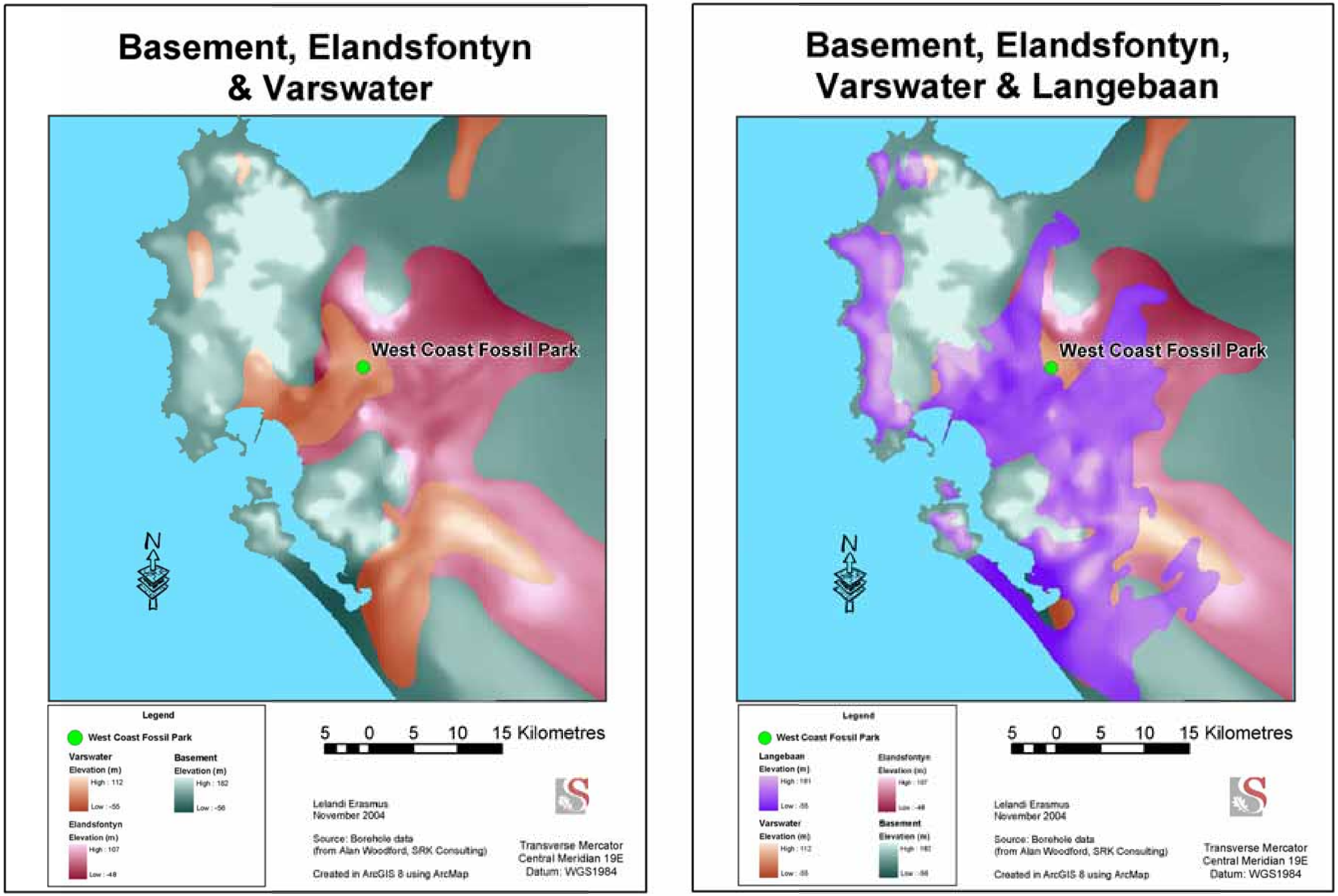


Figure 4.3 Spatial configuration of the basement, Elandsfontyn, Varswater and Langebaan Formations

4.4 THE WEST COAST FOSSIL PARK FORMATIONS

The Varswater Formation is the richest of the fossil-bearing formations, containing fossils of Mio-Pliocene age; therefore it is necessary to look more closely at the lithology and different members comprising the formation.

4.4.1 Occurrence of WCFP formations

Geological profiles were constructed along two transects that captures variation in the kriged surfaces (described in Section 3.4). These profiles give a good indication of the relative thicknesses of each layer, as well as their occurrences. Each profile consists of a range of formation (or member) elevation values sampled at regular distances along a virtual transect. Profile A is a transect in an east-west direction, starting at the edge of the borehole grid (18° 6’ 7.2” E; 32° 58’ 19.2”S), and continuing up and over Anyskop (18° 7’ 19.2”E; 32° 58’ 12”S) (Figure 4.4). Profile B is a transect in a north-south direction, starting to the east of the Varswater Quarry (18° 6’ 46.8”E; 32° 57’ 39.6”S), intersects with Profile B (Figure 4.4) on top of Anyskop, and ends south of it (18° 6’ 54”; 32° 58’ 30”S).

The collar elevation depicted in Figure 4.4 is the elevation of the surface that was reconstructed using the elevation of the surface at the point where drilling started. Effectively this is a reconstruction of topography before mining activites commenced. This explains the large difference in elevation over the extent of the Varswater Quarry; due to mining activities the present-day topography of the quarry will be much more level.

The basement layer and Elandsfontyn Formation have already been discussed in detail in section 4.2 and 4.3. A noteworthy feature of the Elandsfontyn Formation which is not visible in the regional reconstruction, is the pronounced thickness of this formation at the Varswater Quarry (Figure 4.4 and 4.6). This may be interpreted as evidence of fluvial deposits from the palaeo-Berg River. The different members comprising the Varswater Formation, as well as the Springfontein Formation, which overlays the Langebaan Formation, will be discussed next.

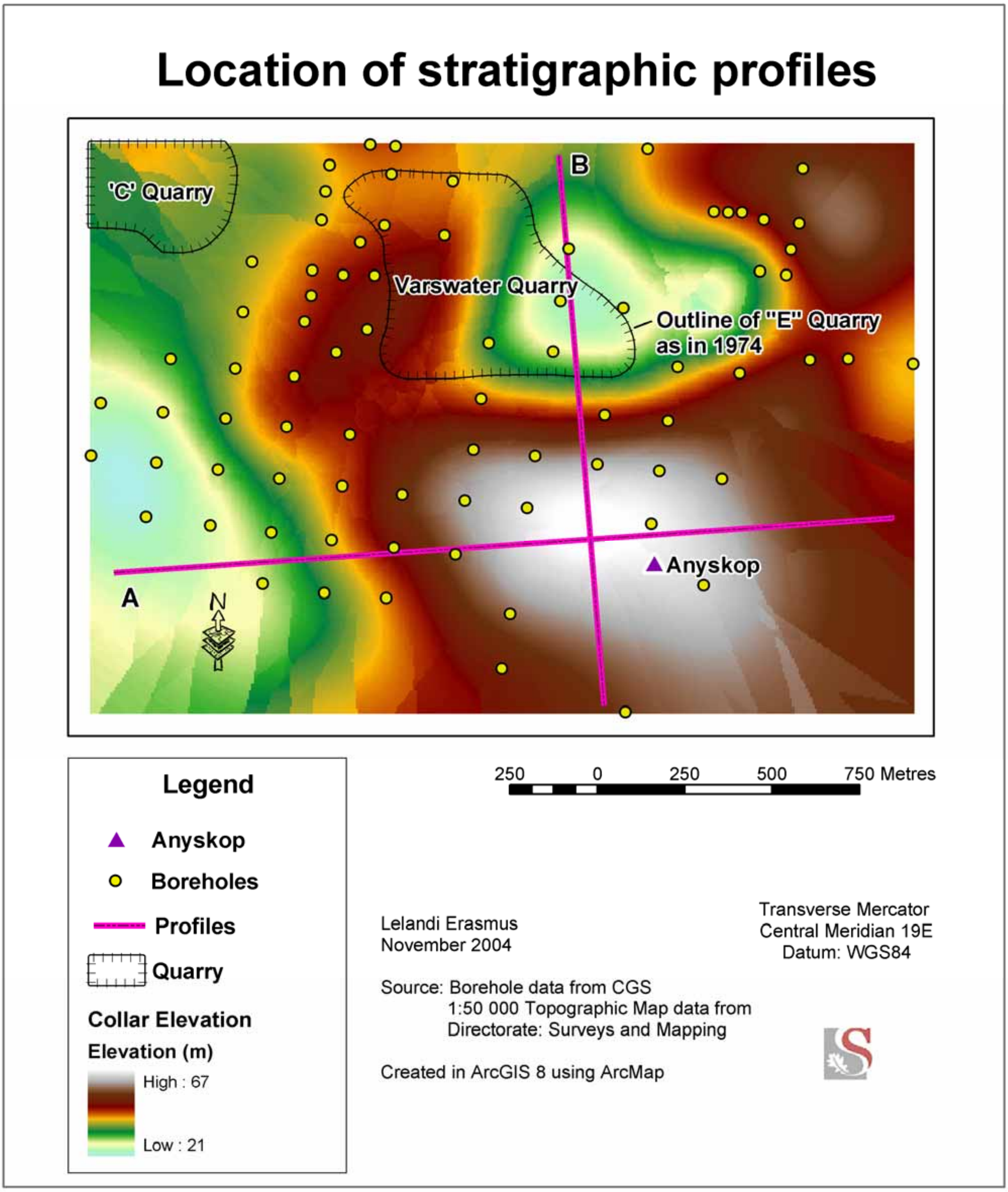


Figure 4.4 A reconstruction of the WCFP topography before mining activities commenced, showing the location of the geological profiles

4.4.2 The Varswater Formation

The **Langeenheid Clay Member (LCM),** named after a nearby railway station, is of Middle Miocene age. It is the lowermost unit of the Varswater Formation and consists mainly of clayey sands (Roberts in press –b). The mean thickness according to Roberts (in press –b) is 10m, with a maximum of 11,5m. The Langeenheid Clay Member was deposited after the Elandsfontyn Formation, and represents the transition from fluvial to estuarine conditions (Roberts in press –b). At the site of the Varswater Quarry, the LCM attains intermediate thickness, and occurs closer to the surface due to the thick layer of the Elandsfontyn Formation (see Figure 4.5 and 4.6). The LCM was only recently classified as a separate member (Roberts in press-b), and the relationship of previous fossil finds to this member is unknown.

The **Konings Vlei Gravel Member (KGM),** formerly called Gravel Member or GM, was named after a local farm. It rests on the Langeenheid Clay Member (Roberts in press –b). Fossils found within this member, for example shark teeth, warmwater molluscs (Hendey 1981b) and teeth of the horse *Hipparion primigenium,* indicate a post-Middle Miocene age (Hendey 1976b). The marine fossil fauna indicate warm water conditions, namely warm temperate to subtropical (Hendey 1981a). It consists of phosphatic gravel, and was probably deposited during a 30m stillstand of the late Miocene regression (Hendey 1981b). The mean thickness of the member is 3m, attaining a maximum thickness of 16m on the western side of Anyskop, as shown in Figure 4.4 and 4.5.

The other members of the Varswater Formation are of Mio-Pliocene age (Hendey 1981b), which is evident in the fossil fauna found within these units (warm water molluscan fauna). It seems that there was a temporal discontinuity in the sequence between the deposition of the Konings Vlei Gravel and the remainder of the Varswater Formation (Roberts 2000).

The **Langeberg Quartzose Sand Member (LQM),** formerly called Quartzose Sand Member or QSM, was also called after a local farm and occurs widely in the Saldanha area. It is up to 2,5m thick (Roberts in press –b) and consists of fine to coarse-grained quartzose sand that generally lacks phosphate (Rogers 1980). Depositional environments include floodplain, salt marsh and tidal flats, which are exposed in “E” Quarry (Hendey 1981a). Large vertebrate fossils of an early Pliocene age were found in fluvial deposits. The marine fossils found (for example molluscs and a seal) indicate cold-water conditions, while pollens belonging to fynbos vegetation types point to wooded areas and grassland (Hendey 1981a). The Langeberg Quartzose Sand Member was laid down during the early Pliocene. This member appears consistently thin across both profiles (Figure 4.4, 4.5 and 4.6).

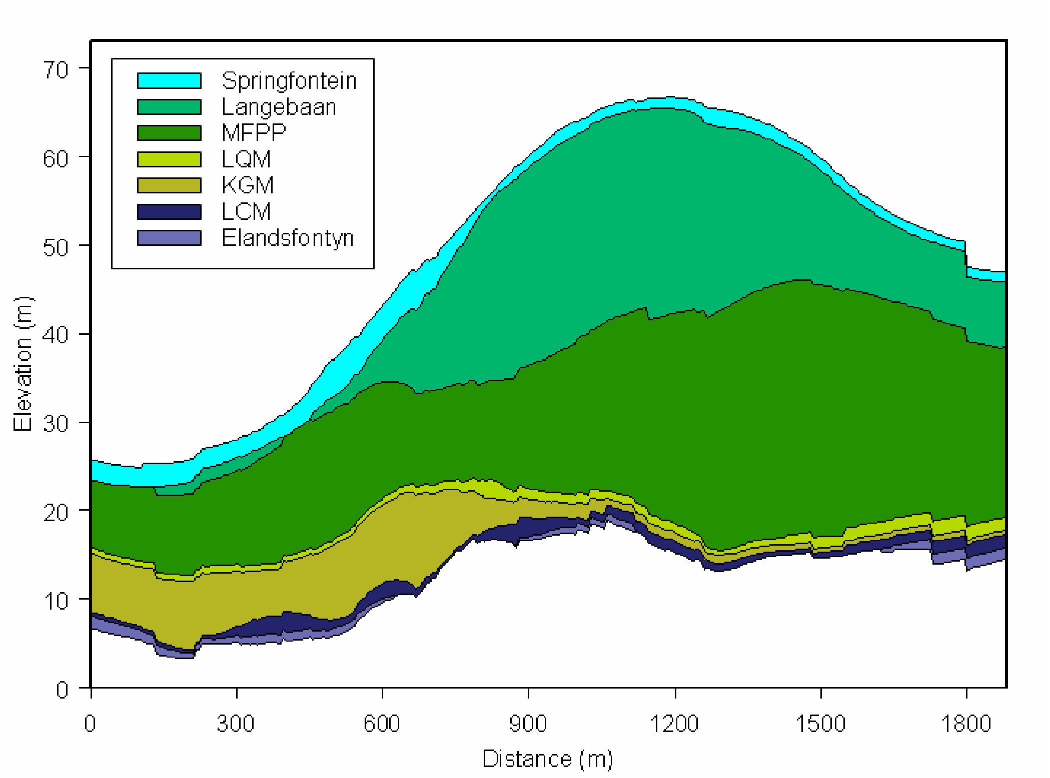


Figure 4.5 Profile of geological formations and members along transect A

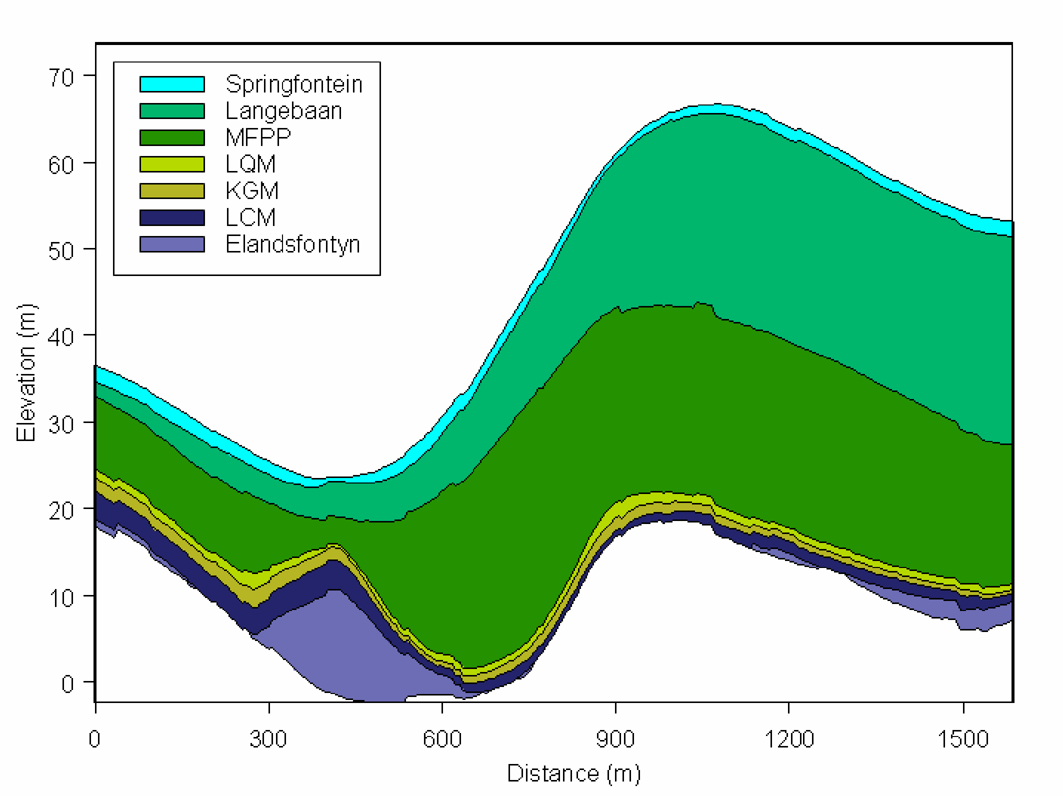


Figure 4.6 Profile of geological formations and members along transect B

The **Muishond Fontein Pelletal Phosphorite Member (MFPP)**, formerly called Pelletal Phosphorite Member or PPM, was also named after a local farm and occurs widely in the Saldanha environs. It rests in places directly on the Konings Vlei Gravel Member (Rogers 1980) or on the Elandsfontyn Formation. This member consists of fine-grained, phosphatic, quartzose sand (Rogers 1980) and its mean thickness is 12m, with a maximum of 34m under Anyskop as evidenced in Figures 4.4, 4.5 and 4.6. The Muishond Fontein Pelletal Phosphorite Member was laid down during the early Pliocene transgression (Hendey 1981a). Cold temperate conditions prevailed in this period, as manifested in the marine fossils found (molluscs and a seal). According to Hendey (1981a) the vegetation changed from woodlands to more open vegetation, and fires were common during the long dry seasons, while the rivers flooded in the wet season. These conditions marked the transition (in this area) from a tropical Pliocene to the more temperate Quaternary (Hendey 1981a).

4.4.3 The Langebaan and Springfontein Formations

The next layer in the stratigraphic sequence, the Langebaan Formation, has already been described as part of the regional geology (Figure 4.3). The Langebaan Formation has a maximum thickness of 27m in the WCFP under Anyskop (Figure 4.5 and 4.6)

The Springfontein Formation is aeolian in origin (Rogers 1980) and consists of well-sorted, fine- to medium-grained, reddish quartz sand, which is muddy and peaty in places. The age (according to Roberts in press –a) is Holocene – Pleistocene. No fossils have been found in the Springfontein Formation (Roberts in press –a). In the WCFP, the Springfontein Formation forms the uppermost layer of the stratigraphic sequence. It does not have any relevance with regards to fossil deposition, and is reconstructed in order to give a complete picture of the local geology (Figure 4.5 and 4.6). This formation is very thin (mean thickness of 1.6m, maximum of 6.5m), and evenly spread throughout the WCFP.

Interpreting the spatial extent and pattern of each geological formation in conjunction with the occurrence of different types of fossils, contributes to our knowledge of the link between past and present landscapes. The next chapter sums up how the objectives set for this research have been met, evaluating results and suggesting ideas for further research.

CHAPTER 5: SYNTHESIS

5.1 SUMMARY OF RESULTS

Borehole data at a regional scale were used to reconstruct the regional distribution of geological formations of the Langebaan area. This reconstruction allowed the spatially explicit visualisation of data that were previously only accessible to specialist geologists. The spatial nature of the output allows the layman to interpret the information. However, this data have much more to offer. In combination with data from different disciplines such as palaeontology and geography, a composite model of the events that may have led to the rich fossil deposits at the WCFP were constructed. Sea-level fluctuations and a change in the course of the Berg River were key elements that contributed to this rich fossil deposit.

The first sea-level rise of importance for this study occurred during the early to middle Miocene, to be followed by a drop in sea-level and subsequent regression of the shoreline in the middle to late Miocene. As mentioned in Chapter 3, this regression is associated with the 30m palaeo-shoreline. During this period, the WCFP was situated on or near the coast, and erosion of deposits formed during previous transgressions took place. These deposits (phosphatic sandstone now reduced to gravel) formed the lower unit of the Varswater Formation, and are characterised by marine fossils such as molluscs, marine shells, shark teeth as well as teeth of the horse *Hipparion primigenium*. After this regression, a transgression took place during the early Pliocene, with the 90m shoreline as its maximum. During the early part of this transgression, the palaeo- Berg River entered the sea near present-day Langebaan, which means that this was a time of terrestrial and freshwater fossil deposition. The Langeberg Quartzose Sand Member as well as the Muishond Fontein Pelletal Phosphorite Member were deposited in this period. Fossils deposited in these layers include large terrestrial vertebrates as well as marine fossils. As the sea-level rose, the sea inundated the site of the WCFP and the Berg River shifted its course northwards, with a corresponding decrease in fossil deposition. During the late Pliocene, a subsequent regression resulted in the 50m shoreline, which removed much of the topmost layer and marked the end of the fossil deposition at the WCFP.

The events that resulted in the formation of each geological layer are thus described and illustrated at a regional scale. However, this is too coarse a scale to guide informed further excavations at the site of the WCFP. The more detailed study based on the borehole data at the WCFP provides a finer scale picture of the potential location of fossil-bearing deposits.

5.2 EVALUATION OF STUDY

Most of the objectives, namely the reconstruction of the geology and sea-level stands of the past 15 my in the Langebaanweg area, as well as the compilation of a database of fossils finds in the WCFP (Appendix A), have been reached. A database with the current topography, infrastructure and drainage data for the study area has been compiled and the different geological formations were graphically reconstructed using available borehole data. The members and formations occurring at the West Coast Fossil Park have also been reconstructed using available borehole data. Different sea-level stands during the past 15 million years were modelled using present day elevation data, and a database synchronising key fossil finds with key stratigraphic units was constructed (Appendix A). A subset of the above results was presented as a poster at the 2002 Annual Student Geography Conference.

The value of this study lies in the reconstruction of the different formations and their members, and the establishment of a spatially explicit methodology. For the first time (as far as is known), the members and formations in which the fossil finds were made are reconstructed using expert knowledge of the geology of the area, as well as borehole data. The reconstructed basement (and other layers) confirms the opinion of other authors (Hendey 1981a; Rogers 1980) that the palaeo-Berg River flowed through or close to the WCFP: there is a valley clearly visible which would be the natural valley created by the flow of a river (Figure 5.1). A hypothetical palaeo-Berg River is drawn, flowing close to the site of the WFCP.

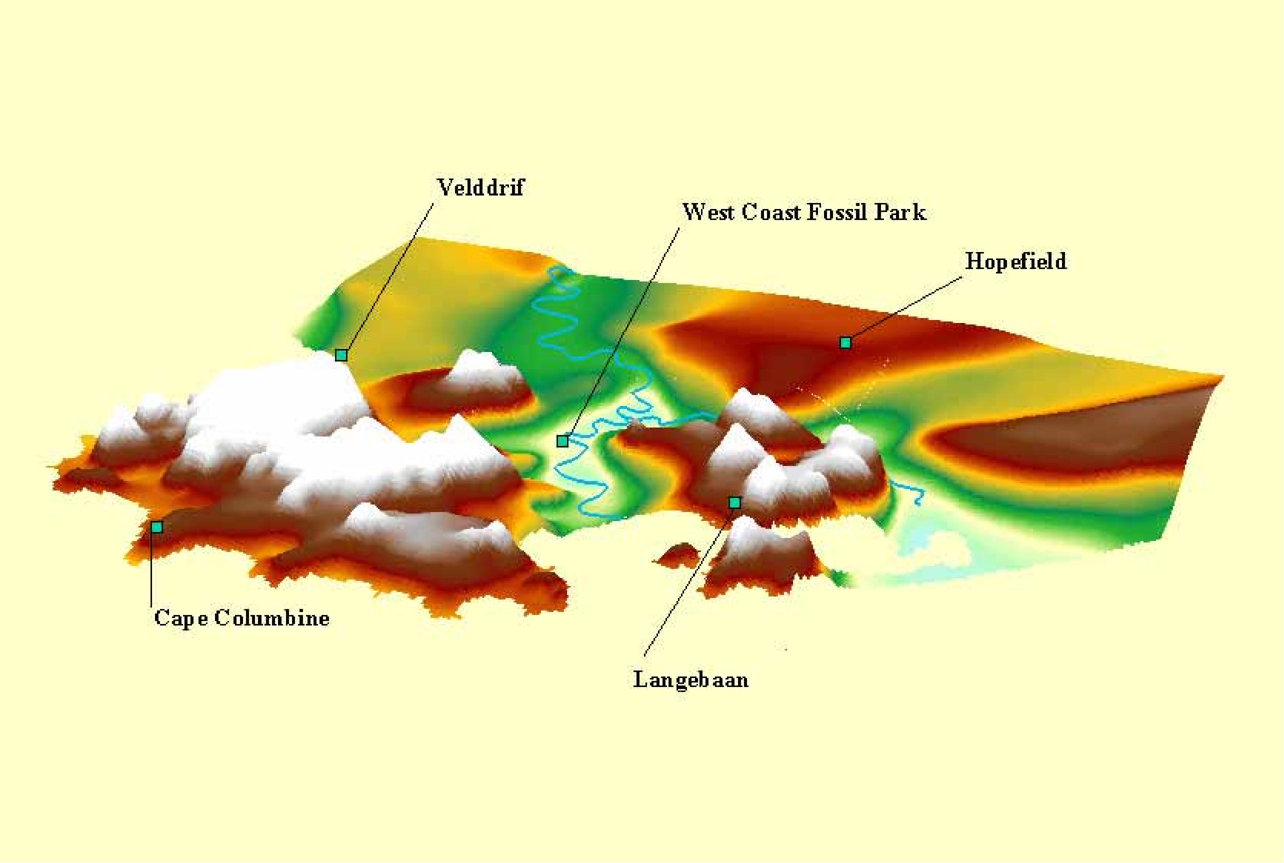


Figure 5.1 A 3D rendition of the basement layer of the study area, viewed from the southwest

The option exists to use this study to guide further excavations. The formations and their respective members are now mapped, and if the elevation values of any formation of interest are compared to the actual elevation, the depth of potential fossil-bearing deposits can be calculated. Once again, this makes previously specialist knowledge available to be interpreted by the general public; it is potentially a valuable tool to attract visitors, and consequently funding.

However, it should always be borne in mind that these outputs are modelled solutions, which are unlikely to match real-world phenomena exactly. This does not render outputs useless. Instead, the explicit documentation of the methodology will allow future researchers to identify and evaluate sources of error in the interpolated geological surfaces. This study serves as a point of departure for such research by not only having all reference material available in one package, but also by showing that GIS can be a useful tool in palaeontological research.

5.3 RECOMMENDATIONS

Recommendations that flow from the experience gained in this study can be summarised in three aspects. First of all, the WCFP needs to invest in some expert knowledge and infrastructure to utilise the information from this study. They would need access to basic GIS software, appropriate hardware and capacity to present the information in a way that would be accessible to the public. A large part of this accessibility revolves around visual interpretation of data, and most of that has already been done here. An interactive mulitmedia interface that is suitable for general use needs to be developed so that people can explore the three-dimensional nature of the data themselves.

The second recommendation is about model improvement and interpretation. The interpolation methods used in this study were selected for ease of use and repeatability. More complex kriging procedures can be applied, and that, combined with more detailed geological data, will hopefully result in more accurate outputs. However, it should not be assumed that the current outputs are wrong by virtue of following a simple approach. In modelling exercises such as this, parsimony in variable selection and model complexity will always be important to keep models understandable and useful. The next step would be to validate the model outputs from this study. This would entail comparing predicted values (either fossil presence/absence, or just the depth and/or presence of a particular geological formation) to actual observed values. These observed values should preferably be the result of new observations, i.e. new borehole data or fossil excavations. There is a well developed literature in other fields to interpret the agreement between observed and predicted values (Fielding & Bell 1997), and such an analysis would inform further model refinement in an interactive process.

The final recommendation from this study is about other opportunities and tools that exist to conduct similar studies. It is recommended that the 3D modelling be done in software written especially for geological applications, or even software such as QuickSurf for AutoCad® (http://www.rockware.com/catalog/pages/quicksur.html). Another good alternative would be to download GRASS from the Internet, which is an open source GIS package and therefore free. There is a whole community that is constantly developing new scripts and modules, which improve GRASS. One of the modules of GRASS is called Nviz, which is a 3D visualization tool. Nviz can also be used for “dynamic visualization of geologic cross-sections and generation of animated image sequences”, according to Masumoto et al (2002:1). At the 2002 Open Source GIS – GRASS Users Conference in Italy, two papers were presented that followed a different approach to geological modelling than was followed in this study. The authors wrote algorithms for 3D modelling and visualization of geological models using the GRASS platform (Masumoto et al 2002; Yonezawa et al 2002).

Taking it one step further is what Shell International Exploration has done: they opened their first large-scale visualization centre in 2000 in Houston, where geophysicists and others can “immerse” themselves in virtual reality by donning stereo glasses. These glasses “transform screen displays of the earth’s inner regions into 3D images that “extend” into the room and entice viewers to reach out and touch them” (GEOEurope 2001: 34). Shell International Exploration sees immersive visualization as a 3D solution to a 3D problem – it is necessary for them to understand the subsurface structures in order to enhance the safety and efficiency of their exploration and drilling operations. The same concept would make a huge difference to the displays at the WCFP, and would attract visitors from all over the world.

According to Burrough (1998: 172), “the variation of a surface over time can be shown by computing and storing the interpolated surface for point data from each step, and then displaying the results as a video”. These time series and accumulation modelling requires that the new attributes and model parameters computed be stored at each step. This means that all intermediate steps in the calculations can be stored and retrieved from the database, in order to provide feedback loops (Burrough 1998). PCRaster is a toolkit for Dynamic Spatial Modelling, and Burrough gives examples of how it can be applied to the dispersion of plants over continuous space, and the routing of surface runoff over directed topological nets. The same methodology can be applied to the geological data of the WCFP: a time series of the regressions and transgressions of the coastline and the accumulation of the geological deposits would form a complete spatial model. Monmonier (in Jones 1999) suggests that animated maps, in which the changes are played out over a short period of time, can be accompanied by graphics such as histograms or pie charts that could change in time with the map.

5.4 FURTHER RESEARCH

Schaetzl et al (2000: 462) are of the opinion that “soils data, manipulated within a GIS, can potentially lead to new discoveries of geomorphic and paleoenvironmental significance”. The same can apply to geological data. Once more borehole data becomes available for the Langebaanweg area, it will be necessary to redo the interpolations. If data of palaeo-water features like rivers, marshes, and estuaries become available, these can be incorporated into the database, and used in TOPOGRID so that the DEM will be hydrologically correct. Faults occurring in this region could also be used to make the geological model more complete.

As new fossils are discovered in the WCFP, their descriptions can be added to the database in Appendix A. It would be useful to know the exact location and elevation of fossil finds too: a GPS could be used to record such information. The localities of the fossils finds can be plotted very accurately using the above-mentioned data.

More research is needed on the different sea-levels of the past 15 my, so that they can be delineated more accurately. That, combined with the reconstructed geology, would depict a more complete palaeo-topography.

REFERENCES

Birch GF 1977. Phosphorites from the Saldanha Bay region. *Transactions of the Royal Society of South Africa* 42, 3:223-240.

Boné EL & Singer R 1965. *Hipparion* from Langebaanweg, Cape Province and a revision of the genus in Africa. *Annals of the South African Museum* 48, 16:273-397.

Burrough PA 1998. Dynamic modelling and geocomputation. In Longley PA, Brooks SM, McDonnell R & Macmillan B (eds). *Geocomputation: A primer*, pp 165-191. Chichester: John Wiley & Sons.

Clegg CJ & Mackean DG 1994. *Advanced biology principles & applications*. London: John Murray Publishers.

Coetzee JA & Rogers J 1982. Palynological and lithological evidence for the Miocene palaeoenvironment in the Saldanha region (South Africa). *Palaeogeography, Palaeoclimatology, Palaeoecology* 39:71-85.

Cressie NAC 1993. *Statistics for Spatial Data*, Revised Edition. New York: Wiley.

Deacon HJ & Deacon J 1999. *Human beginnings in South Africa: Uncovering the secrets of the Stone Age*. Cape Town: David Philip Publishers.

DeMers MN 2002. *GIS modeling in raster*. New York: John Wiley & Sons, Inc.

Denys C 1998. Phylogenetic implications of the existence of two modern genera of Bathyergidae (Mammalia, Rodentia) in the Pliocene site of Langebaanweg South Africa. *Annals of the South African Museum* 105, 5:265-286.

Dingle RV, Lord AR & Hendey QB 1979. New sections in the Varswater Formation (Neogene) of Langebaan Road, south-western Cape, South Africa. *Annals of the South African Museum* 78, 8:81-92.

Farb P 1968. *Face of North America: The natural history of a continent*. New York: Harper & Row Publishers.

Fielding AH & Bell JF 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24: 38-49.

Gentry AW 1974. A new genus and species of Pliocene *Boselaphine* (Bovidae, Mammalia) from South Africa. *Annals of the South African Museum* 65, 5: 145-188.

GEOEurope 2001. Visualise this! May 2001: 34.

Grine FE & Hendey QB 1981. Earliest primate remains from South Africa. *South African Journal of Science* 77:374-376.

Harris JM 1976. Pliocene Giraffoidea (Mammalia; Artiodactyla) from the Cape Province. *Annals of the South African Museum* 69, 12:325-353.

Hendey QB 1969. Quaternary vertebrate fossil sites in the south-western Cape Province. *South African Archaeological Bulletin* 24: 96-105.

Hendey QB 1970a. A review of the geology and palaeontology of the Plio/Pleistocene deposits at Langebaanweg, Cape Province. *Annals of the South African Museum* 56, 2:75-117.

Hendey QB 1970b. The age of the fossiliferous deposits at Langebaanweg, Cape Province. *Annals of the South African Museum* 56, 3:119-131.

Hendey QB 1972a. A Pliocene Ursid from South Africa. *Annals of the South African Museum* 59, 6:115-132.

Hendey QB 1972b. The evolution and dispersal of the Monachinae (Mammalia: Pinnipedia). *Annals of the South African Museum* 59, 5:99-113.

Hendey QB 1973. Fossil occurrences at Langebaanweg, Cape Province. *Nature* 244:13-14.

Hendey QB 1974. Late Cenozoic Carnivora of the Western Cape Province. *Annals of the South African Museum* 63, 1-369.

Hendey QB 1975. A wildlife paradise 4 million years ago. *African Wildlife* 29, 1:28-31.

Hendey QB 1976a. Fossil peccary from the Pliocene of South Africa. *Science* 192:787-789.

Hendey QB 1976b. The Pliocene fossil occurrences in ‘E’ Quarry, Langebaanweg, South Africa. *Annals of the South African Museum* 69, 9:215-247.

Hendey QB 1977. Fossil bear from South Africa. *South African Journal of Science* 73:112-116.

Hendey QB 1978. The age of the fossils from Baard’s Quarry, Langebaanweg, South Africa. *Annals of the South African Museum* 75, 1:1-24.

Hendey QB 1981a. Geological succession at Langebaanweg, Cape Province, and global events of the late Tertiary. *South African Journal of Science* 77: 33-38.

Hendey QB 1981b. Palaeoecology of the late Tertiary fossil occurrences in ‘E’ Quarry, Langebaanweg, South Africa, and a reinterpretation of their geological context. *Annals of the South African Museum* 84: 1-104.

Hendey QB 1982. *Langebaanweg: A record of past life*. Cape Town: South African Museum.

Hendey QB & Repenning CA 1972. A Pliocene Phocid from South Africa. *Annals of the South African Museum* 59, 4:71-98.

Holland HJ 1997. A collated digital, geological map database for the Central Namaqua Province using Geographical Information System technology. MSc thesis. Grahamstown: Rhodes University.

Hooijer DA 1972. A Late Pliocene rhinoceros from Langebaanweg, Cape Province. *Annals of the South African Museum* 59, 9:151-191.

Jones CB 1999. *Geographical Information Systems and computer cartography*. Essex: Longman.

Kaluzny SP, Vega SC, Cardoso TP & Shelly AA 1998. *S+ Spatial Stats – user's manual for Windows® and Unix®*. New York: Springer-Verlag.

Kensley B 1972. Pliocene marine invertebrates from Langebaanweg, Cape Province. *Annals of the South African Museum* 60, 4:173-190.

Kensley B 1977. A second assemblage of Pliocene invertebrate fossils from Langebaanweg, Cape. *Annals of the South African Museum* 72, 10:189-210.

Kershaw DR 1983. *Animal diversity*. Slough: University Tutorial Press Limited.

Klein RG 1977. The ecology of early man in Southern Africa. *Science* 197, 4299:115-126.

Klein RG 1981. Ungulate mortality and sedimentary facies in the late Tertiary Varswater Formation, Langebaanweg, south-western Cape Province, South Africa. *Annals of the South African Museum* 84, 6:233-254.

Maglio VJ & Hendey QB 1970. New evidence relating to the supposed Stegolophodont ancestry of the Elephantidae. *South African Archaeological Bulletin* 25: 85-87.

Masumoto S, Raghavan V, Nemoto T & Shiono K 2002. Construction and visualization of three dimensional geologic model using GRASS GIS. Proceedings of the Open Source GIS – GRASS users conference, Trento, Italy, 11-13 September 2002.

Olson SL & Eller KG 1989. A new species of Painted Snipe (Charadriiformes: Rostratulidae) from the early Pliocene at Langebaanweg, South-western Cape Province, South Africa. *Ostrich* 60, 3:118-121.

Partridge TC 1969. Fluvial features and climatic change during the Quaternary in South Africa. *South African Archaeological Bulletin* 24: 106-116.

Pether J 1986. Late Tertiary and early Quaternary marine deposits of the Namaqualand coast, Cape Province: new perspectives. *South African Journal of Science* 82:464-470.

Pocock TN 1976. Pliocene Mammalian microfauna from Langebaanweg: A new fossil genus linking the Otomyinae with the Murinae. *South African Journal of Science* 72:58-60.

Rich PV 1980. Preliminary report on the fossil avian remains from Late Tertiary sediments at Langebaanweg (Cape Province), South Africa. *South African Journal of Science* 76:166-170.

Ripley BD 1981. *Spatial Statistics*. New York: Wiley.

Roberts DL 2000. Deposits of the West Coast. In Partridge, TC & Maud, RR (eds.) *The Cenozoic of Southern Africa*, pp36-41. New York: Oxford University Press.

Roberts DL 2002. The West Coast Fossil Park: Serving science & the community. *GEOclips* 2: 1-2.

Roberts DL (In press -a). Lithostratigraphy of the Sandveld Group. South African Committee for Stratigraphy Lithostratigraphic Series.

Roberts DL (In press -b). Lithostratigraphy of the Varswater Formation (Sandveld Group). South African Committee for Stratigraphy Lithostratigraphic Series.

Roberts DL & Brink J 2002. Dating and correlation of Neogene coastal deposits in the Western Cape, South Africa: implications for Neotectonism. *South African Journal of Geology* 105:337-352.

Rogers J 1980. *First report on the Cenozoic sediments between Cape Town and Elands Bay*. (Report No. 1980-136). Pretoria: Geological Survey of South Africa.

Rubidge BS & Brink JS 1986. *Life through the ages*: A guide to the paleontology exhibits of the National Museum. Bloemfontein: National Museum.

Schaetzl RJ, Krist Jr FJ, Rindfleisch PR, Liebens J & Williams TE 2000. Postglacial landscape evolution of northeastern Lower Michigan, interpreted from soils and sediments. *Annals of the Association of American Geographers* 90, 3: 443-466.

Simpson GG 1971. Fossil penguin from the Late Cenozoic of South Africa. *Science* 171: 1144-1145.

Simpson GG 1976. Notes on the variation in penguins and on fossil penguins from the Pliocene of Langebaanweg, South Africa. *Annals of the South African Museum* 69, 4: 59-72.

Singer R & Hooijer DA 1958. A stegolophodon from South Africa. *Nature* 182: 101-102.

Skinner JD & Smithers RHN 1990. *The mammals of the southern African subregion*. Pretoria: University of Pretoria.

Smith C 1998. Footprints find stuns scientists. *Saturday Star*, 27 June.

South African Committee for Stratigraphy (SACS) 2004. *What is SACS?* [online]. Available from: http://www.geoscience.org.za/sacs/what.htm [Accessed 1 November 2004].

Tankard AJ 1974a. Petrology and origin of the phosphorite and aluminium phosphate rock of the Langebaanweg-Saldanha area, south-western Cape Province. *Annals of the South African Museum* 65, 8:217-249.

Tankard AJ 1974b. Varswater Formation of the Langebaanweg-Saldanha area, Cape Province. *Transactions of the Geological Society of South Africa* 77:265-283.

Tankard AJ 1976. Pleistocene history and coastal morphology of the Ysterfontein - Elands Bay area, Cape Province. *Annals of the South African Museum* 69, 5:73-119.

Van Dijk DE 2003. Pliocene frogs from Langebaanweg, Western Cape Province, South Africa. *South African Journal of Science* 99: 123-124.

Vitek JD, Giardino JR & Fitzgerald JW 1996. Mapping geomorphology: A journey from paper maps, through computer mapping to GIS and Virtual Reality. *Geomorphology* 16, 3:233-249.

Yonezawa G, Nemoto T, Masumoto S & Shiono K 2002. 3-D geologic modeling and visualization of faulted structures: theory and GIS application. Proceedings of the Open Source GIS – GRASS Users conference 2002, Trento, Italy, 11-13 September 2002.

PERSONAL COMMUNICATIONS

Van der Worm JH 2004. Palaeontological Researcher, Department of Botany and Zoology, University of Stellenbosch. Interview in September 2004 about the fossil lizard fauna of the WCFP.

APPENDIX A: SPECIES CLASSIFICATION

Species are classified in a hierarchical classification system devised by Linnaeus in 1753. Species' scientific names are usually derived from some characteristic of the species or the person who discovered the species, and then latinised. The hierarchical system starts at the highest (most inclusive level), and becomes more specific at each subsequent level, ending with a species-specific moniker. This classification system enables palaeontologists to identify fossil finds to a specific level in the classification based on the specifics of characters that are observable on the fossilised bones. Depending on the group of animals concerned, super- and subdivisions may be identified at any level. This is especially the case in hyper diverse taxa such as insects, where the genus, family and order levels usually contain subdivisions. Although there are taxa-specific norms, and not all taxa have membership at every possible level, in general a classification would proceed as follows, using the lion as an example:

Kingdom: Animalia
Phylum: Chordata
Class: Mammalia
Order: Carnivora
Family: Felidae
Genus: *Panthera*
Species: *leo*
Subspecies: --

Table A.1 Summary of fossil finds at the West Coast Fossil Park and surrounding area. This summary is meant to be illustrative of the diversity of fossils at this site, and should be seen as a point of departure for further studies. Taxonomy reflects the state of knowledge at the time of discovery, and is therefore not consistent across taxa and will not reflect any changes since publication of the reference work. Numbers in the first column refer to like numbers in Table A.2, where more information on each fossil is given.

	Phylum	**Class**	**Order**	**Family**	**Subfamily**	**Genus and species**
1	Arthropoda	Crustacea	Cirripedia			
2	Brachiopoda					*Kraussina rubra*
3	Echinodermata	Echinoidea				*Parechinus angulosus*
4	Echinodermata	Echinoidea				
5	Mollusca	Gastropoda	Aspidobranchia	Patellidae		*Cellana capensis, Patella granularis, Cellana*
6	Mollusca	Gastropoda	Aspidobranchia	Fissurellidae		*Diodora parviforata*
7	Mollusca	Gastropoda	Aspidobranchia	Haliotidae		*Haliotis saldanhae, Haliotis*
8	Mollusca	Gastropoda	Aspidobranchia	Trochidae		*Oxystele tigrina, Gibbula benzi, Oxystele variegata*
9	Mollusca	Gastropoda	Aspidobranchia	Phasianellidae		*Tricolia neritina, tricolia capensis*
10	Mollusca	Gastropoda	Aspidobranchia	Littorinidae		*Littorina, Littorina cf knysnaensis*
11	Mollusca	Gastropoda	Aspidobranchia	Muricidae		*Ocenebra scrobiculata*
12	Mollusca	Gastropoda	Aspidobranchia	Thaididae		*Thais dubia*
13	Mollusca	Gastropoda	Aspidobranchia	Nasariidae		*Bullia*
14	Mollusca	Gastropoda	Aspidobranchia	Turridae		*Crassispira, Clavatula*
15	Mollusca	Gastropoda	Aspidobranchia	Turbinidae		*Turbo sarmanticus*
16	Mollusca	Gastropoda	Opistobranchiata	Pyramidellidae		*Turbonella kraussi, Pyramidella*
17	Mollusca	Gastropoda	Pulmonata	Siphonariidae		*Siphonaria*
18	Mollusca	Pelecypoda		Donacidae		*Donax*
19	Chordata	Amphibia		Bufonidae		
20	Chordata	Amphibia		Brevicipitidae		
21	Chordata	Amphibia		Ranidae		
22	Chordata	Amphibia		Pipidae		
23	Chordata	Mammalia	Artiodactyla	Bovidae	Bovinae	*Mesembriportax acrae*[3]
24	Chordata	Mammalia	Artiodactyla	Giraffidae[4]		
25	Chordata	Mammalia	Artiodactyla	Sivatheriidae		*Sivatherium hendeyi*[5]
26	Chordata	Mammalia	Artiodactyla	Tayassuidae		*Pecarichoerus africanus*[6]
27	Chordata	Mammalia	Artiodactyla	Tayassuidae		*Nyanzachoerus*[7]
28	Chordata	Mammalia	Artiodactyla	Bovidae		
29	Chordata	Mammalia	Perissodactyla	Equidae		*Hipparion*

---

[3] This is the only boselaphine antelope ever recorded in southern Africa.

[4] Smaller than extant species, *Giraffa camelopardalis.*

[5] Ancestral giraffe species with long horns, short neck and larger body than extant species.

[6] First fossil peccary species in Africa

[7] Two species of this genus were found. One species was twice the size of a modern bushpig, and the other the size of a small dog.

	Phylum	**Class**	**Order**	**Family**	**Subfamily**	**Genus and species**
30	Chordata	Mammalia	Perissodactyla	Rhinocerotidae		*Ceratotherium praecox*
31	Chordata	Mammalia	Hyracoidea	Procaviidae		
32	Chordata	Mammalia	Carnivora	Ursidae		*Agriotherium africanum*[8]
33	Chordata	Mammalia	Carnivora	Viverridae	Viverrinae	*Genetta*[9]
34	Chordata	Mammalia	Carnivora	Mustelidae	Lutrinae	*Enhydriodon*
35	Chordata	Mammalia	Carnivora	Mustelidae	Mellivorinae	*Mellivora capensis*[10]
36	Chordata	Mammalia	Carnivora	Hyaenidae		*Euryboas*[11]
37	Chordata	Mammalia	Carnivora	Hyaenidae		*Hyaena brevirostris, Percrocuta sp., Hyaenictis forfex, Proteles cristatus*
38	Chordata	Mammalia	Carnivora	Viverridae	Herpestinae	*Herpestes sp.*[12]
39	Chordata	Mammalia	Carnivora	Felidae	Machairodontinae	*Machairodus transavaalensis; Homotherium problematicus; Megantereon sp; Dinofelis piveteaui.*
40	Chordata	Mammalia	Carnivora	Felidae	Felinae	*Felis obscura, Felis serval, Felis caracal*
41	Chordata	Mammalia	Chiroptera	Vespertilionidae		*Eptesicus*
42	Chordata	Mammalia	Insectivora	Macroscelididae		*Elephantulus sp*
43	Chordata	Mammalia	Insectivora	Chrysochloridae		*Chrysochloris*
44	Chordata	Mammalia	Insectivora	Soricidae		*Myosorex sp; Suncus sp*
45	Chordata	Mammalia	Lagomorpha	Leporidae		*Pronolagus*
46	Chordata	Mammalia	Pinnipedia	Phocidae	Monachinae	*Prionodelphis capensis*[13]
47	Chordata	Mammalia	Primates	Cercpithecidae[14]		
48	Chordata	Mammalia	Proboscidea			*Mammuthus subplanifrons*[15]
49	Chordata	Mammalia	Proboscidea			*Stegolophodon*[16]
50	Chordata	Mammalia	Rodentia	Muridae	Murinae	*Euryotomys pelomyoides*
51	Chordata	Mammalia	Rodentia	Bathyergidae		*Bathyergus hendeyi; Cryptomys broomi; Bathyergus sp.; Cryptomys sp.*[17]
52	Chordata	Mammalia	Rodentia[18]	Muridae	Cricetinae	*Mystromys (3 species)*
53	Chordata	Mammalia	Rodentia	Muridae	Gerbilinae	*Gerbillus; Desmodillus*
54	Chordata	Mammalia	Rodentia	Muridae	Dendromurinae	*Dendromys sp., Steatomys sp., Malacothrix sp.*
55	Chordata	Mammalia	Rodentia	Muridae	Murinae	*Aethomys sp. (large), Aethomys sp. (small)*
56	Chordata	Mammalia	Rodentia	Muridae	Murinae	*Mus sp. (larger), Mus sp. (smaller)*
57	Chordata	Mammalia	Rodentia	Gliridae		*Graphiurus sp.*

---

[8] This is the only member of the bear family (Ursidae) ever to be recorded in sub-Saharan Africa, and it is related to the giant panda.

[9] Extant and ancestral forms

[10] Extant and ancestral forms

[11] Large, hunting hyaena

[12] Extant and ancestral forms

[13] Also occurs in overlying deposits

[14] Earliest record of a primate in South Africa

[15] Ancestor of woolly mammoth

[16] First evidence of the occurrence of this genus in southern Africa

[17] Oldest records of members of these genera.

[18] Classification according to Skinner and Smithers 1991.

	Phylum	Class	Order	Family	Subfamily	Genus and species
58	Chordata	Mammalia	Rodentia	Muridae	Murinae	*Euryotomys pelomyoides*
59	Chordata	Mammalia	Tubulidentata	Oryteropodidae		*Orycteropus*
60	Chordata	Mammalia	Cetacea			
61	Chordata	Aves	Procellariiformes	Spheniscidae		*Spheniscus predemersus (Inguza predemersus)*[19]
62	Chordata	Aves	Podicepidiformes	Podicipedidae		
63	Chordata	Aves	Procellariiformes	Procellariidae		
64	Chordata	Aves	Pelecaniformes	Pelecanidae		
65	Chordata	Aves	Pelecaniformes	Phalacrocoracidae		
66	Chordata	Aves	Pelecaniformes	Sulidae		
67	Chordata	Aves	Ciconiiformes	Ciconiidae		
68	Chordata	Aves	Ciconiiformes	Threskiornithidae		
69	Chordata	Aves	Anseriformes	Anatidae		
70	Chordata	Aves	Falconiformes	Gypaetidae		
71	Chordata	Aves	Falconiformes	Falconidae		
72	Chordata	Aves	Falconiformes	Accipitridae		
73	Chordata	Aves	Galliformes	Phasianidae		
74	Chordata	Aves	Gruiformes	Gruidae		
75	Chordata	Aves	Gruiformes	Rallidae		
76	Chordata	Aves	Gruiformes	Otididae		
77	Chordata	Aves	Charadriiformes			
78	Chordata	Aves	Galliformes	Pteroclidae		
79	Chordata	Aves	Columbiformes	Columbidae		
80	Chordata	Aves	Psitacciformes			
81	Chordata	Aves	Strigiformes	Strigidae		
82	Chordata	Aves	Passeriformes	Coliidae		
83	Chordata	Aves	Coraciiformes			
84	Chordata	Aves	Coraciiformes	Alecidinidae		
85	Chordata	Aves	Piciformes	Picidae		
86	Chordata	Aves	Apodiformes	Apodidae		
87	Chordata	Aves	Passeriformes			
88	Chordata	Aves	Struthioniformes	Struthionidae		
89	Chordata	Osteichthyes				
90	Chordata	Osteichthyes				*Tayasuriya*
91	Chordata	Chondreichthyes				
92	Chordata	Chondreichthyes				
93	Chordata	Chondreichthyes				
94	Chordata	Reptilia	Squamata	Gekkonidae		
95	Chordata	Reptilia	Testudines	Testudinidae		
96	Chordata	Reptilia	Squamata	Lacertidae		

---

[19] First fossil penguin to be recorded from Africa.

	Phylum	Class	Order	Family	Subfamily	Genus and species
97	Chordata	Reptilia	Squamata	Varanidae		
98	Chordata	Reptilia	Squamata			

Table A.2

	Common name	Age	Found in	Reference
1	acorn barnacle	Upper-Pliocene	E Quarry	Kensley 1972; Hendey 1973
2	lamp shell	Upper-Pliocene	E Quarry	Kensley 1972; Hendey 1973
3	sea star	Upper-Pliocene	E Quarry	Kensley 1972
4	sea urchin			Hendey 1975
5	snail	Upper-Pliocene	E Quarry	Kensley 1972
6	snail	Upper-Pliocene	E Quarry	Kensley 1972
7	snail	Upper-Pliocene	E Quarry	Kensley 1972
8	snail	Upper-Pliocene	E Quarry	Kensley 1972
9	snail	Upper-Pliocene	E Quarry	Kensley 1972
10	snail	Upper-Pliocene	E Quarry	Kensley 1972
11	snail	Upper-Pliocene	E Quarry	Kensley 1972
12	snail	Upper-Pliocene	E Quarry	Kensley 1972
13	snail	Upper-Pliocene	E Quarry	Kensley 1972
14	snail	Upper-Pliocene	E Quarry	Kensley 1972
15	snail	Upper-Pliocene	E Quarry	Kensley 1972
16	snail	Upper-Pliocene	E Quarry	Kensley 1972
17	snail	Upper-Pliocene	E Quarry	Kensley 1972
18	snail	Upper-Pliocene	E Quarry	Kensley 1972
19	frogs	Pliocene	Varswater Form	Hendey 1975; Van Dijk 2001
20	frogs	Pliocene	Varswater Form	Hendey 1975; Van Dijk 2002
21	frogs	Pliocene	Varswater Form	Hendey 1975; Van Dijk 2003
22	frogs	Pliocene	Varswater Form	Hendey 1975; Van Dijk 2000
23	antelope	Pliocene	E Quarry	Hendey 1975; Gentry 1974
24	giraffe			Hendey 1975
25	giraffe	Pliocene	E Quarry; Varswater Formation	Hendey 1975; Harris 1976
26	peccary (true pig)	Pliocene	E Quarry; Varswater Formation	Hendey 1976a
27	pigs (2 species)			Hendey 1975
28	buffalo			Hendey 1975
29	three-toed horse		Baard's Quarry; Varswater quarry	Hendey 1975; Boné & Singer 1965
30	rhinoceros	Late Pliocene	E Quarry	Hendey 1975; Hooijer 1972
31	hyraxes			Hendey 1975
32	bear	Pliocene	E Quarry; Varswater Formation	Hendey 1975; Hendey 1972a
33	genet	Pliocene	Varswater Form	Hendey 1975, 1974
34	giant otters	Pliocene	Varswater Form	Hendey 1975, 1974
35	honey badger	Pliocene	Varswater Formation	Hendey 1974

	Common name	Age	Found in	Reference
36	hyaena	Pliocene	Varswater Formation	Hendey 1975
37	hyaena	Pliocene	Varswater Formation	Hendey 1974, 1975
38	mongooses	Pliocene	Varswater Form	Hendey 1975; 1974
39	sabre-toothed cats	Pliocene	E Quarry; Varswater Formation	Hendey 1975, 1974
40	cats	Pliocene	Varswater Formation	Hendey 1975, 1974
41	bats	Pliocene	E Quarry; Varswater Formation	Hendey 1975, Pocock1976
42	elephant shrew	Pliocene	Varswater Form	Pocock 1976
43	golden mole	Pliocene	E Quarry; Varswater Formation	Hendey 1975, Pocock1976
44	shrew	Pliocene	Varswater Form; E Quarry	Pocock 1976
45	rabbits & hares	Pliocene	E Quarry; Varswater Formation	Hendey 1975; Pocock 1976
46	seal	Late Pliocene	Varswater Form; E Quarry	Hendey 1975; Hendey 1972b; Hendey & Repenning 1972
47	primate (vervet family)	early Pliocene	E Quarry; Varswater Formation	Grine & Hendey 1981
48	elephants	Late Pliocene		Hendey 1975; Maglio & Hendey 1970)
49	elephant-like proboscid ancestor	Middle Pleistocene	Baard's Quarry	Singer & Hooijer 1958
50	mice	Pliocene	E Quarry; Varswater Formation	Hendey 1975; Pocock 1976
51	mole rats	Pliocene	E Quarry; Varswater Formation	Denys 1998; Pocock 1976
52	White-tailed mouse	Pliocene	E Quarry; Varswater Formation	Pocock 1976
53	gerbil	Pliocene	E Quarry; Varswater Formation	Pocock 1976
54	climbing mouse, fat mouse, large-eared mouse	Pliocene	E Quarry; Varswater Formation	Pocock 1976
55	veld rat	Pliocene	E Quarry; Varswater Formation	Pocock 1976
56	pygmy mouse	Pliocene	E Quarry; Varswater Formation	Pocock 1976
57	dormice	Pliocene	E Quarry; Varswater Formation	Pocock 1976
58	new mouse sp	Pliocene	E Quarry; Varswater Formation	Pocock 1976
59	aardvark			Hendey 1975
60	whales			Hendey 1975
61	penguins	Early Pliocene	E Quarry; Varswater Formation	Rich 1980, Hendey 1975; Simpson 1971&1976
62	grebes	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
63	petrels	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
64	pelicans	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
65	cormorants	Early Pliocene	E Quarry; Varswater Formation	Rich 1980, Hendey 1973
66	gannets	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
67	storks	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
68	ibises	Early Pliocene	E Quarry; Varswater Formation	Rich 1980, Hendey 1973
69	ducks and geese	Early Pliocene	E Quarry; Varswater Formation	Rich 1980, Hendey 1973, 1975
70	vultures	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
71	falcons	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
72	eagles	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
73	gamebirds (francolin)	Early Pliocene	E Quarry; Varswater Formation	Rich 1980, Hendey 1973
74	cranes	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
75	rails	Early Pliocene	E Quarry; Varswater Formation	Rich 1980

	Common name	Age	Found in	Reference
77	shorebirds (i.e. plover)	Early Pliocene	E Quarry; Varswater Formation	Rich 1980, Hendey 1973
78	sandgrouse	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
79	pigeons	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
80	parrots	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
81	owls	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
82	mousebirds	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
83	rollers	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
84	kingfishers	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
85	woodpeckers	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
86	swifts	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
87	songbirds	Early Pliocene	E Quarry; Varswater Formation	Rich 1980
88	ostrich			Hendey 1975; Rich 1980
89	bony fish		Varswater Form	Hendey 1975
90	catfish			Hendey 1975
91	rays		Varswater Form	Hendey 1975
92	sharks		Varswater Form	Hendey 1975
93	skates		Varswater Form	Hendey 1975
94	geckos			Hendey 1975
95	giant tortoises		Varswater Form	Hendey 1975
96	lizard		Varswater Form	Hendey 1973
97	monitor lizard			Hendey 1975
98	snake		Varswater Form	Hendey 1973

APPENDIX B: GIS CARTOGRAPHIC BACKGROUND

Projection information:

Transverse Mercator 19E
WGS 84
False easting: 0
False northing: 0
Scale factor: 1

TOPOGRID COMMANDS

Base layer	**Elandsfontyn Formation**	**Varswater Formation**	**Langebaan Formation**
:topogrid base100 100	:topogrid ef100 100	:topogrid vars100 100	:topogrid lang100 100
:boundary coast_cov	:boundary coast_cov	:boundary coast_cov	:boundary coast_cov
:contour base_cov id	:contour ef_cov id	:contour vars_cov id	:contour lang_cov id
:datatype contour	:datatype contour	:datatype contour	:datatype contour
:enforce off	:enforce off	:enforce off	:enforce off
:margin 100	:margin 100	:margin 100	:margin 100
:end	:end	:end	:end

GRID COMMANDS

```
:if (base_efmask ==1) base_ef100 = base100 + ef100
:endif


:base_efall = con(base_efmask ==1, (base100 + ef100), base100)


:if (vars_mask ==1) base_ef_vars = base_efall + vars100
:endif


:if (vars_mask ==1) all3 = base_efall + vars100
:else if (vars_mask ==0) all3 = base_efall
:endif


:if (lang_mask ==1) all_lang100 = all3 + lang100
:endif


:if (lang_mask ==1) all4 = all3 + lang100
: else if (lang_mask ==0) all4 = all3
:endif
```