A Collated Digital, Geological Map Database for the Central Namaqua Province using Geographical Information System Technology.

Thesis submitted in fulfilment of the
requirements for the Degree of
Master of Science
of Rhodes University,
Grahamstown

by

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February 1996

Abstract

The geology of the Namaqua Province is notoriously difficult to map and interpret due to poly-metamorphic and multiple deformation events and limited outcrop. Current maps of the Province reflect diverse interpretations of stratigraphy as a consequence of these difficulties.

A Geographic Information System is essentially a digital database and a set of functions and procedures to capture, analyse and manipulate spatially related data. A GIS is therefore ideally suited to the study and analysis of maps. A digital map database was established, using modern GIS technology, to facilitate the collation of existing maps of an area in the Central Namaqua Province (CNP). This database is based on a lithological classification system similar to that used by Harris (1992), rather than on an interpretive stratigraphic model.

In order to establish the database, existing geological maps were scanned into a GIS, and lines of outcrop and lithological contacts were digitised using a manual line following process, which is one of the functions native to a GIS. Attribute data were then attached to the resultant polygons. The attribute database consists of lithological, textural and mineralogical data, as well as stratigraphical classification data according to the South African Committee for Stratigraphy (SACS), correlative names assigned to units by the Precambrian Research Unit, the Geological Survey of South Africa, the Bushmanland Research group and the University of the Orange Free State. Other attribute data included in the database, are tectonic and absolute age information, and the terrane classification for the area. This database reflects the main objective of the project and also serves as a basis for further expansion of a geological GIS for the CNP.

Cartographic and database capabilities of the GIS were employed to produce a collated lithological map of the CNP. A TNTmips™ Spatial Manipulation Language routine was written to produce a database containing two fields linked to each polygon, one for lithology and one for a correlation probability factor. Correlation factors are calculated in this routine from three variables, namely the prominence a worker attached to a specific lithology within a unit or outcrop, the agreement amongst the various workers on the actual lithology present within an outcrop, and the correspondence between the source of the spatial element (mapped outcrop) and the source of the attribute data attached to it. Outcrops were displayed on the map according to the lithology with the highest correlation factor, providing a unique view of the spatial relationships and distribution patterns of lithological units in the CNP. A second map was produced indicating the correlation factors for lithologies within the CNP.

Thematic maps are produced in a GIS by selecting spatial elements according to a set of criteria, usually based on the attribute database, and then displaying the elements as maps. Maps created by this process are known as customised maps, since users of the GIS can customise the selection and display of elements according to their needs. For instance, all outcrops of rock units containing particular lithologies of a given age occurring in a specific terrane can be displayed - either on screen or printed out as a map. The database also makes it possible to plot maps according to different stratigraphic classification systems. Areas where various workers disagree on the stratigraphic classification of units can be isolated, and displayed as separate maps in order to aid in the collation process. The database can assist SACS in identifying areas in the CNP

where stratigraphic classification is still lacking or agreements on stratigraphic nomenclature have not yet been attained.

More than one database can be attached to the spatial elements in a GIS, and the Namaqua-GIS can therefore be expanded to include geochemical, geophysical, economic, structural and geographical data. Other data on the area, such as more detailed maps, photographs and satellite images can be attached to the lithological map database in the correct spatial relationship. Another advantage of a GIS is the facility to continually update the database(s) as more information becomes available and/or as interpretation of the area is refined.

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Acknowledgements

The following people and institutions are thanked for their contribution to this thesis:

- My supervisor, Dr. Rob Harris, who introduced me to computer based geology, and provided invaluable input to this thesis.
- The Geology Department of Rhodes University for financial assistance in the form of graduate assistance bursaries.
- Frans and Toby for stimulating coffee break conversations about anything other than geology.

- My family for their continuous support and financial assistance during this endeavour.
- Finally, Gillian for trying to keep me sane...

CHAPTER 1

Introduction

1.1 Introduction

The purpose of this study is to collate and compile several geological maps of an area in central Bushmanland by using Geographic Information Systems (GIS) technology. The study area (fig.1.1) is the Central Namaqua Province which has important economic potential in the form of basemetal, high-grade sillimanite and sillimanite-corundum, uranium and tungsten deposits. It includes the largest continually exposed part of the Namaqua Province.

The Namaqua Province in central Bushmanland is an Early to Mid Proterozoic Province that has undergone at least four deformation events and metamorphism up to granulite facies (Joubert 1986a, 1986b, Tankard *et al.*1982). The geological complexity of the area has resulted in diverse interpretations of structure and stratigraphy by workers and organisations mapping contiguous areas. Any attempt at collating geological maps of the Namaqua Province is severely complicated by these interpretational differences.

The nine maps that form the basis of this study are those compiled by Joubert 1973a and b, Geological Survey 1972, Toogood 1976a, Strydom *et al.* 1987, Maclaren 1988a and Du Plessis 1989a. This covers an area extending from southeastern Namibia to southeast of Pofadder in central Bushmanland. Included in this area are the towns of Aggeneys and Pofadder, and basemetal mines such as those at Black Mountain, Broken Hill, Gamsberg and Putsberg.

Three tectonic Subprovinces of the Namaqua Province are represented in the study area, namely the Gordonia, Richtersveld and Bushmanland Subprovinces. These are further divided into Terranes which some have proposed to be allochtonous, namely the Aus, Pella, Okiep, Garies and Kakamas

Tectonic Subdivisions
of the
Namaqua Province

Provinces and Subprovinces

Gordonia Koras

Richtersveld Kheis

Kaapvaal Bushmanland

Cover

Structures

- - - - belt   shearzone

▲ ▲ thrust

Atlantic Ocean

Orange River

Copperton

Key to Tectonic Terranes

AT - Aus Terrane   UT - Upington Terrane

GT - Garies Terrane   VT - Viooisdrif Terrane

KT - Kakamas Terrane

OT - Okiep Terrane   WD - Wilgenhoutsdrif Formation

PT - Pella Terrane   WCB - West Coast Belt

50 0 50 100 Kilometers

Study area

Figure 1.1

Locality map for the present study area

terranes (Praekelt and Colliston 1988, Praekelt *et al.* 1986, Joubert 1986, Hartnady *et al.* 1985) (fig.1.1). According to Moore *et al.* 1990, the basement to the Namaqua Province can be divided into three regions which coincide with the three Subprovinces as defined by Hartnady *et al.* (1985). The basement to the Richtersveld Subprovince represents an active Andean-type continental margin with calc-alkaline volcanic (Orange River Group) and plutonic (Vioolsdrif Igneous Suite) rocks. The metasedimentary rocks of the Grunau Sequence in the Gordonia Province accumulated in a back-arc environment between the Richtersveld arc and the Kaapvaal Craton. The basement lithologies of the Bushmanland Subprovince are porphyroblastic and banded biotite gneisses and migmatites which are believed to represent the basement of an exotic terrane that accreted to the Richtersveld arc ca.1750Ma (Moore *et al.* 1990).

1.2. Previous work

1.2.1 Maps by Joubert (1973a and b)

The general geology of the area around Aggeneys and Pofadder was mapped in a reconnaissance style by Joubert between the years 1971 and 1972. There are two sheets, one for the Aggeneys area - S29°00' E18°30'to S29°30' E19°00' - and one for the Pofadder area - S29°00' E19°00' to S29°30' E19°30'. The maps were prepared at a scale of 1:100000. No description of the projection used is given, either on the map or the annual report (Joubert 1973c). There are tic marks at every minute interval and a fifteen minute grid of latitude and longitude lines is marked on the map.

These are primarily lithological maps with units indicated in different colours and single character codes. Outcrop boundaries are drawn in dotted lines with contacts between units in solid lines. Lines of strike, taken from aerial photographs, are also indicated. Strike and dip marks, lineation arrows and fault traces are present.

The cadastral data includes trigonometrical beacons, farm boundaries and fences, main and farm roads, and dry water-courses.

The maps share a key, which is attached to the map of the Pofadder area. Since the maps were done in reconnaissance fashion, the key is simple, with mostly lithological information. Descriptions of the units are short and only indicate the most important lithologies encountered. Further information on the geology of these areas was reported in two Annual Reports of the Precambrian Research Unit (Joubert 1971 and Joubert 1973c). Herein Joubert correlates these units with those he mapped in Namaqualand in the area surrounding the town of Garies.

These maps form the basis of further detailed mapping undertaken in central Bushmanland by Colliston *et al.* (1989), Odling (1987) and Moore (1977).

1.2.2 Map by the Geological Survey (1972)

The Geological Survey compiled a map of the area between the Orange River and the area that Joubert mapped, from work done by various geologists during the period 1941 to 1943 for the Geological Survey of South Africa. The map overlaps slightly with the two sheets by Joubert (1973a and b) in the south, which makes it easier to correlate units across that map boundary. To the east it adjoins the area mapped by Du Plessis (1989a).

The map is detailed and contains a large amount of information, both geological and economical. It was mapped at a 1:125000 scale which is a smaller scale than most of the others, but it still contains a large ammount of geological detail and is clear and uncluttered. The legend on the other hand, does not convey enough information. The stratigraphy is outdated and the lithology ambiguous. Units are colour, pattern and character coded. The character code consists of a stratigraphic string combined with a texture code - e.g. Kh2Q - Kh for Kheis System, 2 for Kaiing Series and Q for quartzite. Only two main Namaqua Province stratigraphic units are recognised, namely the Kheis System and the Richtersveld Igneous Complex, now more generally accepted as the Kheis and Richtersveld Subprovinces respectively. The Kheis System is further subdivided into the Kaiing (or Kaaien) and Wilgenhoutsdrif Series. The correlation between the rocks of the CNP and the Kheis Subprovince is severely outdated. The Kheis Subprovince is now known to be structurally and chronologically distinct

from the younger Namaqua Province (Joubert 1986b, Hartnady *et al.* 1985). It is obvious then that correlation of units across map boundaries might present an obstacle.

The structure legend is extensive, but does not include any lineation information. There is also a key to the symbols used for economical information such as mineral deposits and mines, and for cadastral data such as boreholes, fountains and trigonometric beacons.

No mention of a map projection is made on the map or accompanying report.

1.2.3 Map by Toogood (1976a)

Toogood (1976a) mapped the area north of Onseepkans, bounded in the south by the Orange River and in the north by the Nama Group rocks. Mapped areas adjoining this map are: Warmbad (Beukes 1973) to the west, mapped as part of an unpublished D.Sc thesis; Upington (Geringer 1973) to the east, also part of an unpublished D.Sc. thesis; and Dabenoris and Onseepkans (Geological Survey 1972) south of the Orange River, compiled for the Geological Survey of South Africa.

The area mapped by Toogood is irregular in shape as it is bounded only on one side by a longitude line (E 19°00'). The other boundaries are the escarpment formed by the Nama Sequence rocks in the north and the Orange River in the south. He had to use a diagonal layout which makes for a larger map-sheet than any of the other maps. The projection used for the map is not indicated and the latitude and longitudes are only indicated by tickmarks - no coordinate lines are drawn in on the map. Only one latitude line (S 28°30') is marked. The map is drawn to a scale of 1:100000.

Cadastral data includes farm boundaries and houses, farm roads, perennial rivers, and spot heights. No trigonometrical beacons are present.

In the legend the units are divided into two Groups, pre- and syntectonic, consisting of several formations. Toogood (1976b) states that no stratigraphic or structural succession is implied in the

legend. Only the quartzite (Pella Formation) is correlated with units on other maps of the Eastern Namaqua Province (e.g. Joubert 1973a and b). The various units are in different colours and patterns, and each is assigned a code, e.g. GnA for Austerlitz Gneiss Formation. The legend contains only the most important lithological information, because the map is accompanied by a bulletin containing detailed descriptions. Outcrop boundaries are marked with a dotted line and lithological contacts by dashed lines. Lineation and foliation information is clearly indicated.

1.2.4 Map by Maclaren (1988a)

As part of a study of the Pofadder Shear Zone (PSZ), Maclaren (1988a) mapped an area east of Pofadder. This map is of an area adjacent to and to the east of the Pofadder area map by Joubert (1973a, b). The scale is 1:100000 and no projection is mentioned. The latitude and longitude lines are marked with tickmarks at every fifteen minutes and the grid intercepts are marked with crosses. No gridlines are drawn in.

Cadastral data include trigonometric beacons, farm boundaries, main, secondary and farm roads, powerlines, farmhouses and dry water-courses.

The key to the map contains more information than those maps mentioned previously. The lithology is chronologically divided into periods, with the Mokolian (to which most of the Namaqua Province rocks belong) separated into pretectonic and syn- to post-tectonic units. The pretectonic rocks are placed in the Bushmanland Group. Apart from the colour scheme, a two to three character code is used to identify the units. The first character indicates the period and the rest identifies the compositional and lithological features, the fabric features and any additional features that are important in recognising the unit - e.g. Mclm is the code for Mokolian calc-silicate layered marble. The key to this code is found in the accompanying Bulletin (Maclaren 1988a).

1.2.5 Map by Du Plessis (1989a)

During 1977 and 1978 Du Plessis mapped an area east of Onseepkans as part of an M.Sc.-thesis (Du Plessis 1978). In 1989 the map, with minor changes, was reissued as an annexure to a Bulletin of the Geological Survey of South Africa (Du Plessis 1989b). On the revised map theNaros Granite has been subdivided into a leucophase, mafic phase and a main body. The Swartmodder Granite has been added and some outcrops that were originally classified as Witwater Granite have been reclassified as Swartmodder Granite.

The map was drawn at a scale of 1:50000 and no projection is mentioned. The latitude and longitude lines are drawn at fifteen minute intervals and there are no tickmarks. The area under consideration is east of the area mapped by the Geological Survey (1972) and south of that mapped by Toogood (1976a). The area to the south is covered by Maclaren's map (Maclaren 1988a).

Cadastral data on this map include secondary and farm roads, farm boundaries, trigonometrical beacons and farm houses. The map also contains geographic information on economic mineral deposits.

The geological units are differentiated on the map by patterns and not colour. The 1983 map had a text coding scheme, but in the more recent release it has been replaced with a pattern. According to the legend the lithology of the Namaqua Province in this area consists primarily of intrusive rocks, which are syntectonic, which intruded a Precambrian metasedimentary unit.

1.2.6 Map by the Bushmanland Research Group (1987)

In 1987 the Bushmanland Research Group (BRG), at the University of the Orange Free State (UOFS), released a map of Namaqualand, Bushmanland and southern Namibia (Strydom et al. 1987). This map was compiled from a number of older maps (including those mentioned above) as well as more recent and detailed work realized by the BRG in the central Bushmanland and in Namaqualand. In a paper by Colliston et al. (1989) a slightly altered version of this map is included as a figure. This revised map

is available from the Geological Department at the UOFS.

The title of the map is 'The tectonic units of parts of Namaqualand, Bushmanland and southern South-west Africa/Namibia' reflecting the more recent developments related to plate tectonic theory since Joubert mapped around Aggeneys and Pofadder. The scale is 1:250000. No projection is mentioned on the map or the in the more recent paper and revised map. The coordinate lines are drawn in at fifteen minute intervals. Sections through several pertinent units and geological structures are included on the map, and more detailed maps and sections of complex structures, such as the Dabenoris synform and the Swartberg area, are presented on the back of the map.

Cadastral information included on the map are farm houses and boundaries, trigonometrical beacons, pans and roads.

The key to the map is comprehensive and detailed as the area covered by the map is extensive. The units can be recognised by colour, patterns and a two or three character code which has the era of deposition or formation as a first character, and an abreviation of the unit name as second and third characters, e.g. Mho for the Mokolian Hotson Formation.

The main categories for the units are plutonic rocks, supracrustal rocks and undifferentiated gneisses. The plutonic rocks are subdivided into suites, gneisses and granites. The supracrustal rocks are classified into sequences, groups, subgroups, formations and members.

Structural information provided is more extensive than on the previously mentioned maps. Apart from foliation orientation data, geological contacts and faultlines, various types of shear zones such as ductile shear zones without mylonite, subvertical shear zones and shear zones with mylonite, and thrust faults are included. No lineation information is provided.

1.3. Disadvantages of a Paper Map System

The problems related to paper maps are not confined to the study of the Namaqua Province, but they are highlighted by the confusion that can arise in the study of the geological history of a complex area, because the paper maps are not always adequate to the task. The problems will be discussed in general terms first and then it will be shown how this applies to the maps used in this study.

1.3.1 Flexibility

The paper map is a static, two dimensional database representing geographical features on the surface of the earth (Burrough 1986, Marble 1990). It is static in the sense that the database cannot be updated or altered easily and this imposes a serious restraint on its usefulness. Geographical features change continuously, even though the change may often be undetectable in the framework of a human lifetime. In the case of meteorological features, for instance, these changes happen rapidly and the maps need continual updating. This is practically impossible with a paper map system.

It is not always the change in features that need updating on a map, but often it is the way they are interpreted on the map that changes. As interpretation of paradigms in science change, so also will the interpretation of geographic features. This is usually accompanied by information that becomes available with more detailed mapping. The mapping of the Namaqua Province is a good example of this type of change. At the outset of the mapping project, for instance, very few thrust faults were recognised (e.g. Joubert 1973a and b, the Geological Survey 1972, Toogood 1976a), but more recently these same areas are seen to contain several major thrust faults (Moore *et al.* 1990, Colliston *et al.* 1989, Strydom *et al.* 1987, Van Aswegen *et al.* 1987, Joubert 1986a) and a number of terranes separated by thrust faults have been recognised (Hartnady *et al.* 1985, Joubert 1986a). This change is probably due to the more general acceptance of the plate tectonic theory in the last three decades, a greater appreciation of the significance of mylonite textures, new mapping techniques in structurally complex areas (*e.g.* Colliston *et al.* 1989, Harris 1992c) and accompanying this, a more detailed knowledge of the structure and stratigraphy of the area. Another controversial aspect, in which virtually every map differs, is the stratigraphical interpretation of the lithology of the area. Therefore, as new information

becomes available, the maps need updating, but for papermaps this is an arduous task which invariably involves redrawing the map.

Joubert mapped the areas around Aggeneys and Pofadder in a reconaissance fashion so as to outline the general geology thereof (Joubert 1971). Workers like Moore (1977), Odling (1987), Colliston (1983) and Colliston et al.(1989) remapped sections within this area, in more detail and at a larger scale. In comparing Joubert's maps with these and the maps by Strydom et al.(1987) and Moore et al.(1990) the major new element that appears on these maps, excluding differences in stratigraphic interpretation, are the recently recognised thrust faults, e.g. the Groothoek and Wortel thrusts (see also Van Aswegen et al.1987, Joubert 1986a and Hartnady et al. 1985). Similar changes can be seen when comparing the Geological Survey's map with these more recent maps. The general outcrop patterns and lithology stay the same, but stratigraphic contacts, structural information and tectonic boundaries change as new information becomes available, and in order to keep geological maps useful they need to be updated regularly. In the case of paper maps this usually means redrawing and reproducing the map.

As mentioned earlier, the map by Du Plessis (1978) was reissued later with minor changes, and the map by Strydom et al.(1987) accompanied a later paper by Colliston et al.(1989, fig.2) with significant alterations. This is understandable as new information that become available should be incorporated in the maps. The problem lies in the fact that the paper map cannot be simply updated, but actually needs to be recreated in order to show these changes.

Factors discussed in the following paragraphs will be seen to be related to the static nature of paper map databases. They are inflexible and any changes made to them have to be done manually to the master film of the map and new maps must be issued. This is expensive and time consuming.

The digital spatial database is the cartographic and geographic equivalent of a wordprocessor. Changes can be made easily and efficiently to the database, resulting in an end-product that is always up to date and reflecting the scientific knowledge of the day. The spatial data is stored in computer memory as matrices, and other similar mathematical structures, of numbers and these can be manipulated in a

computer by automated procedures. Vast numbers of procedures, such as sorting and calculating, can be done to large databases, in a very short time and with a minimum of interaction with the user. The results of alterations can be displayed to the computer screen or can be printed to paper. The spatial database can therefore be seen as a template of the map, which can be altered, and a copy of the altered template can then be displayed or printed. The database can be displayed or printed as often as alterations are made, with as many copies as are needed.

1.3.2 Scale vs Detail

There is a fine line between having too little information on a map to be practically useful, and to clutter a map with so much detail that it is rendered illegible. The purpose of the map will dictate its scale and the level of detail presented on it. The smaller the scale of the map, the easier it is to make the map unreadable with excess detail.

Two maps were compiled from other maps and are at smaller scales - the Geological Survey (1972) at 1:125000 and Strydom et al.(1987) at 1:250000. These maps cover very large areas and cannot convey much detail without the sheet size being impractical. It is clear from comparing these maps with the maps from which they were compiled, that a significant amount of detail had to be sacrificed in order to prevent confusion. The original map of Du Plessis (1978), in contrast, was completed as part of an Honours-project and therefore covered a smaller area at a scale of 1:50000. Allthough it does not necessarily have more detailed lithological information than the 1:100000 maps, elements like outcrop boundaries and lithological contacts will be more accurately drawn.

According to Toogood (1976b) on p.6: ' The scale of the accompanying map ... does not permit narrow horizons of individual formations to be shown and rather than make the map illegible they have been omitted.' Some information therefore gets lost in the process of mapping. Most of the maps used in this study were compiled on a regional scale - which means that they are not detailed, but give an overview of the geology of the area. They were drawn at 1:100000. The functions of the maps by Joubert (1973a) and Maclaren (1988a) dictated the difference in the amount of information displayed on the maps, even though they have the same scale. Joubert mapped only to give an outline of the

geology of the area, while Maclaren mapped in greater detail because he needed more information to investigate the influence of the Pofadder Shear Zone on the geology of the area (Maclaren 1988a). For instance, Joubert did not make a destinction on his maps between quartzites with different textures or between amphibolite types. Maclaren distinguishes between glassy and granular quartzite units and between para- and ortho-amphibolite. It can be clearly seen from the legend on Maclaren's map that it contains more information than that of Joubert.

A database for the Namaqua Province in the paper map system will have to include all these separate maps to save as much information as possible, although this database will still not possess all the valid data that were originally gathered in the field. Thus the paper map database can soon become unwieldy and only represents a portion of the information available for an area, as the mapper must, of necessity strike a balance between scale and detail.

The term 'scale' has a different meaning to the traditional paper map scale when applied to a digital map. There are several scales to consider when dealing with digital maps. The scale most similar to that of the traditional understanding of scale is the scale at which the digital map is printed onto paper. There is also the scale at which the map is displayed on the computer screen, which is a more nebulous term, since this is continually changing as the user investigates the map. A small section of map can be selected to be displayed at the size of the screen, or the whole map can be made to fit the size of the screen. Since the level of detail is a function of the scale of the map, it will also change. The user can select a scale at which to display the map so that the maximum detail is available without making the map illegible. This aspect of a digital map makes it possible for the geologist to add all the information, gathered in the process of mapping, to the map without confusing the user of the map with too much detail. The size of the database is only determined by the capabilities of the hardware and software, which are currently capable of managing vastly more data than any paper map.

1.3.3 Accuracy

In the process of making and producing a map, it is understandable that errors will be made. These errors create a degree of inaccuracy in the maps and when they are recognised, the maps need to be

rectified, and once again the paper map is very inflexible in this respect. Often if the accuracy of a map is in question, the map data becomes useless and it is necessary to redo the whole map.

For example, in the case of the Onseepkans map by Toogood, there is no way to assess the positional accuracy of the map short of visiting the area with a Global Positioning System, since only one latitude line is indicated on the map and the projection is not specified (Toogood 1976a). By using the computer methods discussed in chapter 3 this problem was partially circumvented (refer to chapter 3 section 3.2.3).

On the Strydom *et al.* (1987) map, in the Onseepkans area, there is a marked disparity between the geological map and the 1:50000 topographic map, concerning the position of the S 28°45' latitude line and the position of the Orange River. This brings into question the overall positional accuracy of the features on Strydom's map.

The Global Positioning Systems technology makes it imperative for modern maps to have a very high level of accuracy. These systems can pinpoint a location within 100m². The positional accuracy of a geological map is of importance to a user who needs to visit a very specific locale, for instance to verify a lithological contact, to study a small structure in a complex structural terrain or to visit a sample site in an inaccessable or remote area.

Aspects of a digital map pertaining to the accuracy of a map, such as georeferencing, rectification and verification of accuracy, will be discussed in chapter three in the section on converting paper maps to digital maps.

1.3.4 Map legends and the Depiction of Lithology

A map is a two dimensional representation of geographic features in the real world. These features are depicted by three map elements, namely: points, lines and areas. Since there are only three map elements to protray all geographic features, a very wide variety of symbols, colours and patterns are

used to differentiate among them. The map legend provides clarification on these symbols, colours and patterns, as used for the features represented on the particular map. There is usually not much space for the legend, unless a separate sheet is used as in the case of the map by Harris (1992c), and the descriptions of the feature need to be concise and much abreviated. As with any symbology, a generalisation and, therefore, reduction of information is necessary to make the symbols useful. This means that some information cannot be conveyed on the map.

Most geological maps used in this study are accompanied by a text in the form of a bulletin or thesis where map features are further described, but the map by Strydom *et al.*(1987) relies only on its legend. The legend is complex and often confusing, as the descriptions of many units, as defined on the map, differ only marginally from each other. There are a number of granites that have exactly the same description, but it is not clear why they should have different names since they are often found close to each other spatially. The Oonab, Koeipoort, Naroep, Aroams, Coboop, Houms-rivier and Pelgrimsrus granites are described as:

'Leucocratic foliated granite. Consists of two phases: red-brown weathering fine- to medium-grained granite and yellow-brown weathering megacrystic granite...'

The BRG remapped large areas of the Bushmanland Subprovince in detail and discovered several thrust faults (Strydom and Visser 1986, Van Aswegen *et al.* 1987, Colliston *et al.* 1989) in the area which, according to them, subdivided the Subprovince into numerous small fault bounded terranes (Praekelt *et al.* 1986, Praekelt and Colliston 1988, Colliston *et al.* 1989). The discovery of the presence of the thrust faults in an area having a fairly well established stratigraphy (Joubert 1986b), caused them to re-evaluate the constituent formations of, and their positions in, the Bushmanland Group (Colliston *et al.* 1989), since thrust faulting causes the superpositioning of older units on younger units. The existent subgroups and formations were subdivided, separated and regrouped in different combinations, resulting in numerous formations containing very similar sequences of quartzite and schists (Strydom *et al.* 1987, Colliston *et al.* 1989). These lithological issues are discussed in detail in chapter 4.

Another problem that arises with such a comprehensive map, where so many different units are

displayed, is that many of the colours used to depict the units are so similar that those not marked with a lithological text code are frequently difficult to identify.

The key to the map compiled by the Geological Survey (1972) is not very informative as units are often described simply as schist or paragneiss, without further clarification as to what distinguish them from other schist or paragneiss units in the area. Although the map is accompanied by an explanatory text, it is cumbersome to have to refer to it in order to understand the map. The stratigraphic system used in the key differs radically from the system used on the other maps mentioned. This stratigraphic interpretation will be discussed in paragraph 3.7.

The geological history of the Namaqua Province included several metamorphic and deformation events, which makes the representation of the geological features of this area on a map an arduous task. In trying to keep his map understandable and still convey the relevant information, it was necessary for Harris (1992c) to have a separate mapsheet for the key to the map. The key is very comprehensive for the scale at which the map was drawn.

It is clear that the keys to most of these maps are not always adequate for the maps to be used to their full capacity as databases, without the accompanying texts where more information on the lithology is given. These texts (bulletins, theses and reports), while useful, is difficult to access and cross correlate to the maps, in any reasonable time frame.

Digital maps have changed the concept of a map legend completely. The function of a map legend is to define the symbols, colours and patterns displayed on the map, and to provide additional information on the features represented by these symbols. This has become all but obsolete in a digital map database since all the information is included in the database, and linked directly to the spatial elements, making the usual cartographic symbology unnecesary. The database, called the attribute database, contains all the information pertinent to a geographic feature and this information is immediately available to the user by selecting the element or feature of interest. Chapter 3 contains more information on the attribute database and ways in which this database is managed and used in the display of digital maps.

1.3.5 Availability and Durability

There are several maps of the Namaqua Province which are not freely available to everyone since they are either part of an unpublished thesis (for instance, the maps by Beukes (1973), Geringer (1973), Colliston (1990) and Harris (1992c)), or part of an exploration project by a private company.

Paper maps need to be replaced after continuous use (especially in the field) and this can be expensive or, if the map is out of print or part of a thesis, impossible. This is the case with the maps by Joubert, Toogood and the Geological Survey as they are almost two decades old. The information on the maps can still be pertinent and accurate, and any study of the Namaqua Province without the aid of these maps will be incomplete. As a purely historical record of the contribution to the South African geology made by these workers, paper maps are inadequate as they are prone to degradation unless under proper and expensive curatorship.

Large digital map databases can be stored in a very small area using relatively inexpensive computer hardware. The databases can be readily available to any number of users, depending on confidentiality of the maps and the hardware and software which is used to store the database. The most recent developement in digital cartography and GIS is the availability of digital geographic data on the international network of computers, known as the Internet. Geographical data is therefore internationally available to anyone with a computer and a link to the Internet (discussed in chapter 2).

The durability of a digital database needs a slightly different definition since a myriad of new concepts are introduced. The issue of durability depends, perhaps, on the ease with which copies of the digital database can be made. The durability of the database will depend on the durability of the hardware on which it is stored, but since it is possible to make any number of copies, paper or digital, of the database this is not necessarily the issue. Whether a digital database will last, is therefore more dependant on the storage space available, the capabilities of the hardware used to store it and the effectiveness of the curator in making regular backup copies of the database.

1.3.6 Map Analysis

Any analysis done on a paper map database is bound to be time consuming since there is no way to automate the analytical and comparative procedures and calculations. Even finding the distance between two points on a map involves a fair amount of calculation because the scale and projection of the map must be accounted for. Analyses involving lines and areas are even more complex and work intensive, such as for example determining the outcrop area of a specific rock unit, or compiling a list of units traversed by a given fault structure. For this reason spatial map analysis has not featured much in science until the recent introduction of computer technology.

Analyses involving overlaying of different thematic maps on each other, are impractical in terms of time and labour, as transparencies of the relevant maps have to be made. This means that the datasets must first be transformed to the same projection and scale. The transparent maps are then overlayed to produce a composite overlay of the relevant sites under study (Marble 1990, Burroughs 1986). These paper map techniques are still used, but due to the cost in labour and time only the larger companies involved in map analysis can afford to use it. The regular integration of different paper map datasets is therefore not practical with a paper map system. It would be useful, for instance, in exploration geology to overlay geological data on topocadastral data for planning an exploration project. Overlaying geological data on the Digital Elevation Model of an area provides a three dimensional view of an area which might be inaccessible to geologists. Another example might be to integrate geological data with aeromagnetic data to aid in geophysical studies. Currently the datasets in the examples above are available in digital format only and it is therefore necessary to have a digital map database to be able to utilise the datasets at all.

It is difficult to use paper maps as modelling tools, since it is so time consuming to alter them. Modelling consists mainly of testing the effect of change in one or more variables on other variables. Queries of the type 'what if...?' cannot be answered easily since it is implicit in a query of this kind that some form of alteration of the paper map is necessary. The effect of introducing a dam to a specific catchment area for instance, cannot be easily modelled using a paper map, but for a GIS this is a simple exercise in spatial data integration. In the case of a geological map it might be interesting to

study the effect of a shear zone on the geology of an area. In order to investigate the preshear configuration of the area, the strains imposed by the shearing need to be removed from all the rock units influenced. This procedure would be all but impossible to do on a paper map and is usually shown only diagramatically, with little detail or accuracy displayed on the diagram. Harris (1992c) presents an accurate simulation of this situation for a part of the Pofadder Shear Zone. In order to do this, however, his maps had to be specifically digitised. If digital maps were generally available such modelling would become more commonplace.

Digital map analysis will be discussed in the following chapters, as it is related to the study of the geological history of the Namaqua Province.

1.3.7 Issues specific to compiling a digital map of the Namaqua Province from paper maps

If assigned the task of compiling a regional map for the Namaqua Province from existing paper maps, a geologist is confronted with a number of key problems:

Scale and projection differences

The maps of the Namaqua Province are not all drawn to the same scale or projection so that they do not fit together like pieces in a jigsaw puzzle. The first step is therefore to convert them to a common scale and projection, which is not a simple process with paper maps.

Colour and text encoding of units

Most geological maps employ a colour coding system to differentiate units. If everyone mapping the region had used the same symbols, colours, patterns and text encoding, it would have been a matter of visually following the units across map boundaries. This is seldom, if ever, the case, and certainly presents a major problem in an area as complex as the Namaqua Province. Correlating units on the two maps by Joubert (1973) is simple since they share a legend and thus have the same colour codes. All the other maps used in this compilation differ appreciably in colour usage and it is therefore impossible to visually correlate the maps.

No easy visual correlation exists between units on the map by the Geological Survey (1972) and other surrounding maps. There are a number of reasons for this, but the most obvious are the differences in colour coding and the fact that the scale to which the map is drawn is different from the other maps. There is a significant overlap on the southern margin of the map with the northern parts of the maps by Joubert (1973a and 1973b), but even here it is very difficult to compare units (fig.1.4). Following units across the boundaries of the map by Du Plessis (1989a) is even more difficult (fig.1.5), as Du Plessis uses patterns rather than colour to depict units, and his map is drawn to a much larger scale than any of the others. A gap of seven latitude minutes between the southern boundary of Du Plessis's map and the northern boundary of Maclaren's map makes correlation of units with those on Maclaren's map impossible, especially since outcrops in this region are scarce and, generally, small (fig.1.5).

Differences in detail

A difference in detail between the maps of Joubert (1973b) and Maclaren (1988a) hamper easy correlation of units even though the colours of lithilogically similar units are very similar.The yellow coloured quartzite unit on the Pofadder map (Joubert 1973b) is subdivided by Maclaren into a glassy quartzite unit and a granular quartzite unit (Maclaren 1988a). The iron formation on Maclaren's map is also colour coded yellow. The grey gneiss unit, with minor schist and amphibolite (light blue) on Joubert's map near Nouzees, is observed by Maclaren to be ortho-amphibolite (light green) with pods of olivine gabbronorite (black, fig.1.2). On the southeastern map boundary of Maclaren's map he indicated an outcrop of para-amphibolite that is not recognised by Joubert at all (fig.1.3). The quartzo-feldspathic gneiss unit on Joubert's map is orange, but on Maclaren's map is subdivided into five units and coloured dark green.

Stratigraphic interpretation

The interpretation of the stratigraphy of the Namaqua Province has changed considerably from the first attempts to map the Province (SACS 1980). Every geological map of the Namaqua Province reveals different interpretations and new stratigraphic names and units. The Geological Survey (1972), for instance, uses an outdated stratigraphic classification for the Namaqua Province on their map, and very little information is provided on the lithology of the units. This makes it almost impossible to correlate units on their map with units on surrounding maps.

Map boundary

Map by Maclaren

Nouzees farm

Pofadder map by Joubert

Figure 1.2 The map boundary between the map by Joubert (1973), west, and that of Maclaren (1988), east. Light blue units are Nouzees mafic gneiss outcrops and green polygons are ortho-amphibolite outcrops.

Map by Maclaren

Map boundary
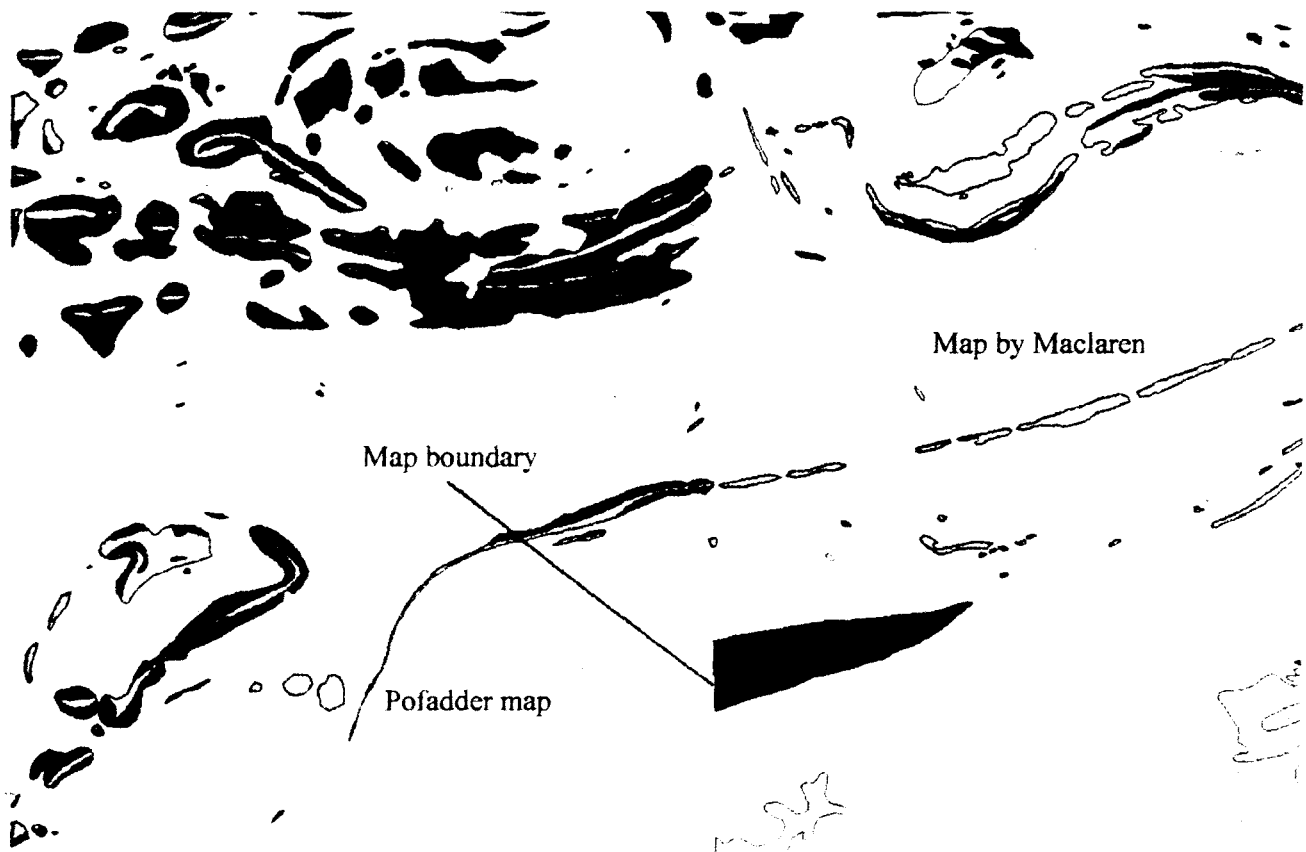
Pofadder map

Figure 1.3 Same map boundary as in figure 1.2. Notice that the amphibolite outcrop (green) is not recognised on the Pofadder map. Quartzite units just north of the amphibolite outcrop can be followed across the boundary, but it is impossible to say whether

Figure 1.4   Map boundary between the Geological Survey map and the Aggeneys and Pofadder maps.
Differences in colour coding complicate correlation between maps. Quartzite units,
for example, are indicated by completely different colours across map boundaries.
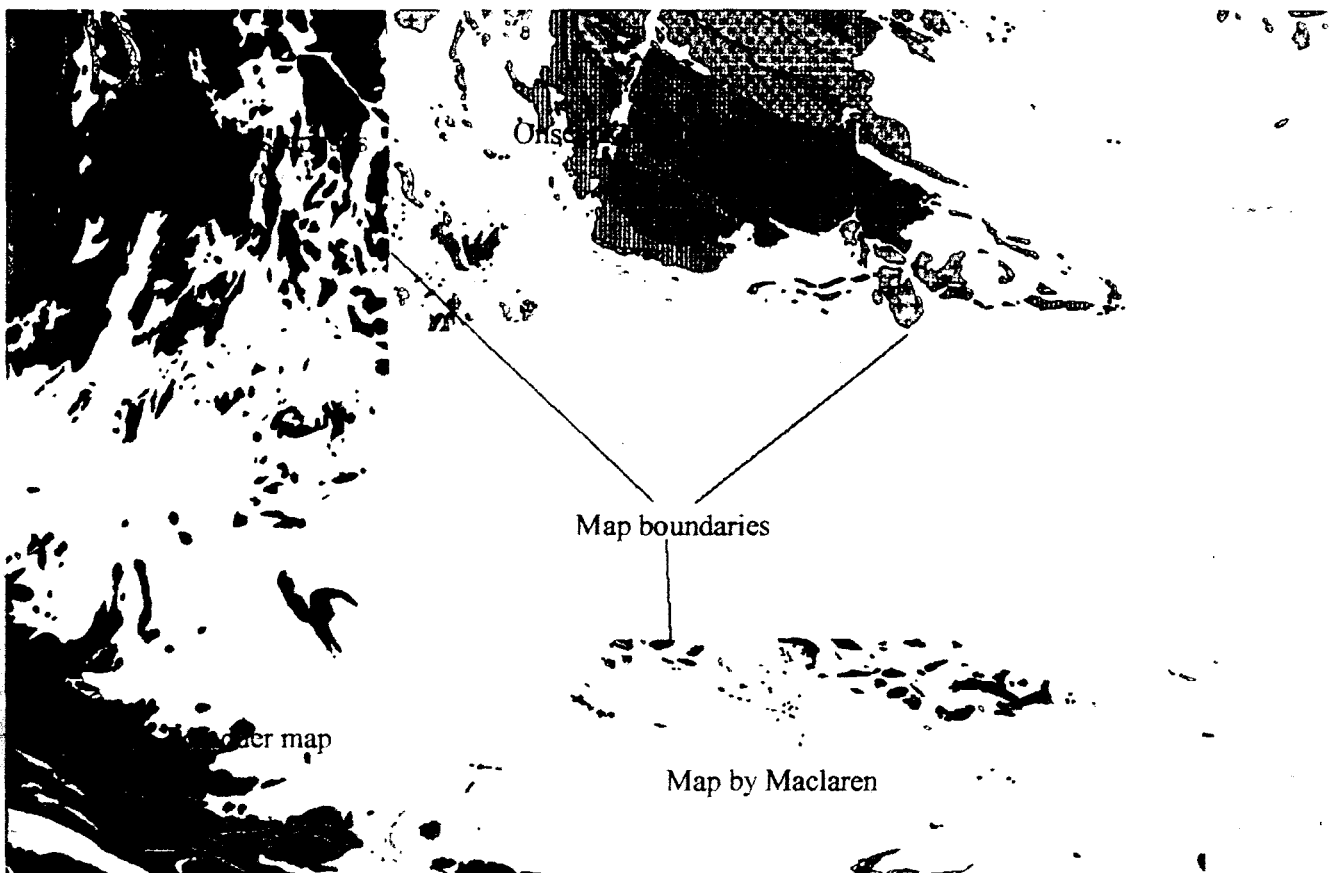
Figure 1.5   The map by Du Plessis is pattern coded only, and any unit correlation between this map
and the maps adjoining it is difficult. The gap between the map by Maclaren and that of
Du Plessis complicates matters. The lack of outcrops in the area mapped by Maclaren
adds to the problem.

1.4. Aims of the Project

This project is the initial phase in establishing a Geographic Information System for the geology of the Namaqua Province. It will include the creation of a digital map database from existing paper maps. As an example of the potential value of such a database, the data will be collated and the digital maps merged, with the aid of GIS technology, to produce a unified, lithological paper map of the Central Namaqua Province. In order to accomplish this task the following aims need to be realised:

1.4.1 To establish a digital map database of the Central Namaqua Province. The database will consist of a spatial database and an attribute database.

1.4.1.1 The spatial database will be a vector object (defined in the chapter 2) containing unit contacts and outcrop boundaries as data elements.

1.4.1.2 The attribute database attached to the spatial elements will contain lithological, textural and paragenetic information, information on tectonic terrane classification of rock units, age data where available, stratigraphic classification of units according to the South African Committee for Stratigraphy (SACS), and information on correlation of units across the study area according to various authors. The attribute data will be sought from the map legends, journals and bulletins accompanying the maps, as well as from papers written on the geology of the area.

1.4.2 To inspect the relationships existing among the various variables in the attribute database by using the database query functions and the display capabilities inherent to any GIS. The results of the queries will be displayed in the form of customised maps.

1.4.3 To use the database developed in 1.4.1 and 1.4.2 in such a way as to collate the maps mentioned earlier in this chapter, and produce a unified, digital, lithological map for the Central Namaqua Province.

CHAPTER 2

Digital Cartography and GIS Technology

Several authors have commented on the necessity of digital cartography and GIS in almost all scientific fields (Nickless and Jackson 1994, Burroughs 1986). Digital cartography is rapidly spreading to all other sciences that employ cartography in order to highlight the
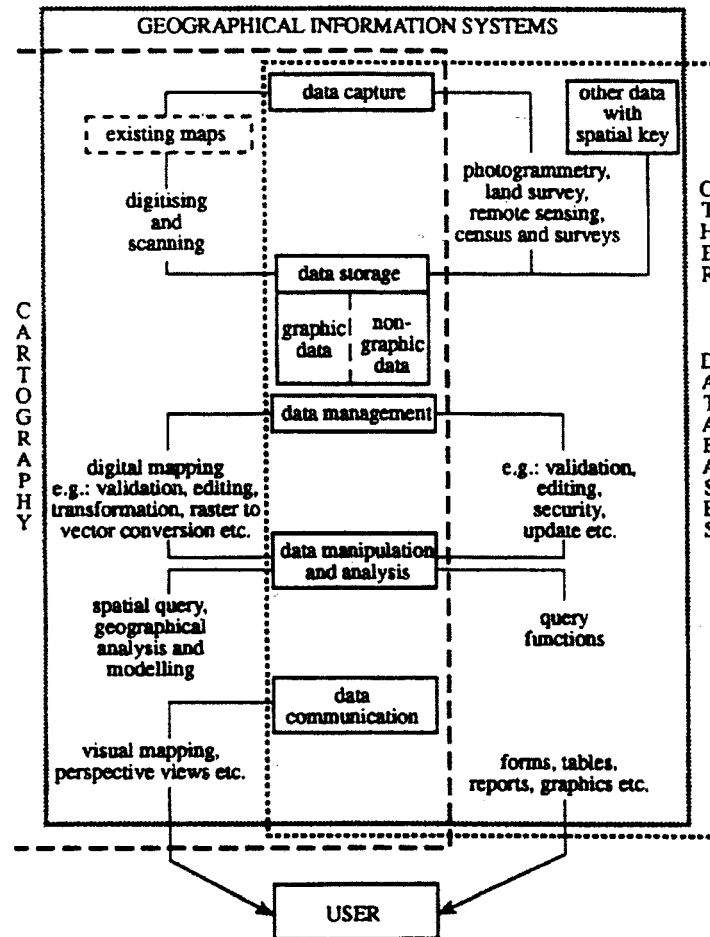
Figure 2.1 *Geographic Information Systems and their integration with cartographic and other databases, spatial and non-spatial (after Cassettari 1993).*

spatial relations that exist among their variables. There are authors who see GIS as the demise of cartography (Aangeenbrug 1991), but since the map remains an important visual tool for the display of information in a GIS, this is doubtful. The relationship between digital cartography and GIS is portrayed in figure 2.1 and is described briefly in section 2.1. Section 2.2 describes the benefits of a digital map database as opposed to the traditional paper map database (see also chapter 1). The current project focuses on the cartographic functions of a GIS that are most applicable to the collation of maps which differ in scale, detail, interpretation and accuracy. Section 2.3 discusses the relevance of using GIS technology in collating geological maps of the Central Namaqua Province.

2.1 An Outline of GIS and Digital Cartography

2.1.1 Definition of GIS

The most widely accepted definition of a Geographic Information System (GIS) is that of Burroughs (1986): '...a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world'. He adds that a GIS is a model of the real world. In testing this model under certain conditions, predictions can be made for the real world and in this sense a GIS can be thought of as a spatial decision support system (SDSS).

The one capability of a GIS that separates it from other similar digital mapping systems is what Burroughs calls the 'transformation' of spatially referenced data (Goodchild 1992, Cowen 1988, Burrough 1986). Different spatial data sets or digital maps can be integrated to produce new data and information. The integration and generation of data plays a crucial role in the process of collating geological maps. Querying the database appropriately can

reveal relationships between units at map boundaries, and these relationships form new databases which can be profitably utilized in the process of map collation.

Several thematic variables can be integrated and displayed in map form to reveal the spatial relations among them. For example, a topographic database may be integrated with a geological database to investigate the influence of geology on the topography. The new database may reveal the relationship between elevated areas and the underlying lithology, or the influence of geological structures such as folds, faults and joints on the topography.

The four essential elements of a GIS are the hardware, software, data and the users (Maguire 1991, Frank et al. 1991). The general hardware configuration of a GIS will be discussed. The software section entails a discussion of concepts such as data models and structures used in a GIS, some tools that are specific to a GIS and the database management systems that are incorporated within most GIS's. Data for a GIS are most often received in the form of maps, satellite imagery, orthophotographs and digital elevation models.

2.1.2 Hardware

Data Capture

A GIS provides a number of tools to transform spatial data of various types into digital format. Hardware associated with these tools are manual locating devices, such as digitizers, and automated devices, such as scanners.

Manual locating devices require a user to directly manipulate a device which is attached to the computer in such a way that its spatial location is known to the computer. A digitizer consists of a digitizing tablet with a grid of embedded wires, and a locational device called a cursor. The magnetic field generated by the wires enable the computer to detect the position of the cursor on the tablet.

Scanners automatically extract spatial data from maps or photographs via a photodetector or optical laser which moves across the document, discerns variations in reflectivity on the surface of the document and digitises the signal as a line or column of values. As the laser moves across the document a matrix of lines and columns of values is formed, and each matrix cell value can be spatially located by its line/column coordinate (Antenucci *et al.* 1991).

Data Storage

Geographic data is complex and requires considerable computer storage space. Hardware commonly used to store geographic data includes hard disks, erasable optical disks, digital tapes and write-once-read-many (WORM) compact disc drives. Compact Discs (CD-ROM) are now used for archiving data sets, transfering satellite images and marketing digital information. Spatial data is also becoming available on international computer networks, such as Internet, so that a single large database is accessible to multiple users simultaneously. The data reside in one or a small number of localities, but is available to many users. There are a number of such archival sites on the Internet, notably sites storing meteorological data and satellite images.

Data Analysis

Analysis and processing of spatial data involve complex and calculation intensive procedures which makes the choice of a computer a significant task - especially when time and finance are considered. Ideally a minicomputer or a mainframe computer is needed, but most GIS software packages can now be run on personal computers, although there are slight differences in processing speed. The hardware technology is advancing rapidly and the latest personal computers have the capacity to compete with most minicomputer workstations (Frank *et al.* 1991).

Output

The output can be in the form of another analogue or paper map, an image on a computer screen, a database or a text document report. The graphical nature of GIS output requires that the devices used are capable of high quality output. Output devices that are generally used in a GIS include plotters, graphic-printers and high resolution visual display units (VDU). The hard copy technology has advanced so far in recent years that near-photographic quality printing is possible. A processed photographic image can therefore be printed out in quality comparable to a photograph.

2.1.3 The Database

Antenucci *et al.* (1991) define a data base as a collective term for digital data, without any one particular structure, that can be accessed, expanded and updated rapidly. A database is a specific set of data managed by database management software. Using this definition of
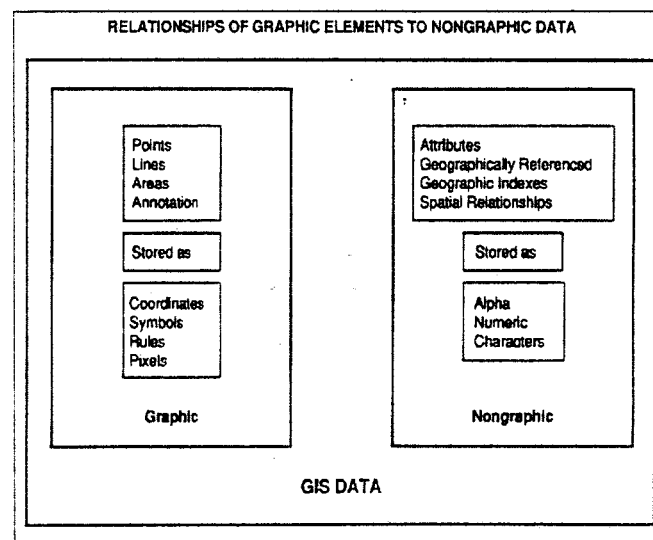
Figure 2.2 *The two data types are stored and managed in different ways by a GIS. (after Antenucci et al. 1991)*

data base, there are two major data types found in the data base of a GIS (fig.2.2, Mukund 1993, Antenucci *et al.* 1991, Burrough 1986). The graphic (spatial) and non-graphic

(attribute) data are stored and managed in different ways by the GIS. Some systems separate the management task for these two data types completely and utilise existing alpha-numeric relational Database Management Systems (DBMS) such as DBASE IV to manage attribute data and the functions of the GIS itself to manage the spatial data. Recent systems employ either a relational DBMS combined with a file system containing the spatial data or an integrated system where spatial and non-spatial data are stored in tables. Relational databases consist of tables containing spatial and attribute data, and tables storing relational information on the spatial and attribute data. Relational information includes fields for interlinking spatial and attribute data, information on relationships between various spatial elements, and relationships existing among various tables of attribute data. Accessing one data table provides immediate access, through the relational table, to related data tables. The simple task of selecting a spatial element provides access to all the other spatial elements and attributes related to it through the relational table. Spatial relationships are calculated internally by the GIS from positional information such as xy-coordinates, while attribute-attribute and attribute-spatial element relationships are provided by the user.

Spatial Data

Spatial data contained in the computer data base, represent features of the real world in digital form. A certain amount of abstraction of the real world takes place in digitising the features, and the spatial database can therefore be seen as an abstraction of the real world (Goodchild 1992, Peuquet 1990). The size and detail of the database is directly related to the level of abstraction necessary. This model of the real world can be conveniently analysed and manipulated with computer technology.

A data model is the first level of abstraction and pertains to the way in which some geographical features are perceived and conceptualised by an observer. It contains only properties significant to the observer and the way the observer will apply the data. The choice of model will depend on the application of the data, the data capturing device and the software package in use. The two major data models, used by GIS-software packages for

spatial data, are the raster and vector models (fig.2.3, Peuquet 1990). The raster data model is also known as the tesselation or grid model. A third model exists, that of Computer Aided Design (CAD), but there are doubts whether CAD-systems are true GIS, since they often do not have spatial analysis capabilities (Cowen 1988).

The size of spatial databases is such that very special and complex data structures and algorithms are required to represent and manipulate the data models (Peuquet and Marble 1990). The data model is represented in computer memory by a data structure, which contains the data entities, organised in such a way as to make access and manipulation as fast and memory efficient as possible.

Raster Data Structures

Raster data structures, used mainly for photographic and satellite images, are based on a matrix of lines and columns with values for every cell. A regular grid is therefore
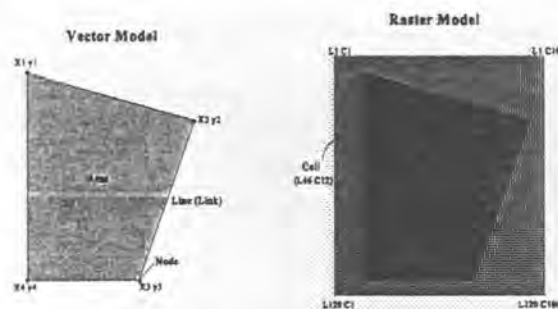
Figure 2.3 *The two data models - raster and vector. The vector model represents the relationships between lines, points and areas, while the raster model divides geographical features into cells with an attribute attached to each cell.(after Antenucci et al. 1991)*

created and geographical variation is indicated by values in the cells of this grid. The values can be colour, reflectivity or any other important geographical feature at that position, such as elevation or slope. On the computer screen the cell-values will be indicated by different colours so that changes in elevation, for instance, are shown by changes in colour. The
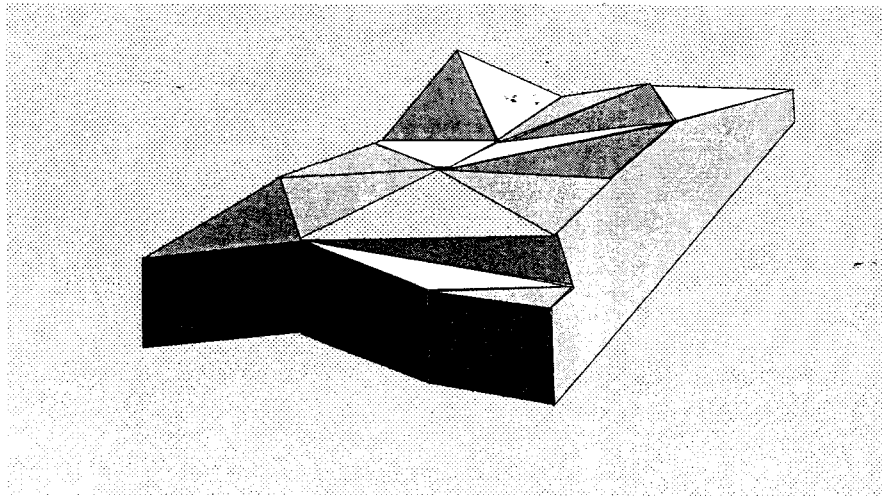
Figure 2.4 *Using a triangular grid to represent surface data (after Peuquet 1990)*

resolution of this grid will depend on the detail needed for the task at hand and also on the availability of data at that resolution. The raster is ideal for image processing and photogrammetry and as a background to a vector object. Rasters are scanned using an optical scanner, or come in digital form directly from the satellite image producers. This data structure takes up a significant amount of memory and can therefore be slow to access and analyse. Recent advances in raster data structures has improved the memory efficiency in raster data storage and the speed at which it can be accessed and manipulated.

The grid used for the raster data structure need not be rectangular, other common grids used are triangular and hexagonal. Each grid type has its own advantages. The rectangular grid is simple to implement in the array data type found in most computer languages and, since it was the first grid to be used there is a vast amount of data available in this format. The hexagonal grid has the advantage that all cells neighbouring a given cell are equidistant from that cell's centerpoint. Its radial symmetry makes for easy radial search and retrieval of data. The triangular grid, due to the irregular orientation of the triangles, is ideal for modelling terrain data such as topography and geomorphology, or geological data such as fault and bedding surface modelling (fig.2.4).
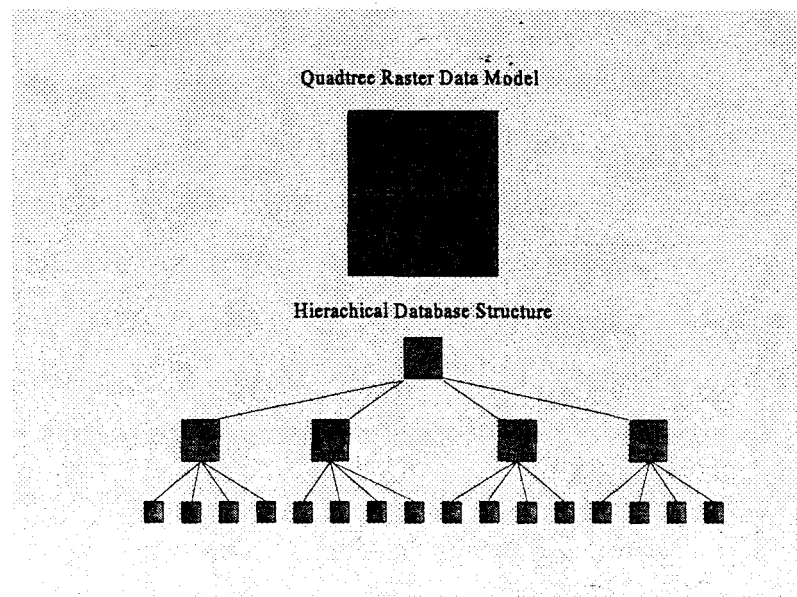
Figure 2.5 *The Quadtree Data Model is a tesselation or grid model that is structured for ease of access and manipulation. This model developes naturally into a hierachical database structure, which has been studied for purposes other than spatial database management, since years before GIS emerged as a science (after Peuquet 1990).*

Further data structures can be derived from the basic three grid structures by subdividing the regular grid into smaller cells recursively . A commonly used structure is the quadtree which is obtained by dividing a rectangular grid, recursively, into smaller rectangles (fig.2.5). This structure lends itself to a hierarchical database structure which is a very thoroughly studied structure in computer science for non-spatial databases. For a detailed discussion on further raster data structures the reader is referred to Peuquet (1990).

Vector Data Structures

The vector model most often used, is based on topology, a branch of mathematics which deals with points and lines and the relation between them. End-points and intersections of lines are recorded as nodes, and the lines as links between nodes. All relationships such as adjacency and connectivity are recorded in a relational table as part of the vector element (fig.2.6, MIPS v3.30 On-line Documentation 1992, Antenucci *et al.* 1991,

Dangermond 1990, Peuquet 1990). More storage space is necessary for this data structure than for a simple vector structure without topology, but the retrieval, analysis and accuracy of the data is better, and techniques, such as chain coding, can compress the structure for memory efficiency (Peuquet 1990).

There are further topological implementations of the vector data structure, such as the Dual Independent Map Encoding (DIME) model, but these are usually specialised for certain applications. The DIME-model is used by the US-government for storing street maps to aid in census data capture (U.S. Bureau of Census 1990). Line elements like streets, rivers, railroad lines and municipal boundaries are stored as straight line segments. A segment ends where two lines intersect or where a line changes direction. Nodes are defined at these points and at line endpoints. Line records contain adjacency and connectivity information, but in addition, a directional element is included. The two nodes at line segment endpoints are identified in the line segment record as From and To nodes. Node 1 and 2 in the Topologically Coded Network and Polygon File (fig2.6) for a DIME vector structure will become a From Node and To Node respectively. This provides a directional element to the line which can be used to check for errors and missing sections in a vector object. A census block (or polygon) is a chain of lines which can be followed around the block by matching the From node of one line segment with the To node of the next, enabling detection of missing lines or incorrect node identifiers.

Coded Network Map

Topologically Coded Network and Polygon File
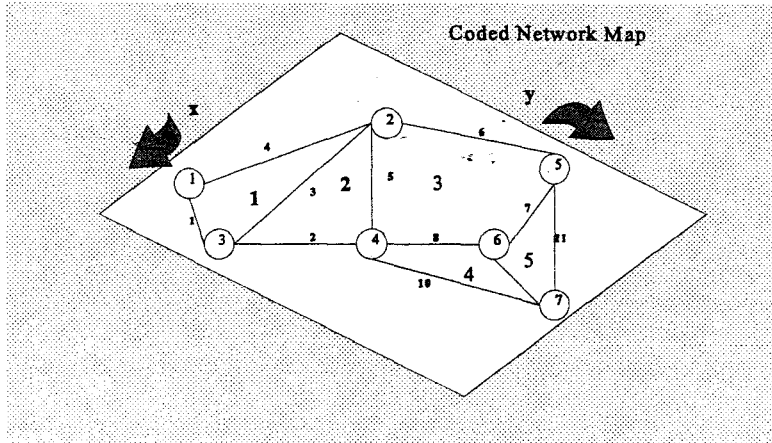
Link#	Right	Left	Node 1	Node 2
1	1	0	3	1
2	2	0	4	3
3	2	1	3	2
4	1	0	1	2
5	3	2	4	2
6	3	0	2	5
7	5	3	5	6
8	4	3	6	4
9	5	4	7	6
10	4	0	7	4
11	0	5	5	7

X, Y Coordinate Node File

Node#	X	Y
1	23	8
2	17	17
3	29	15
4	26	21
5	8	26
6	22	30
7	24	38

Figure 2.6 *The Topologic Vector Data Model and File Structures. All connectivity and adjacency information is stored with each element in a relational table. This is inspected rigorously by GIS software to ensure the presence of all vector elements and to make analysis of relationships between features possible. The topologically coded network and polygon file is a relational table for line elements in the vector object as depicted in the network map. From the table it can be seen that line 1 (or link 1) is a link between node 3 and node 1, and the polygon to the right of line 1 is polygon 1. There is no polygon to the left of line 1. The position of line 1 is from node 1 (with an xy-coordinate (23,8)) to node 3 (29,15). Only node coordinates are necessary, since the relational table describes the relationships between lines and nodes (after Peuquet 1990).*

Attribute Data

The exact way in which the data is stored and manipulated will depend on the DBMS used by the GIS-package, but these details are usually transparent to the user (NCGIA 1994). The attribute data is maintained as tabular data sets. Each data set contains records which are linked to the spatial data elements by pointers or relational tables. The records are further subdivided into fields that contain the relevant data. For example, a geological database file might contain data sets for lithology, age and geochemistry. A record in the lithology data set can have fields for major lithology, secondary lithology, texture and a reference to the spatial element(s) it is attached to, such as a polygon representing the outcrop area for that lithology. As an example of a geological attribute database the reader is referred to Chapter 3 Section 3.3 of this document.

2.1.4 Data Sources

Paper maps are the original sources of geographically referenced data, so it is understandable that maps are the building blocks of a GIS (Cowen, 1988). Other sources of spatial data that are currently used, are aerial photographs, satellite images and digital maps created by using global positioning systems (GPS). Large archival sites on the Internet are also becoming major sources of digital spatial data. Attribute data can be collected from documents, reports, field notes and from map legends. Existing data in a GIS serve also as a source for more data through overlay processes, image processing of satellite images and map analysis techniques. By processing or classifying a satellite image (refer to section on satellite imagery), for instance, a vector object indicating land use for the area covered by the image can be created, which is a new spatial database.

Maps

Paper maps are analogue spatial databases and therefore ideally suited as sources of data for any GIS. Maps are visual databases using lines, points, colours, patterns and symbols to represent features of the real world. The key, or legend, is a description of these spatial elements, and serves as a source of attribute data. Maps are scanned or digitised, or entered directly into the digital database by means of a GPS.

The present study used geological maps to establish a digital geological database of a geological province. Geological maps were scanned and outcrop areas and unit contacts vectorised[1] to produce a vector database containing outcrop and unit polygons. Attribute data was gathered from map legends, theses, map reports and bulletins.

Aerial Photography

Photogrammetry is the science of producing a map from an aerial photograph (Map fact sheet 1995). Accurate measurements of geographical features can be taken from these photographs and used on a map. The air photos are taken, in sequence, vertically from an aircraft according to a specific flight plan covering an area in parallel lines. Air photos can be incorporated into a GIS, either as photographic documents, or as backdrops to maps. If they are to be used as backgrounds to maps, it may be necessary to remove the distortion in the photograph (due to camera angle, focal length of the optical system or surface topography). Rectified air photos are known as orthophotos (orthogonal).

Aerial photographs and orthophotos can provide a GIS with elevation data from stereo pairs of photos, cadastral data such as the distribution of towns, farms, roads, rivers and dams, geological features such as lithological units, faults and folds, land use data and temporal

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[1] *Vectorisation is a process whereby raster objects are converted to vector objects. The reader is referred to Chapter 3 for a discussion on various methods available for the conversion process.*

information such as change in land use over a period of time. Aerial photos cover smaller areas in more detail than satellite imagery and are cheaper and more readily available. They are usually entered into a GIS by scanning and reside in the GIS as a raster object. There are computer processes to extract elevation data from stereo pairs of photos, and other features on the photos can be mapped by using them as backdrops within a vector creation and editing process supplied by the GIS software.

Geological features of inaccessible areas can be mapped from aerial photographs and digital mapping techniques are improving rapidly, so that subsurface and three-dimensional mapping of geological features is becoming commonplace (Slabber *in prep*). Preliminary geological mapping from aerial photographs of unmapped areas can facilitate the planning stages of exploration and mapping projects, identifying potential areas of interest.

Satellite Imagery

More recently satellite imagery has become a data source for cartography and, now, for GIS. Satellite images are digital images obtained by special sensors on a satellite, and very little conversion or alteration is needed to incorporate these rasters into a GIS. Through processing and interpretation of these images, information about the geographical features of the earth, is gathered.

Satellite images cover much larger geographical areas than standard aerial photographs, but at a smaller scale. In some cases, such as for very remote areas or politically unstable areas, they are easier to acquire than aerial photographs. Satellite images are being collected continuously, around the world, covering the same areas at regular intervals, so that enormous archives of satellite imagery exist covering every area of the globe. This data is in digital format and can be entered into the GIS directly.

Multi-spectral imagery provide new insight into geographical features and allow new quantitive methods of analysing them. A common use for satellite imagery is in mapping land use and landcover. Each cell of the image (called a pixel) is assigned a class pertaining to landcover or land use, such as vegetation type. This is done by studying the spectral qualities of a small number of pixels belonging to a class, and then assigning other pixels in the image, with similar spectral qualities, to the same class. The image can then be simplified by creating a thematic vector map from the image. Most of this process can be done through automatic routines provided by a GIS. Similar methods for geological mapping are also being investigated (Harris *pers.com.*).

Global Positioning Systems

With the aid of a number of special navigational satellites orbiting the earth, it is now possible to measure accurately the latitude, longitude and elevation of any point on the earth. This system of satellites and measuring equipment is known as a global positioning system (GPS). Since a GPS ordinarily locate points on the globe, they are invaluable for mapping point and linear features. They are, however, not limited to collecting point data, since the latest models are capable of collecting data from a moving receiver. Internal software enables mapping of polygonal features, such as geological outcrops and lithological units, so that a GPS unit can become a digital mapping unit for field work where accurate mapping is essential. It is therefore envisaged that geologists will, in future, be able to directly enter information on geological features into computer memory by mapping with GPS's connected to portable computers (Nickless and Jackson 1994). These digital maps can then be entered directly into a GIS.

GPS's are also used to accurately locate ground control points for satellite image rectification and georeferencing. Distortion in satellite images can be rectified through computer techniques requiring three or more ground control points, which are points on the satellite image corresponding to points on the ground. The image is referenced to these ground

locations and geometrically corrected to align it with these points. Chapter 3 discusses georeferencing and rectifying of spatial data.

2.1.5 GIS Software

In Antenucci *et al.* (1991) the software components integral to most GIS are discussed in detail (see also Dangermond 1990). For clarity a quick summary will be given in this section.

The software components found in a GIS can be divided in two large groups:

- the core package (graphics processing, DBMS, basic cartographic and geographical operations)
- special applications (spatial analysis and specific mapping utilities)

Core package

Graphics processing

Graphic processing components of a GIS make it possible to enter graphics, such as vector and raster objects, into the system. There are functions for editing and altering of these objects and the elements in them. Paper maps are still an important outputs from a GIS and there are facilities for printing or plotting, and the necessary software to handle quality display of graphics on a video display unit. The graphics processing unit is the spatial data equivalent to the attribute database management system.

DBMS for attribute data

Management systems for GIS attribute databases are often external to the GIS. Any DBMS such as DBase IV or Oracle can be used, as long as the GIS software can link this database to the appropriate graphical elements in the geographical database. The components of this DBMS include a data definition language in which the template data record is created. The data entry component makes it possible to fill these fields for each record. A component

for entering and processing of user queries to the database is necessary, as is software for linking records to the appropriate graphic elements.

Basic cartographic and geographic analysis

These software components control basic manipulation of maps and images, and the conversion processes between the raster and vector data types (Antenucci *et al.* 1991, see also Chapter 3, this document). Included in the cartographic analysis component are processes for map projection transformation, rubber sheeting processes (to remove distortion on satellite images and air photos; also known as warping), map merging, map overlay and mapping functions for creating thematic maps. The geographic analysis component is mainly concerned with polygon overlay procedures to answer queries of the sort: 'Which elements fall within this area?' or, 'how many of a particular element are located within an area?' Map analyses functions such as distance and size queries are possible. Buffer zone creation and radius searches are included.

Special Applications package

Special applications packages varies with the function of the GIS and may include processes for analysis of networks such as road and communication networks, terrain analysis such as topographic and geomorphological features, or surface-subsurface modelling of geological features (table 2.1).

Application Category	Specific Application
Network Analysis	Vehicle routing; water flow analysis
Coordinate Geometry	Entry of subdivision and lot lines
Terrain analysis	Slope or drainage analysis
Surface-subsurface Modelling	Mining reserve estimation; analysis of geologic structures
Engineering/Site Design	Bill-of-materials estimation; cut-and-fill analysis

Table 2.1 *GIS Applications (after Antenucci et al. 1991)*

2.1.6 Customised maps

Once a database has been established in the GIS it is possible to query the database in such a way as to create new thematic maps, depending on the themes present in the database. As a simple example, a map showing only the distribution of quartzite outcrops can be produced from a geological database of an area. It is often necessary to isolate certain fields in the database in order to investigate correlations between them, for instance the correlation between elevation and quartzite outcrops might be of interest. A map highlighting these two variables can be produced for investigation so that other variables existing in the database do not clutter the map with information which is extraneous to the solution of the defined problem.

2.2 The benefits of a digital spatial database and GIS

The advantage of digital mapping can be compared to that of digital word-processing and is most evident in the fact that alterations and updating of documents or maps can be made

easily and instantly. It is seldom necessary to redo the document from scratch, and copies can be made as often as necessary. The document that resides in the computer can be described as a template which can be edited at anytime to reflect corrections, reinterpretations and new information received. From this template copies of the maps can be made, either in the form of paper maps or as digital files on various storage media.

GIS adds to digital cartography the tools for spatial analysis and the ability to integrate various thematic data sets. Spatial analysis involves answering questions such as routing and modelling problems (Maguire 1991). Integration of spatially referenced data sets is done by overlaying different thematic maps, images and/or airphotos. For instance a geological map overlain on a satellite image depicts a geological database integrated with a remote sensing database in order to create a new spatial database which clarifies certain features displayed on the satellite image. According to Cowen (1988) spatial analysis is a special case of the integration of appropriate, spatially referenced data sets. The importance of a GIS lies therefore in its ability to integrate various spatially referenced data sets, thereby creating more data sets which can be analysed and converted to useful information. Since any GIS software package also includes a basic cartographic system it is essential for any geological research to have digital map database within a GIS environment (Nickless and Jackson 1994, Maguire 1991, Marble 1990, Dangermond 1990).

Rhind (1977) presented a list of advantages for using computers in cartography, and as technology has developed, this list has grown. The advent of GIS- and GPS-technology, and satellite imagery has also added to this list. The advantages of digital mapping can be categorised in the following manner.

2.2.1 Production of maps

The process of transforming an analogue database to a digital spatial database is still a daunting task, since the digitising of maps is an intensive manual process. This will eventually become unnecessary as most mapping projects are now done in digital form from the start, due to the rapid improvement in satellite imagery and GPS-technology, and all significant analogue maps will eventually be digitised and stored in computer memory (Nickless and Jackson 1994).

Digital maps take up a lot less space than paper maps. Compare a Digital Audio Tape (DAT) storing around one hundred and twenty 1:100000 maps in a 5cm by 3cm tape, to a map cabinet containing the same number of paper maps. Retrieval of digital maps is very fast and simple, since the database needs only to be queried by name, area, theme, etc. for the map to be located.

Once the maps are in digital format, they can be reproduced easily and as often as necessary by printing them on paper sheets. The conversion from digital to analogue maps is very simple and takes little time compared to the traditional production of a paper map. The initial cost of an appropriate high quality printer or plotter will quickly be made up for by the reduction in cost of reproducing the maps. Digital cartography puts quality map production in the hands of everyone who can afford a microcomputer and a good quality printer. This does not guarantee the quality and accuracy of the cartographer, but if the mapping was done to an acceptable standard the output can be every bit as impressive as a professional cartographic product.

2.2.2 Altering maps

As was mentioned in the first chapter, paper maps are static databases and resistant to change. In a digital map system changes can be made easily with the editing functions of the software, as this does not involve permanent ink. The changes are made to an ephemeral template in the computer memory. Updating maps is therefore simple and it is feasible to produce maps containing thematic information that changes rapidly, such as meteorological data.

Changes in scale and projection can be brought about by making the digital map available to a function or program that converts the co-ordinates in the current projection to co-ordinates in the new projection. These functions will also alter the features of the map, such as the shapes of lines and polygons, to fit the new projection. Maps of different themes can be combined by changing their projection and scales to a common scale and projection and then fitting them together, creating a composite map.

2.2.3 Data density

Data density refers to the detail level of a map, that is, the amount of information present. If this density is too great the map becomes illegible and therefore useless. It is usually a function of the scale of a map. The smaller the scale of the map, the less the detail that can be shown on it. Since a digital map is independent of scale this problem does not occur.

It is possible, with the zoom function of any cartographic software package, to select a specific section of a map and display the information for that section only. The zoom function changes the scale of the map. A small area of a map with a high data density can be selected and displayed in order to investigate the information more easily. A GIS can store and display even more information in such a way as to still make it understandable, using

processes such as data integration and hyper indexing. These GIS functions are discussed in section 2.2.5.

2.2.4 Durability

The map template can be stored on magnetic media such as DAT, hard disks and optical disks. Copies of this template can be stored on several media at once so that anyone with a copy, a microcomputer and a quality printer can reproduce the map as often as necessary. There is therefore a relation between durability and reproduction of data. Archives of original templates, under proper curatorship and management, are more durable than paper maps since it is possible to transfer templates easily from one storage medium to the other. Renewal of storage media is a matter of transferring digital data from the old medium to a new medium, which is more feasible than reproducing a paper map. The template and production of a map is not limited to large printing companies anymore and the paper map printout is the only part of the system that is not durable.

2.2.5 Benefits specific to GIS

A geographic information system extends the basic cartographic tools available to digital cartographic systems, to make spatial analysis and data integration possible (Maguire 1991, Cowen 1988, Burroughs 1986). The paper map method of overlaying is a tedious process, but with digital maps this is simple and very fast. The process is in fact a combination of several spatial databases and their attached attribute databases within the same spatial framework. By integrating the data, new spatial and attribute databases are created, which can be visually analysed as they are or which can be integrated with other databases. GIS creates new data from digital maps and as a result produces a more appropriate model of the earth than the original paper map (Cowen 1988).

Rhind (from Maguire 1991) produced a classification of the generic questions which can be answered with a GIS (table 2.2). The first two question sets involve location and condition and can be answered by using a digital mapping system since their solution involves ordinary database searching only, and no overlaying capabilities are therefore necessary. Answering the 'trend' question set involves overlaying of time variant data sets and will require GIS capabilities. Changes in variables through time can be traced by subtracting one data set from the next set in time and then creating a map from this result. Routing and pattern queries require complex network analytical functions which are only provided by GIS software packages. These functions are essential to road and communications network design. Using a GIS to model the effect that events or phenomena might have on the earth or sections thereof, transforms the GIS into a decision support system that can be an invaluable tool for management (Cowen 1988).

1.	Location	What is at ...?
2.	Condition	Where is it ...?
3.	Trend	What has changed ...?
4.	Routing	Which is the best way ...?
5.	Pattern	What is the pattern ...?
6.	Modelling	What if ...?

Table 2.2 *Set of questions that can be answered by a GIS (after Rhind 1990)*

Complex maps can be created in order to answer the above generic questions. As an example, the effects of an oil spill near a coastline can be investigated if all the necessary databases are present in the GIS. This may involve, among others, oceanographic, meteorological, zoological and ichthyological databases which provide information on the area. All these databases will be integrated by the GIS in order to reproduce as accurately as possible the real situation. Queries to this integrated database may be, for example, to show what might happen to the reef fish population in the Eastern Cape if an oil spill of a certain magnitude happens during a cold front situation of a certain severity. The answer to this

query might be a series of maps showing the decline of the fish population for the area over a number of months. These maps then also becomes part of the database.

A geological map analysis, integrating a number of databases, may be used investigate the effect of tectonic events on geological features of an area. Map analysis will involve integration of lithological, structural and age data sets. Harris (1992c) developed computer techniques accessing similar data sets, to investigate the pre-shear geometry of geological features in an area straddling the southeastern extension of the Pofadder Shear Zone, south of Kakamas. These computer routines can be incorporated into a GIS as a special applications package which can then utilise the powerful spatial database capabilities of the GIS to integrate the various geological data sets.

2.2.6 Hypermedia

The idea of non-linear (or 'hypertext' - Bush 1945) documents has been investigated for centuries, but has only been introduced to electronic based systems since 1945 (Hirmes 1993). A hypertext document consists of linked nodes, where the nodes are paragraphs or pages of text with their own links to other nodes, and the links are simply words or sentences that reference a particular node. A reader can select a link which will then transfer him to another part of the hypertext document. It is obvious that hypertext documents can become very complex networks of textual information. Any word in a document that needs defining can be made a link to a node where it is defined. If the reader knows the definition of the word there is no need to follow the link and the document can be read like any normal text document.

As computer technology improved, hypertext incorporated images, sound and video-clips as nodes in the hypertext document. Hypertext changed to hypermedia, and some GIS software packages also incorporate this as a way to manage spatially referenced databases. A basemap of an area is created with links to nodes. In GIS hypermedia the links can be any

point, line, area or even a label or symbol (such as the legend or compass). The nodes can be maps of different scale, maps depicting different themes, textual documents such as explanatory notes, theses or project reports. Satellite images, orthophotographs or photographs of features highlighted on the map may be used as nodes. Even video clips and sounds are being used as nodes. Hypermedia is a very powerful way of managing a geographically referenced database. The nodes do not all have to be located on the same storage media, but can be loaded from any number of media as the specific link is selected. It is even possible to have databases across the world that can be accessed by selecting a specific link (NCGIA 1994). This network method is discussed in the next section.

Skrdla (1992) lists a number of topics for which spatially referenced hypermedia are especially suited, such as electronic atlases, digital museums, anatomical indices and multimedia tours of countries (see also Cassetari 1993, Muller 1993, Raveneau et al. 1991). In geology this can be a very valuable educational tool. The map database, developed in this project, can be extended to a hypermedia database. Detailed, large scale maps of areas such as Gamsberg, Aggeneys, Namies and Dabenoris can be incorporated as nodes, with the collated map as a base map. Specific features of interest on these maps may link to explanatory notes and figures (sections and models), theses such as Moore (1977, 1989) and Odeling (1987), and various bulletins and reports. The text documents may contain links to photographs of specific structural or lithological features, photographs of thin sections. Hypermedia is therefore a logical way of archiving geological information of the Namaqua Province.

2.2.7 Computer Networks and GIS

The concept of hypermedia has brought about a revolution in the international world of computer networks. On these networks anyone with access can find hypermedia documents that can be read with the aid of special programs, called browsers. These documents are linked to other similar documents, databases, images, video-clips, electronic magazines and

sounds, which in turn are linked to each other and to other objects or nodes. This has created a whole new network of hypermedia objects and is known as the World Wide Web (WWW).

There are several GIS databases available on the WWW, but currently the emphasis is on the United States of America and Canada. The latest development in the science of GIS is to combine the WWW and GIS so as to have an international GIS which can be accessed from anywhere and can perform the necessary functions of a GIS on databases located across the world. At the moment there are rudimentary GIS capabilities for constructing customised maps of Canada available at the WWW-site of the National Atlas and Information Services of Canada (Newton, 1994). This program (NAISmap) is still under development, but the possibilities are impressive. Already there are several data layers available, including cadastral, geological, hydrological and environmental layers. The layers are vector objects and the custom map output is a raster file (Newton 1994).

An important function of computer networks is as an archive of digital data. Data is stored on one, or a small number, of computers, but is readily accessible to many computer users. A geological database of the Namaqua Province will benefit from a computer network, by being easily accessible to researchers of Namaqua Province geology across the country, and internationally. This will improve communication, which in turn will improve the accuracy of the database. New information, such as age data, new maps or reports can be added to the database as it becomes available.

2.3 Advantages of a Digital Map Database to Studying the Geology of the CNP

2.3.1 Introduction

The maps mentioned in Chapter 1 are the source documents for the spatial database of the Central Namaqua Province (CNP) map database. Legends, documents and journal articles accompanying the maps are sources for the attribute database. Once these databases are established and linked, the GIS will be much more than just a digital map database, due to the functions inherent to GIS software. Issues discussed in Chapter 1 concerning the specific paper maps of the Namaqua Province can then be resolved within the digital database.

2.3.2 Archive of information for the geology of the Central Namaqua Province

The digital map database will contain collated information from a wide range of sources encompassing a number of decades of research into the geology of the Namaqua Province. The spatial database will cover approximately one sixth of the outcrop distribution for the Namaqua Province at the detail level of a map with a scale of 1:100000, while attribute data will include the most up to date information on lithology, age, stratigraphy and tectonic terranes from literature concerned with the CNP. All this information will be accessible through a commercially available, reasonably priced Geographical Information System (TNTmips™), developed for use with microcomputers.

2.3.3 Selective displays and customised maps

It has been mentioned in a previous section that a digital database provides the means to select certain geological features and variables, such as specific outcrops and units, for display, without obscuring possible relations among them with irrelevant information. This is, probably, the most significant value of the digital lithological database. The map database

developed as a part of the present study will enable the user to investigate possible relations among a wide range of lithological and stratigraphical variables.

Lithological Map of the CNP

As an example, a lithological map of the CNP will be produced, by displaying only lithological information associated with outcrop polygons present in the vector object. Lithologies will be selected according to criteria stated in a query[2] to the attribute database, and vector elements (outcrop and lithological unit polygons) linked to the selected lithological data, will be displayed in a style defined by another set of criteria, in order to highlight possible relations among lithological units which might aid in correlating units across the CNP. For example, all outcrops containing quartzo-feldspathic gneiss as a dominant lithology will be displayed in orange. Outcrops meeting criteria stated in the query will be displayed on the map as orange throughout the CNP, giving an indication of the distribution pattern of quartzo-feldspathic gneiss in the CNP. Colour differences at map boundaries are therefore avoided. The reader is referred to Chapter 4 for a discussion of the lithological map and correlation issues that arose from it.

The collated map will provide a unique view of the CNP, since it will incorporate two maps not used for the compiled map by Strydom *et al.* (1987), namely Du Plessis's map (1989) and Maclaren's map (1988). There will also be no colour differences across map boundaries, so that one colour will indicate the same unit anywhere on the map. Stratigraphic differences among units will be not be indicated so that lithological relations among units can be studied.

Terrane Analysis

Elementary terrane analysis is possible by selecting a combination of lithological and tectonic terrane variables and displaying them in such a way as to distinguish terrane bound lithologies. Current terrane boundary positions, as demonstrated by Hartnady *et al.* (1985),

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[2] *Database queries are discussed in Chapter 3 Section 3.3.2 and examples can be found in Chapter 5 and Appendix C and D.*

can be investigated by displaying basement lithologies according to the terrane classification. For example, basement gneisses in the Aus Terrane can be displayed in blue, basement gneisses in the Pella Terrane in green and in the Okiep Terrane in yellow. Overlap of basement gneisses on two terranes might indicate the need for a review of the terrane boundary positions.

Stratigraphy

Lithological distribution patterns might aid SACS in classifying units in newly mapped areas. Maclaren (1988b) made no attempt at rigorous stratigraphic classification of units mapped in the area east of Pofadder, and by displaying, for instance, supercrustal quartzites in the CNP, in one colour, quartzites on his map might be correlated with quartzites on Joubert's maps (1973a and b). The quartzite units mapped by Joubert have been stratigraphically classified, albeit, perhaps, not a definitive classification (SACS 1980, Colliston *et al.* 1989). If the result of the query, therefore, indicates a correlation between quartzites on Joubert's map and those on Maclaren's, they should have the same stratigraphic classification.

2.3.4 Future Expansion of the Digital Map Database

The addition of further geological databases, will introduce new avenues of investigation into the geological history of the CNP. The spatial database could, in future projects, be expanded to include, for instance, the area mapped by Harris (1992) south of Kakamas, and other areas surrounding the present area of study, to cover the geology of the CNP at a regional scale.

The complex deformational and metamorphic history of the Namaqua Province requires that the database be expanded to include structural and metamorphic attribute data. A structural database will make three-dimensional modelling of geological features, such as the large synformal structures at Aggeneys and Gamsberg, possible. Reconstructions of pre-Pofadder Shear Zone geometrical configurations of units for the CNP could be attempted, as Harris

(1992) demonstrated for a small area south of Kakamas. Metamorphic maps can then be produced by selective display of paragenetic data in order to explore the relevance of metamorphic patterns displayed on current metamorphic maps (Toogood 1976b, Joubert 1986a).

Chapter 3

Developing a Digital Map Database for the Lithology of the Central Namaqua Province

3.1 Introduction

The creation and organization of the two major database components are discussed in this chapter. The spatial database consists of vector polygons depicting outcrops of, and contacts between, lithological units in the Central Namaqua Province. The attribute database contains mainly lithological information describing the outcrops. The attribute database has been designed with the objectives of the project in mind, but also establishes a foundation for further expansion of a geological information system for the Namaqua Province.

3.2 The Spatial Database

3.2.1 Introduction

The spatial database is established by converting the necessary spatial elements on the paper maps to their digital equivalents. This process is notoriously complicated (see Chapter 2), and will be discussed in some detail. The next stage involves the creation of an attribute database and the attachment thereof to the spatial elements. The attribute database reflects the purpose of the map database, which in the case of the present study is the collation of geological maps of an area and the production of a lithological map from the database. The emphasis is on lithological classification of units, as this is thought to represent the most objective approach.

3.2.2 The Conversion Tools

Methods for the conversion of paper maps to digital maps were discussed in chapter 2. The size of the digitizer available to this author is such that it excludes manual digitizing as a viable option for capturing the map data, since it would be a cumbersome process for maps larger than A3-size. There are several automatic processes available in the array of software tools provided by the GIS, but these can also be problematic when converting colour, geological maps. One method, that of automatic line tracing (Dangermond 1990), was tested and will be discussed. The conversion method that was settled upon is very similar to manual digitising, but is faster and more accurate, with very little post-conversion editing of the vector necessary. It involves the 'on screen' tracing of lines on a raster background, that is, manual line tracing, in the vector editing module of the GIS.

File structures in the TNTmips™ environment

A TNTmips™ RVC file contains folders with objects (raster, vector, database, CAD and/or text objects), which in turn can hold sub-objects. It is therefore possible to store all objects pertaining to a project in one large file, with folders for raster, vector, CAD and text objects respectively (Skrdla, 1991). This is risky because all the information is in one file and if the project-file becomes corrupted all information is lost. When an unstable operating system such as DOS or Microsoft™ Windows is used it is preferable to save the different object types in separate RVC files.

Scanning

Scanning is the process by which raster-objects are primarily created. An image is scanned using an optical scanner, and the product is a raster-object which is the digital version of the analogue map or image. In order to use the automatic line tracing process it is necessary to trace the lines of outcrop and unit contacts onto a glossy, A3-size, white folio with a fine, felt-tipped, black pen. Glossy paper prevents the ink from spreading and minimizes line thickness. The sheets are then scanned and raster objects created. If the map is larger than an A3-sheet, it

is possible to combine the resultant raster objects by using special raster tiling routines. The same scanning (and subsequent tiling) procedure can be employed for the colour maps, for the purposes of the manual line tracing process.

Thresholding

Part of the preprocessing of raster objects for the automatic line tracing procedure is the creation of a *binary* raster from the original raster. As was mentioned in the previous chapter, a raster is a matrix of x-y coordinates (or lines and columns) with each cell containing a value
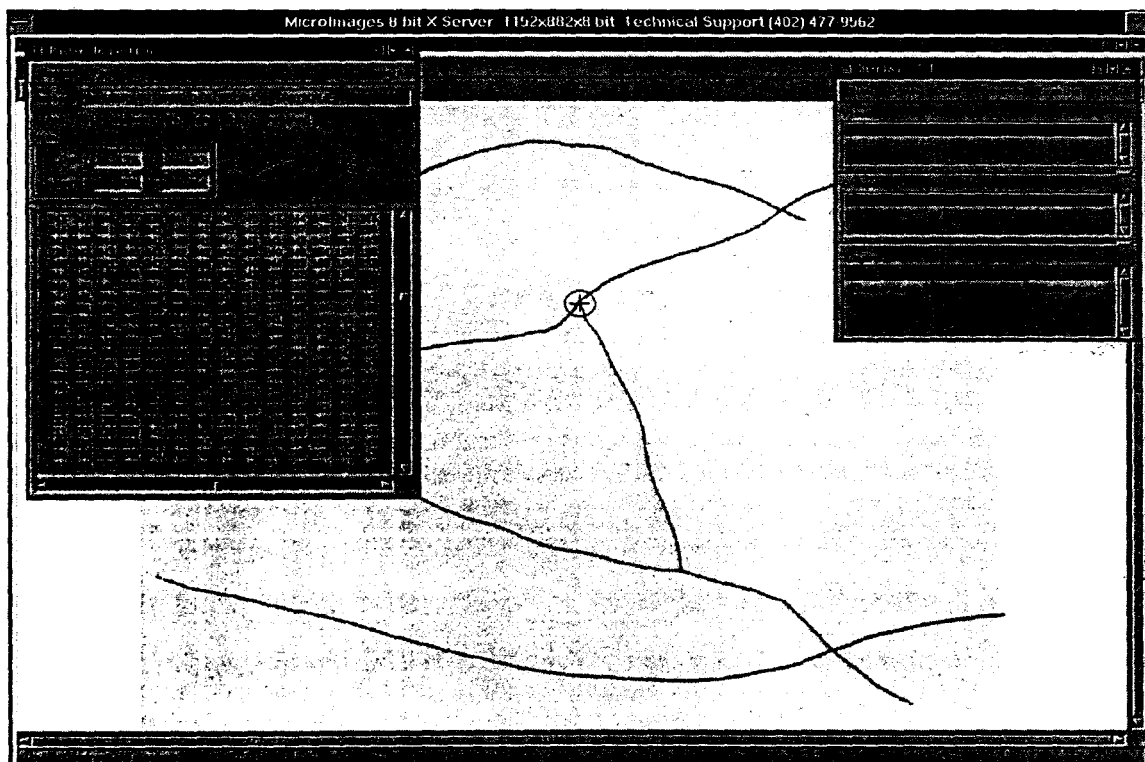
Figure 3.1a *Scanned grayscale image. A threshold value is selected by inspecting the colour values of the raster (displayed here in the Raster Inspection window on the left). The threshold value should define the lines such that when the binary raster is created, lines will be in one colour and background in another. In this case a value of 180 should be sufficient. Values above 180 will be reset to o (black) and values below 180, to 1 (white), or vice versa.*

which describes the colour and intensity of the point (or pixel) at that location. In a binary raster the cell contains only the number 1 or 0 depending on whether it is white or black, respectively. Thresholding is the process by which a binary raster is produced from an ordinary raster. Through manual investigation of the cell values of a raster it is possible to determine the cell value parameters that define the lines in a raster (fig.3.1). From this set of values a threshold
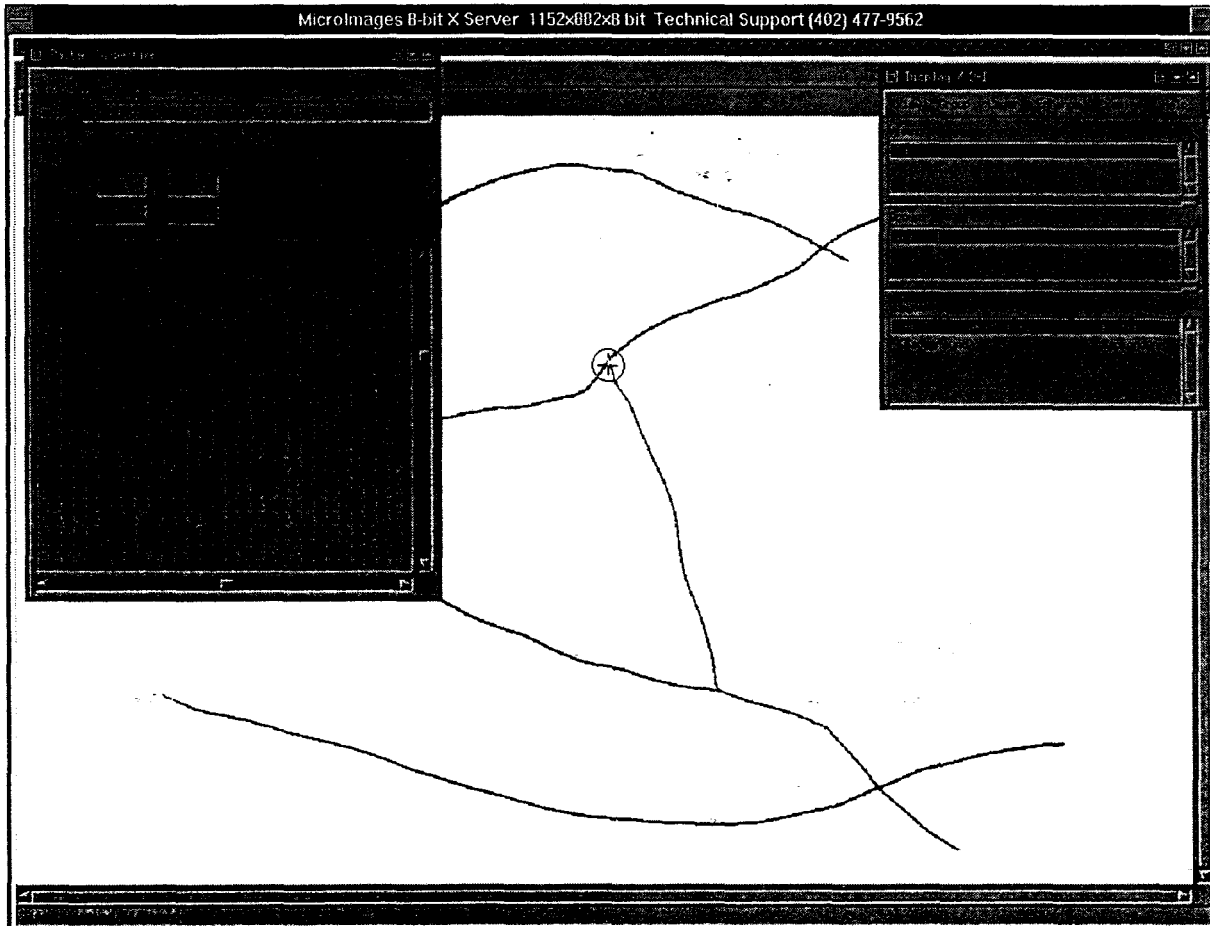
Figure 3.1b *A binary raster. The Raster Inspection window reveals the binary character of the raster. Lines are black (0) and the background is white (1). Line thickness is defined by the number of 0 values next to each other. A thinned raster line is only one value (pixel) thick.*

value is chosen for which any cells with values above the threshold value will be reset to zero and those with values below will be reset to one (or vice versa). A binary raster matrix cell will therefore contain a value of either zero or one depending on whether it is part of a line or part of the background (fig.3.1b).

Line Thinning

The thinning process removes pixels from lines until all lines are only one pixel wide
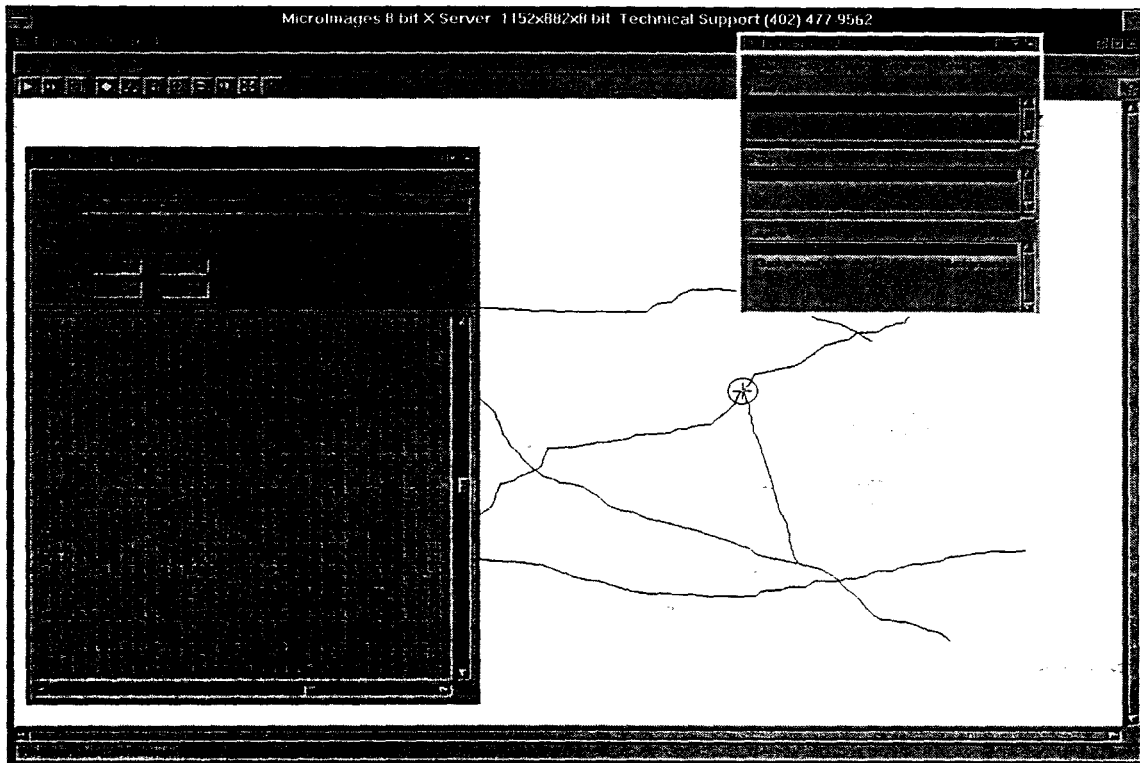
Figure 3.2 *Thinned Binary Raster Object. All lines are now only one pixel wide and the object is ready for the automatic line tracing process.*

(fig.3.2). If the original raster contained thick lines, it often happens that as a result of thresholding, lines in the binary raster may contain islands of zero value pixels. During line thinning, definite polygons are then formed around them, or a line may be split in two, forming superfluous lines. Other errors are overshoots and undershoots. These are formed in a similar way to the previous errors and cause unenclosed polygons and more superfluous line segments, usually at line intersections. These errors are then carried over to the line tracing process and excessive editing of the vector object may be needed. GIS packages such as TNTmips™ have raster editing and vector editing procedures to eliminate these defects. If manual editing is required, this can be an onerous and time consuming task. Fortunately, more up to date systems have automated elimination of defects such as undershoots, spurs and superfluous polygons.

Georeferencing

This is the process by which a raster or vector object is 'brought into alignment with some geographic coordinate system' (Skrdla, 1991). The scanned raster contains no spatial information other than the lines and columns of the matrix and the lines and columns of the computer screen. It is therefore necessary to specify the coordinate system associated with the original map. Georeferencing can be done either by aligning the raster to an already georeferenced raster or vector, or by selecting points on the raster and entering their coordinate information. Once a map projection is indicated the software can calculate a grid for that projection and then compare positions for points on the scanned image with positions for the same points on the calculated grid. The idealised grid is calculated from the map projection by using a geometric transformation model. This creates a georeference sub-object, which is then always associated with that raster or vector object. The inaccuracies of the original map - due to mapping errors, print processes - and the slight changes brought about by the scanning process can be picked up during georeferencing (fig.3.3). The position of the control points entered will differ slightly from where the points should be according to the mathematical model of that
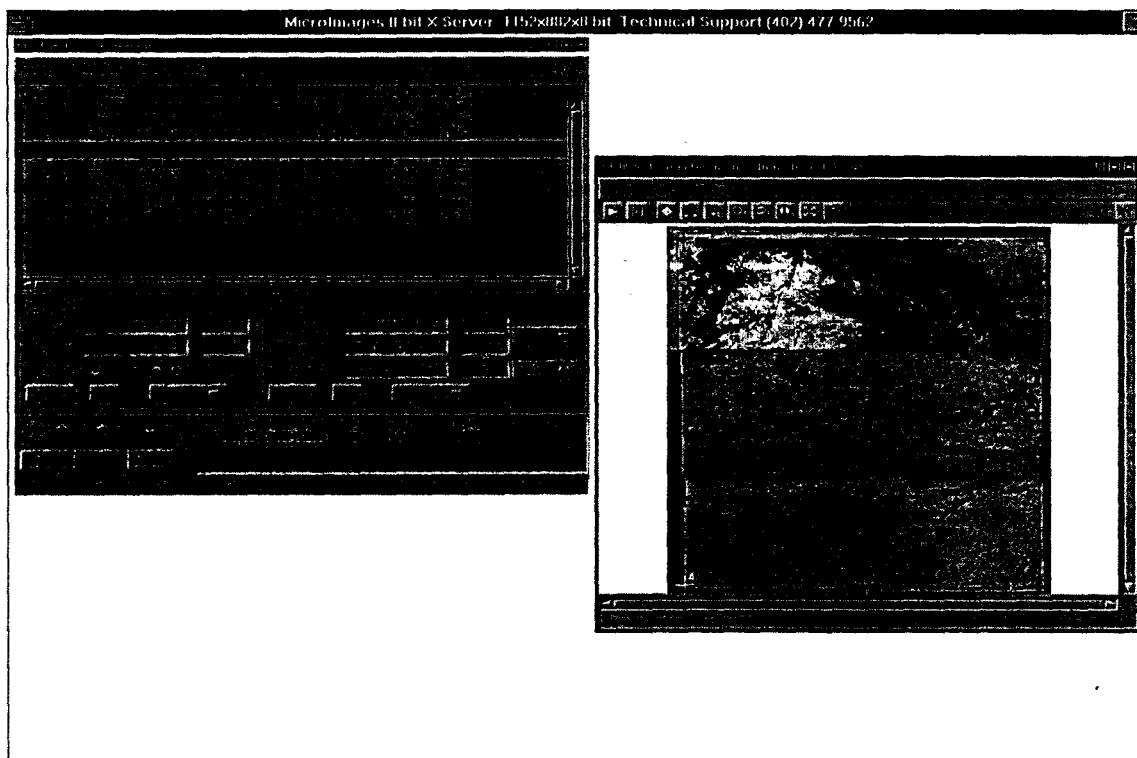
Figure 3.3 *Georeference Window. The map raster depicts the geology of the Pofadder area (Joubert 1973b). The raster was compiled by tiling A3-size scanned images of the original map. The control points are points of intersection of latitude and longitude lines (indicated by numbered crosses on the map). There was very little distortion during the paper map to raster conversion, as can be seen by the low residual values.*

projection. This error is indicated during georeferencing of the object, as residuals, and the object can then be geometrically transformed to fit the idealised grid for the map projection better. Georeference information is also used when the map projection of the image or vector needs to be changed. The georeference sub-object in figure 3.4 was created for the raster image of the Pofadder map by Joubert (1973b). After tiling (discussed in a following section) the various raster images created from scanning A3-size sections of the map, georeference window was opened with sub-windows containing the map and the empty georeference object. Control points were selected on the raster image of the map at coordinate line intersections (indicated by cross-hairs in figure 3.4), and their geographic coordinates entered.

Geometric Transformation Models and Map Projection

Map projection is the process of transforming a position on the globe to a position on a planar surface. Since the projection is from a curved surface to a planar surface, certain properties such as lengths, angles, distances and shapes are distorted. Different projection models result in distortion of different properties. A projection model minimises distortion on some properties, while causing distortion in others. Selecting the correct projection for a map will depend therefore on the properties that are important for the function of the map.

Geological maps and other thematic maps usually employ the Transverse Mercator projection, since it ensures high levels of precision for georeferencing the entire globe. The Transverse Mercator projection is a variation of the Mercator projection, which is conformal (angles are preserved), and over small areas, the shapes of objects are preserved. Coordinate lines intersect at 90° which makes it easier to present the map in the geographic (latitude/longitude) coordinate system. Areas are not preserved and distortion increases towards the margins of the map.

The Tranverse Mercator model projects points from the globe onto a cylindrical surface which touches the globe along a central meridian (fig.3.4). This line of contact is also a line of no distortion of scale. For calculation purposes an idealised shape of the earth is used - in the case
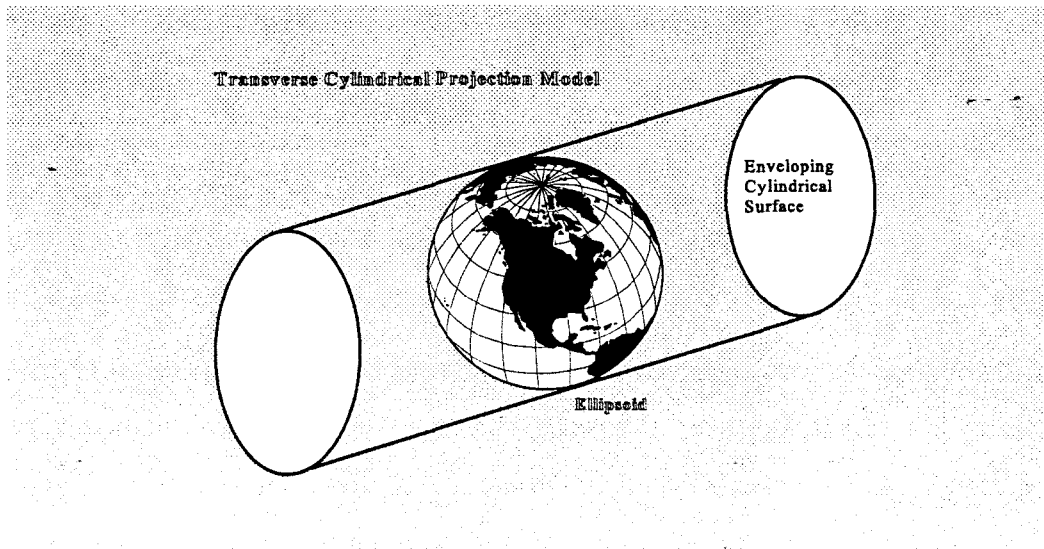
Figure 3.4 *The cylindrical enveloping surface used in the Transverse Mercator map projection. The geode used in this project is the Clarke 1880 ellipsoid (after Snyder 1982).*

of the present study, an ellipsoid used in mapping Africa, called the Clarke 1880 ellipsoid (Snyder 1982).

In changing the projection of a map, points and lines are mapped from one coordinate system onto another by geometric transformation of the coordinate system. A map is scanned into the computer as a raster object with lines and columns as its coordinate system. The paper map coordinate grid is drawn according to the map projection. The link between the raster object and the original map is the geometric transformation model. It transforms the line/column coordinate system to the map projection used in the original map. The user selects points (known as control points) on the raster object for which the map coordinates are read from the original map and entered, with the map projection, into a georeference sub-object. The georeference sub-object, therefore, contains the map projection of the original map, a number of control points and the line/column and original map coordinates of these points. The transformation model defines a surface with the coordinate information supplied in the map projection and then projects the control points in the georeference sub-object onto the surface. The residual values indicate the

difference in position of the point in the raster object from the same point in the idealised grid calculated for the selected map projection (table 3.1 to 3.3).

The two major groups of transformation models are the affine and curvilinear models. The affine transformation model is the less complex of the two, and retains parallel lines. The surface defined by the affine transformation contains orthographic coordinate lines. The curvilinear transformation models do not necessarily retain parallel lines and lines on the surface are not necessarily straight. The surface is complex and points are not transformed evenly over the surface.

TNTMIPS™ includes several geometric transformation models under these two groups. The choice of a model will depend on the distortion inherent in the digital object. Affine models are fairly simple and can be used with low distortion values. Curvilinear models are used when external and internal errors distort the object. External errors are due to the creation process of the original document, as well as subsequent processes such as scanning or digitising. Internal errors are more nebulous and include spatial distortions such as centering and scale effects.

Once the model is chosen the object can be 'warped' to fit the projection chosen. Positions of points and lines, or pixels, relative to the old coordinate system are altered to reflect the change in projection.

Table 3.1

Num	Status	Column	Line	Latitude	Longitude	Residuals (metres)	
1	A	184.25	163.75	S 29 00 00.0	E 19 00 00.0	12.07	10.998
2	A	4018.75	180.75	S 29 00 00.0<	E 19 30 00.0	-68.534	-27.485
3	A	4034.75	4536.25	S 29 30 00.0	E 19 30 00.0	-9.128	19.384
4	A	192.25	4523.25	S 29 30 00.0	E 19 00 00.0	-30.032	6.643
5	A	2114	2350.25	S 29 15 00.0	E 19 15 00.0	58.38	12.221
6	A	4034	2357	S 29 15 00.0	E 19 30 00.0	53.032	15.354
7	A	188.5	2345	S 29 15 00.0	E 19 00 00.0	-5.918	-10.238
8	A	2104	171	S 29 00 00.0	E 19 15 00.0	3.521	7.764
9	A	2114	4533.5	S 29 30 00.0	E 19 15 00.0	-13.391	-34.641

Table 3.2

Num	Status	Column	Line	Latitude	Longitude	Residuals (metres)	
1	A	184.25	163.75	S 29 00 00.0	E 19 00 00.0	-2.128	0.548
2	A	4018.75	180.75	S 29 00 00.0	E 19 30 00.0	-44.004	-2.338
3	A	4034.75	4536.25	S 29 30 00.0	E 19 30 00.0	-23.229	8.954
4	A	192.25	4523.25	S 29 30 00.0	E 19 00 00.0	-5.559	31.699
5	A	2114	2350.25	S 29 15 00.0	E 19 15 00.0	47.974	-2.489
6	A	4034	2357	S 29 15 00.0	E 19 30 00.0	58.339	0.693
7	A	188.5	2345	S 29 15 00.0	E 19 00 00.0	-0.726	-24.979
8	A	2104	171	S 29 00 00.0	E 19 15 00.0	-6.894	15.162
9	A	2114	4533.5	S 29 30 00.0	E 19 15 00.0	-23.774	-27.25

Table 3.3

Num	Status	Column	Line	Latitude	Longitude	Residuals (metres)	
1	A	184.25	163.75	S 29 00 00.0	E 19 00 00.0	12.336	-1.368
2	A	4018.75	180.75	S 29 00 00.0	E 19 30 00.0	-17.487	-14.242
3	A	4034.75	4536.25	S 29 30 00.0	E 19 30 00.0	-8.858	7.03
4	A	192.25	4523.25	S 29 30 00.0	E 19 00 00.0	20.745	19.84
5	A	2114	2350.25	S 29 15 00.0	E 19 15 00.0	7.04	11.355
6	A	4034	2357	S 29 15 00.0	E 19 30 00.0	26.142	7.101
7	A	188.5	2345	S 29 15 00.0	E 19 00 00.0	-33.162	-18.507
8	A	2104	171	S 29 00 00.0	E 19 15 00.0	5.108	15.597
9	A	2114	4533.5	S 29 30 00.0	E 19 15 00.0	-11.864	-26.806

Table 3.1 to 3.3 *Georeference control points for the map of the Pofadder area by Joubert (1973). The map projection is Latitude/Longitude and the geometrical transformation model is (3.1)* **affine planar, (3.2) plane projective** *and (3.3)* **order 2 polynomial.** *The effect of the transformation model can be seen in the residual values. The residuals are low and the affine model will be sufficient to rectify the raster object. The control points are points of intersection of the latitude and longitude lines on the map. (Num indicates the control point number. Status A indicates active control points - points used in calculating residuals.)*

Tiling

One of the purposes of georeferencing raster scans of maps is to facilitate the process of tiling. 'Tiling' is the word used to describe the procedure for aligning and joining raster images or vector objects. Maps often have to be scanned in sections since they are larger than most scanners are capable of accommodating. These rasters can be combined without using the georeference sub-object, by manually indicating to the process how the rasters fit together. The procedure would therefore be to scan a map in sections (of a size allowed by the scanner) and then tile the resultant raster objects. Once the rasters are tiled a georeference sub-object for the whole map can be created by using the coordinate points indicated on the maps as intersections of coordinate gridlines.

If maps of different scales and map projections need to be combined it is necessary to georeference them first. Tiling rasters or vectors using the georeference information is done automatically if the map projections are the same. The objects therefore need to be converted to a common map projection before they are delivered to the tiling procedure. If the objects fit the calculated grid for that map projection well, the tiling should create a raster or vector object with no gaps or overlaps.

3.2.3 Conversion Processes used in this project

Automatic Line Tracing

The software provides a number of features for automatic raster to vector object conversion. Not all of them are applicable to the conversion of thematic, in this case geological, maps. The automatic line tracing process converts binary, thinned rasters to topologically correct vector objects.

The map of the Onseepkans area, by Toogood (1976), was converted using the automatic line tracing process. Lines of outcrop and unit contacts were traced onto A3-size folios, concentrating on making the lines as thin as possible. Four sheets were then scanned and entered into the spatial database as raster objects. The raster objects were transformed into binary rasters and then thinned.

Georeferencing the map posed special problems, since there is no mention of the map projection used on Toogood's (*opp.cit.*) map, and only one latitude line is present on this map. The positions of the S 28°15', S 28°45' and S 29°00' latitude lines had to be calculated and drawn in on the original map. The coordinate points where these lines intersect with the E 19°00' and E 19°30' longitude lines were used as control points for the raster objects. Tiling the raster objects revealed the inaccuracy of this method and it was decided to combine the objects manually since there was sufficient overlap on them. Georeferencing the combined raster proved easier but, as was learned later, no more accurate. This problem highlighted the need for compilers of paper maps to ensure that projection information is given and that adequate coordinate data is plotted on the map.

The automatic line tracing process produced a vector object from the raster, but the result was far from ideal and editing of the lines and polygons was necessary. Common errors were overshoots and undershoots, spurious polygons and lines, and areas that were not enclosed entirely. All these elements are usually quite difficult to rectify as they are small and hard to find. Another problem that arose, albeit perhaps not crucial, was the ragged shapes of the lines and polygons, such that when overlayed on the original map raster, the elements did not always fit well, and a map produced from this vector might not meet the aesthetic standards of cartography. Considerable time was spent editing and repairing these errors.

Manual Line Tracing

The automatic line tracing was done using the MIPS v.3.00 software and the recent version of this process is more effective (TNTMIPS™ Version 5.2). Unfortunately the appropriate software was unavailable at the time of conversion and the manual line tracing method was decided upon, mainly because it is accurate (as accurate as the original map and scanning thereof allows), moderately fast (certainly faster than manual digitising) and requires very little subsequent editing. It is still slower than the automatic process and requires excessive amounts of computer memory for the raster objects.

The original maps were scanned as low resolution (75 dpi) colour rasters in A3-size sections to save space. The sections were manually tiled before georeferencing, using tie-points on

overlapping areas. The combined raster objects were then georeferenced to the original map latitude and longitude coordinate systems. All the maps showed residual values of less than 100 metres (equal to a 1mm inaccuracy in position when plotted at a 1:100000 scale) and could therefore be safely transformed by using the affine transformation model.

The vector editing window was then used, with the raster object (map) as a backdrop, and the lines of outcrop and unit contacts were drawn in as vector lines using a locating device (mouse) to trace along lines on the displayed raster map. The georeference information of the raster object is retained in this process, being automatically transferred to the newly created vector object. This method is accurate since it is possible to select a small enough area of the raster to work on, using the 'zoom'-function, so that lines on the raster are wide enough to trace comfortably and precisely.

The vector objects, created from the various source maps, were then geometrically transformed to a common map projection, the Transverse Mercator projection (fig.3.5), in order to combine them in the vector tiling process. Before this was done, however, the points of intersection of the latitude and longitude lines on the original maps were entered into the vector object as nodes. These were used to determine the accuracy of the final combined vector map.

All the vector objects can be combined simultaneously or sequentially. Sequentially means that two vector objects are combined, and then a third one is added to the combined vector object and so on. This has the advantage that it is easier to pick up any errors, since a large vector object can be labourious to investigate. The easiest way to calculate the accuracy of a combined vector object is to use the coordinate nodes. Nodes on different maps indicating the same coordinate point should lie on top of each other in the combined map, and the distance between the nodes will give an indication of the accuracy. Most maps showed an accuracy of less than a hundred metres. The map by Toogood (1976a), however, showed a latitudinal shift of over a ten kilometres, compared to positions indicated on adjoining maps. This was obviously caused by the lack of projection and coordinate information on the map and/or a north-south distortion in the paper map.
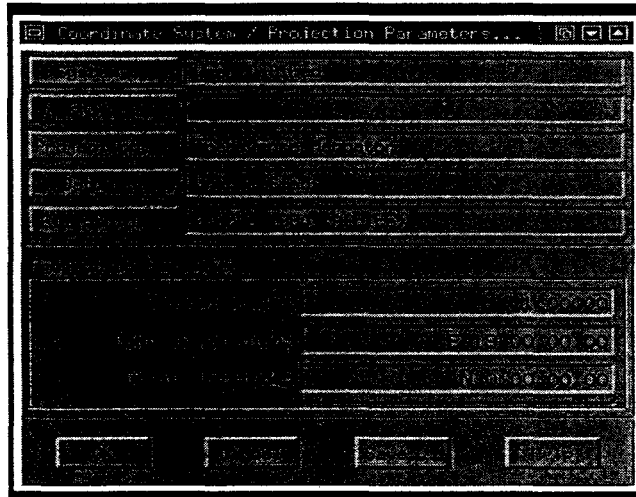
Figure 3.5 *Transverse Mercator Projection for the Central Namaqua Province.*

Control points for a new georeference sub-object for the vector map, covering Toogood's (*opp.cit.*) were collected from a topographical map sheet (Upington 1:500000 SE29/18) covering roughly the same area. At first points of intersection of the Orange River with other rivers recognizable on both maps were used, as they were the only features represented on both maps. The transformation models could not compensate for the linearity in the spread of control points, and although the vector object did fit better than before, more corrections were needed.

To overcome this problem, a satellite image of the area was scanned (digital data was not available), georeferenced to topocadastral maps of the area, and rectified for distortion. The composite vector object was georeferenced to the image by using points and polygons (visible outcrops) recognizable on both the vector and the satellite image. Outcrop polygons were stretched to fit the visible outcrops on the image by creating tie points (points tying together elements of the vector object and the image). This improved the fit of the whole vector object considerably. Unfortunately the satellite image only covers a part of the total mapped area and areas to the east (Du Plessis and Maclaren) are not included. The distortion of the composite vector object in these latter areas is therefore still unknown and a satellite image covering the whole area will be needed to reach the desired level of geographic accuracy. Inaccuracy is clearly visible when studying the width of the Orange River in the Dabenoris area which forms the boundary between the maps of Geological Survey (1972) and Strydom *et al.* (1987).

Final editing of the combined vector object was then completed, which involved the removal of excess lines formed at map boundaries where slight overlap occurred. The spatial database for the purposes of the current project was now complete and the next step was to attach the attribute database.

3.3 The Attribute Database

3.3.1 Introduction

The attribute database design is critical in that it should contain all the information necessary to fulfill its purposes, and be structured in such a way as to make access and analysis of the data simple and fast. The exact purpose of the database should be made clear before the database can be designed (Antenucci *et al.* 1991). The limits of the data manipulation language and hardware should be taken into consideration. Attribute database design is therefore often an exercise in predicting the future use to which the GIS will be put.

The main purpose of this project is to create a digital geological database to aid in collating the existing maps of the Central, and eventually the whole, Namaqua Province using GIS technology. A collated lithological paper map of the CNP is produced using the database. This objective is reflected in the design of the attribute database.

Previous mapping included considerable stratigraphic interpretation. Since each research unit had its own model according to which it interpreted the geology of the area, a large number of stratigraphical names exist for units with similar lithological compositions. It was therefore thought appropriate to use a more independent variable in correlating units on the various maps. Possible independent, objective variables are directly observed properties of the rocks, such as mineralogy, texture and lithological makeup. Subjective interpretation is restricted to a minimum, if these variables are used to describe the units.

The spatial database contains unit contacts and outcrops in the polygon vector element form. Lines and points are not considered in this project except possibly to indicate landmarks such as

towns. The attribute database is therefore attached to polygons and describes mainly the lithology of units represented by the polygons. The database is subdivided into nine data tables:

Class - the list for the classification of polygons, using a broad lithological classification, such as granites, pelitic schist, psammitic schist or quartzite.

Originfo contains information from the original map legends, such as lithology and stratigraphy, for each polygonal area.

Lithbase - a table containing fields for five major lithotypes, textures and mineral assemblages occurring within an outcrop polygon. This information was gathered from map legends, journal papers and theses.

Tectobase indicates whether a unit is part of the basement, or the supracrustal layers, whether it is intrusive or extrusive, whether it is migmatised or if it is tectonic in origin (e.g. mylonite).

Correlbase is a data table useful in correlating units across map boundaries - it contains the different unit names used by the major research units in the area - UOFS, PRU, SACS and the Geological Survey.

SACSbase - SACS stratigraphical information for units.

Divbase - data table for the tectonic subdivision of the area into terranes and subprovinces.

Chronobase- table with age information. Relative age information (syntectonic, post-tectonic or pre-tectonic) and absolute ages are entered where these data were available.

Mapbase contains a pointer which indicates on which paper map the polygon (or outcrop) is found. This data table is useful in calculating the correlation probabilities discussed in Chapter 4.

3.3.2 The Attribute Database Management System (DBMS)

Display

Although not strictly part of the attribute Database Management System (DBMS), the display functions for vector objects are closely linked to the attribute database. Each spatial

element in the vector object can be displayed in a manner that reflects the attribute data associated with it. The way in which a vector element (line or polygon) is displayed includes colour and patterns and is called its display style. Line thickness, colour and pattern and the fillcolour and fillpattern are with which polygons are drawn are variables that can be altered by the user. Point features can be displayed as symbols, in different colours and sizes. The display style can therefore be customised to fit the purpose of the map that is displayed.

There are two ways of configuring the display properties of data elements. The first employs the classification database whereby a style is associated with every class of element. The style is predefined according to a key field (simply defined as an important field - MicroImages 1995) in the database. Any database containing a key field can have a predefined style for the vector elements. The other method is to display selected vector elements according to styles specified in a database query. Predefined display styles are stored as a part of the attribute database. The attribute DBMS therefore specifies which elements in the spatial database are to be displayed and how they are to appear.

Data Tables and Forms

TNTMIPS™ provides several options for organising the attribute database. It can either be done by commercially available DBMS external to the software package, an external version of the TNTMIPS™ attribute DBMS or a DBMS internal to the software package. This project utilised the internal DBMS, since it was more convenient for attaching the attribute database to the spatial database.

The data definition language of the DBMS makes it possible for the user to create a template of a database table. In the template the characteristics of the data fields are defined, for instance the data type (character, string, integer or logical), data field sizes and data field names necessary to manage the attribute data (Antenucci *et al.* 1991). The template data table for a geological database may contain fields for the unit name, lithology and age. This template is called up and displayed in a window by the software every time attribute data is to be entered, linked, edited, queried or examined. A particular record with data can be selected and displayed by record number or by selecting a vector element to which the record is attached.

The display of attribute data is configurable through a DBMS function, namely a data form. Selected fields from a data table can be displayed in a freeform way and it is therefore possible for other users of the data base to customize the display of the attribute data in a way they find convenient (TNTmips™ Online Manual).

Attaching an Attribute Database

Attaching a record to a vector element means that a link is established between the vector element and the attribute record, and therefore between the spatial and attribute database. This link is usually saved in a relational data table containing data on the features to which the link pertains and also on the relationships existing between the spatial data and the attribute data. The link is formed by selecting a vector element, filling in the attribute data table with the attributes of the vector element and then selecting an 'attach' process.

Attribute Data Manipulation

A user accesses and manipulates data through the DBMS data manipulation language. This is an easy-to-use query language by which data can be accessed in a logical fashion (Antenucci *et al.* 1991). The user can design criteria according to which the DBMS then searches the database. In such a way a geological database can, for example, be queried on lithological criteria, to show all instances of a particular rock type. The language also makes it possible to make more complex queries. An example of a database query can be seen in figure 3.6.

3.3.3 Description of the Attribute Data Tables

Class Data Table

A GIS is a digital model of the real world and the elements of a GIS are representative of objects in that world, the same as graphicelements on a map are symbols depicting objects in the real world. The legend on a map indicates to the user what the symbols define. In a GIS the legend is incorporated in a class list which contains the different classes into which the elements are categorised, as well as the style in which each class of element is to be displayed. Each element

is provided with an attribute. The classes used in this project all pertain to polygons which represent outcrops of lithological units. The class list therefore contains the unit lithologies found on the keys to the paper maps (table 3.4).

Class List

Header Lines: 6
Desc: Classes from RVF

Fields: 1
Name: Class   Type: Char   Start: 1   Length: 79

Unclassified
Granitic
Calc_Silicate
Superficial_Deposits
Quartzite
Quartzo_Feldspathic
Pelitic
Psammitic
Amphibolite
Mixed
Migmatitic
Mafic
Kimberlite
Pegmatite
Mellilite
Granite
Quartz vein
Unknown Lithology
Marble
Granodiorite_Tonalite
Diorite
Karoo-cover
Karoo-dolerite
Iron Formation
Tillite
Shale
Mylonite
Nama-cover
Granodiorite
Charnockite
Leucogranite
Aplite
Ultramafic

Table 3.4 *List for the classification of polygons in the Namaqua Province vector object. The list, combined with the Style object defined for the list, is similar to the key of a paper map.*

The vector edit process can be configured so that when a vector element is entered, the computer will prompt the user for a class name for that element and a selection can be made from the class list if it exists. The classification can also be done after the vector object has been created by selecting polygons and then assigning classes to them. The class list shown in table 3.4 is a

general list of lithologies encountered in the central parts of the Namaqua Province and was used only as an initial list which was later surpassed by the more comprehensive lithological database.

Origininfo Data Table

This data table can be used to produce maps similar in style to the original paper maps. It contains information derived directly from the paper map legends, in the form of the name that
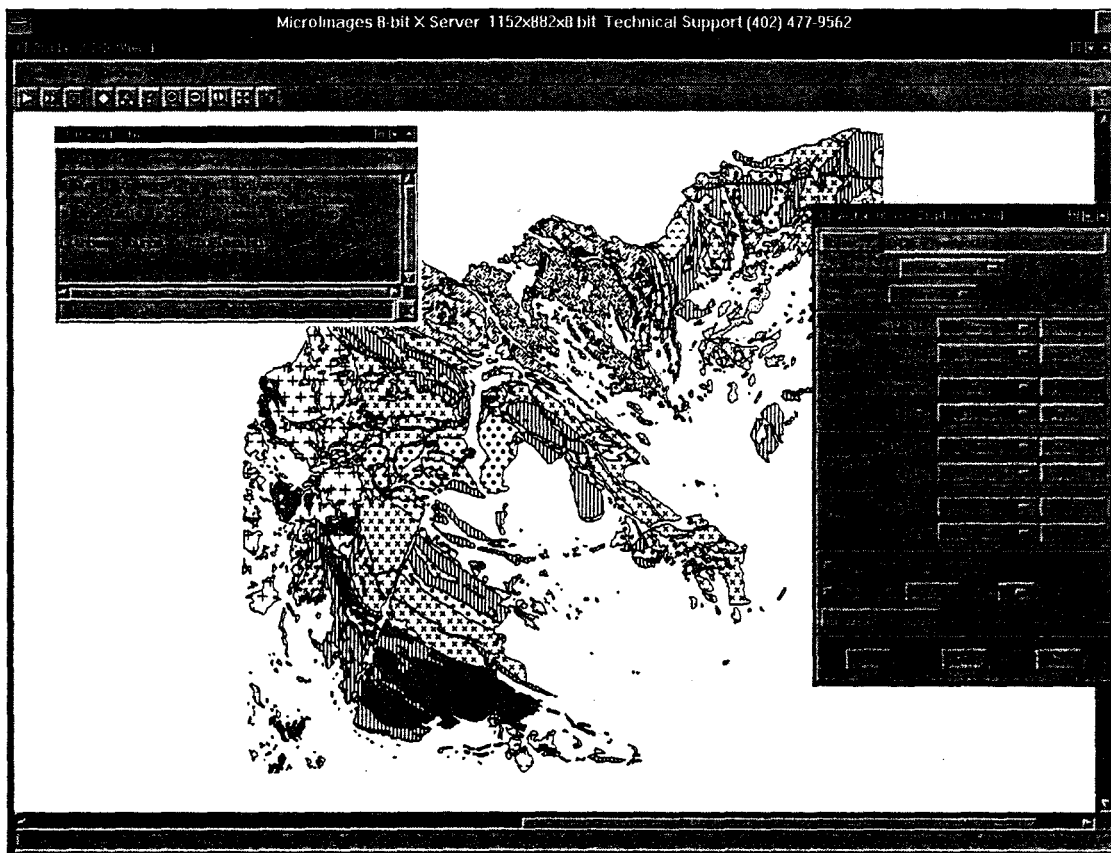
Figure 3.6 *Polygons selected according to a query (see Query Editor window in figure) and displayed according to the style indicated for the Originfo data table. The result is a map very similar in pattern encoding to the map by Du Plessis (1989).*

the author of the map gave to the unit and a short lithological description from the legend. There are two fields in the table: Strat and Description. Strat is the name of the unit as displayed in the paper map legend. Description is a short description of the lithology of that unit. See table 3.5 for the layout of the Originfo database. The Pella quartzite on Joubert's maps (1973a and b) has the following entry in the data table : Originfo.Strat = 'Pella_quartzite', and Originfo.Description = 'quartzite.' This allows one to display the vector object in colours and patterns similar to that

of the original paper maps, such as the map by Du Plessis, illustrated in figure 3.7. The Strat field is the key field of the table, which is similar in function to the class field in the classification data table so that vector elements can be displayed according to a predefined style for the values in the key field.

Originfo

Header Lines: 7
Desc: information from original paper map

Fields: 2
Name: strat   Type: Char   Start: 1   Length: 15
Name: description Type: Char   Start: 17 Length: 20

Table 3.5 *Originfo Data Table*

Lithbase Data Table

This data table contains the lithological data for the area. This is the most important table of the database since it will hopefully facilitate the correlation of units across map boundaries. It consists of twenty fields: six layers each of lithology, texture and mineralogy, a metadata field for the source of the data and a field for the name of the unit (table 3.6). The six categories for the lithology, texture and mineralogy are from major rock type to minor rock type for a unit. A lithological unit normally consists of a number of lithologies. The major lithology is the most abundant lithology in the unit. The mineralogy data highlight paragenetic minerals for some units. The metadata field contains a reference to the source of the data for that record. Metadata is in effect data about data, such as accuracy, age and source of the data to which it refers.

Each geological unit on a map usually consists of a characteristic combination of several lithologies. An attempt to capture this categorisation is made by defining six lithological fields. Again this categorisation of units is subjective and can fall prey to the same confusion that pervades the stratigraphic classification (Harris 1992). In a database such as this, the subjective

element can be avoided to a degree, since lithological fields can be accessed individually. This means that outcrops can be displayed not only according to combinations of lithologies present in the outcrop, but also according to specific individual lithologies. All outcrops *containing* quartzite in whatever proportion can be displayed, irrespective of whether the outcrops are characterised (according to the original cartographer) by complex or composite unit assemblages such as quartzite+quartz-muscovite schist members.

Lithbase

Header Lines: 25
Desc: lithological information from various sources

Fields: 20

Name: Source	Type: Char	Start: 1	Length: 10
Name: Name	Type: Char	Start: 12	Length: 25
Name: Lith0	Type: Char	Start: 38	Length: 25
Name: Texture0	Type: Char	Start: 64	Length: 20
Name: Mineral0	Type: Char	Start: 85	Length: 50
Name: Lith1	Type: Char	Start: 136	Length: 25
Name: Texture1	Type: Char	Start: 162	Length: 20
Name: Mineral1	Type: Char	Start: 183	Length: 50
Name: Lith2	Type: Char	Start: 234	Length: 25
Name: Texture2	Type: Char	Start: 260	Length: 20
Name: Mineral2	Type: Char	Start: 281	Length: 50
Name: Lith3	Type: Char	Start: 332	Length: 25
Name: Texture3	Type: Char	Start: 358	Length: 20
Name: Mineral3	Type: Char	Start: 379	Length: 50
Name: Lith4	Type: Char	Start: 430	Length: 25
Name: Texture4	Type: Char	Start: 456	Length: 20
Name: Mineral4	Type: Char	Start: 477	Length: 50
Name: Lith5	Type: Char	Start: 528	Length: 25
Name: Texture5	Type: Char	Start: 554	Length: 20
Name: Mineral5	Type: Char	Start: 575	Length: 50

Table 3.6 *Lithbase Database Table*

Most of the study area is covered by the map drawn by the Bushmanland Research Group (BRG) (Strydom *et al.* 1987 and Colliston *et al.* 1989), and since the lithological descriptions of units are comprehensive, this map was used as a major source for the data table. The map by the Geological Survey (1972) also overlaps considerably with the Aggeneys and Pofadder maps, and it is possible to do some direct correlation of units in this area of overlap. In creating the database it was important to retain as much information from first-hand sources, so that the original maps

could not be discarded in favour of the compiled maps by the BRG (*opp.cit.*). The problem was how to achieve this. Either an amalgamation of data from the various sources were used, or more than one record could be attached to one polygon, with each record entry information from a different mapper. The amalgamation process would require some degree of subjective interpretation and correlation, and since the aim of this project is to make the correlation of units as objective as possible, the former method was discarded in favour of the latter. Two more lithological tables were therefore created to aid in simplifying queries, and to indicate the sources of information.

A table was created for data from the maps by the BRG (*opp.cit.*) called UOFSLith, and a second, separate table for the map by the Geological Survey (1972) called SURVLith. These tables are identical to the Lithbase table except that the Source field is absent from the Survlith table. Data for the two extra tables were only obtained from areas where definite overlap of these maps occurred on the maps by Toogood and Joubert . If only one map covered an area data was taken from that map only, therefore minimising any subjective extrapolation and correlation. The tables include all possible lithologies as mapped by the various authors. It is assumed that where a unit consists of an assemblage of lithologies, that the first lithology described by an author is the major, characteristic lithology of the unit. For example, the Pella quartzite, as described by Joubert (1973a), has a major lithology of quartzite and a subordinate lithology of mica schist.

SACSbase

Header Lines: 12
Desc: stratigraphy according to SACS

Fields: 7
Name: Suite	Type: Char	Start: 1	Length: 30
Name: Subsuite	Type: Char	Start: 32	Length: 30
Name: Sequence	Type: Char	Start: 63	Length: 30
Name: Group	Type: Char	Start: 94	Length: 30
Name: Subgroup	Type: Char	Start: 125	Length: 30
Name: Formation	Type: Char	Start: 156	Length: 30
Name: Member	Type: Char	Start: 187	Length: 30

Table 3.7 *SACSbase Data Table*

Once this group of tables was added it was possible to query them in such a way as to aid in the addition of subsequent data tables.

SACSbase Data Table

The SACSbase table contains stratigraphic information according to SACS (1980, Agenbacht *et al.* 1992, Praekelt *et al.* 1992). It is divided into stratigraphic fields for Suite, Subsuite, Sequence, Group, Subgroup, Formation and Member names. To date not all units are classified by SACS, but this data table is useful in correlating units that are classified, and the table might aid in stratigraphic classification of units in areas outside that of the current SACS classification, such as units in the area mapped by Maclaren (1988a). The table layout can be seen in table 3.7. It is assumed, for the purposes, of this table that units named by the various authors according to the SACS classification, are correlated with units as classified by SACS. That is, if an author classifies a unit as Pella Quartzite, it is assumed that the unit is correlated with the SACS classification of Pella Formation.

Tectobase

Header Lines: 14
Desc: tectonic information database

Fields: 9

Name	Type	Start	Length
Name: Empty_fiel	Type: Char	Start: 1	Length: 5
Name: Supercrust	Type: Char	Start: 7	Length: 1
Name: Basement	Type: Char	Start: 9	Length: 1
Name: Intrusive	Type: Char	Start: 11	Length: 1
Name: Extrusive	Type: Char	Start: 13	Length: 1
Name: Migmatite	Type: Char	Start: 15	Length: 1
Name: Tectonic	Type: Char	Start: 17	Length: 1
Name: Cover	Type: Char	Start: 19	Length: 1
Name: Uncertain	Type: Char	Start: 21	Length: 1

Table 3.8 *Tectobase Data Table*

Tectobase Data Table

This database is descriptive of the probable genetic origin of the units found on the maps. All fields are logical (otherwise known as Boolean), in other words they contain only true or false values. A migmatitic unit will have a true or 'yes' value in the migmatite field. The GIS can then be queried to display only the migmatitic units of the Central Namaqua Province. Table 3.8 shows the layout of this data table. The fields are Supracrustal, Basement, Intrusive, Extrusive, Migmatite, Tectonic, Cover and Uncertain. The Uncertain field was included to make provision for uncertain and debatable classifications, such as the question of whether units should be classified as supracrustal or basement units (Watkeys et al. 1988, Watkeys 1986, Joubert 1986b, Hartnady et al. 1985). Although intrusive and extrusive are sometimes subjective terms, it has been shown conclusively that units such as the Orange River Sequence are extrusive in nature, and units belonging to the Vioolsdrif Suite show definite intrusive relationships with surrounding rocks (Joubert 1971, 1973c, 1974a, Du Plessis 1989, Minnit 1992a, 1992b). During the early tectonic events many rock units were exposed to anatexis and are migmatised to some extent, hence a field to denote whether a unit is migmatised. Outcrops where tectonic mixing of units has occurred and where individual units cannot be separated, are indicated in the Tectonic field (see Harris 1992). Large areas of mylonite are also examples of tectonic units. The Cover field makes it simple to exclude cover rock units from analyses of the Namaqua Province units. The first field in the data table (Empty_field) is meaningless and is only included to circumvent an error in the database definition language which prevents logical fields from being the first fields in a data table.

Correlbase

Header Lines: 10
Desc: dbase for correlated units in the Namaqua Province
(central)

Fields: 5

Name	Type	Start	Length
Name: SACS	Type: Char	Start: 1	Length: 30
Name: PRU	Type: Char	Start: 32	Length: 30
Name: UOFS	Type: Char	Start: 63	Length: 30
Name: GeoSurvey	Type: Char	Start: 94	Length: 30
Name: Other	Type: Char	Start: 125	Length: 30

Table 3.9 *The Correlbase Data Table*

Correlbase Data Table

The Correlbase table has been designed as an attempt to make sense of the various stratigraphic names given to units in the Namaqua Province. It contains fields for names given to units by the major research teams which mapped the Province (table 3.9). These are the Precambrian Research Unit from the University of Cape Town, the Bushmanland Research Group of the UOFS and the Geological Survey of South Africa. A field also exists for the official SACS name, if the unit is classified by SACS. The 'Other' field denotes any other name the unit is known by, for instance 'Pink Gneiss' for the Hoogoor Suite rocks. Often authors correlate units in their study areas with units in other areas, and these correlations are also entered in the appropriate fields in this data table.

Divbase Data Table

One of the paradigm shifts that occurred recently in the science of geology, is the recognition of tectonic terranes in highly deformed areas. These are discreet and allochtonous geological

Divbase

Header Lines: 8
Desc: tectonic divisions - subprovinces + terranes

Fields: 3
Name: Subprovinc Type: Char Start: 1 Length: 30
Name: Terrane   Type: Char Start: 32 Length: 30
Name: Zone   Type: Char Start: 63 Length: 30

Table 3.10 *Divbase Data Table*

areas that accreted at the edge of an active margin. Tectonic terranes are separated by faults, and contain unique and distinctive lithological assemblages (Schermer *et al.* 1984). Hartnady *et al.* (1985) and Joubert (1986a) divided the Namaqua Province into Subprovinces and tectonic Terranes. This terrane classification is important in unravelling the tectonic history of the area, but it is not certain that the terrane classification by Hartnady *et al.* (1985) and Joubert (1986a) reflects the true extent and geometry of the terranes (Harris 1987, Harris 1992b, Moore *et al.*

1990). Many other authors also suggest allochtonous terranes in the Namaqua Province (Praekelt and Colliston 1988, Praekelt *et al.* 1986, Strydom and Visser 1986) This table will therefore aid in validating the existence and position of the terrane boundaries[1] (table 3.10). It will also be possible to display units according to the terrane classification, as presently defined by these authors.

Chronobase Data Table

The Chronobase data table is divided into two sections - one for unit ages relative to tectonic events and the other for absolute ages (e.g. PbPb, RbSr, table 3.11). The two relative age fields

Chronobase

Header Lines: 13
Desc: ages - relative and absolute

Fields: 8
Name: Namtectage	Type: Char	Start: 1	Length: 20
Name: Tectage	Type: Char	Start: 22	Length: 20
Name: PbPb	Type: Int	Start: 43	Length: 6
Name: PbU	Type: Int	Start: 50	Length: 6
Name: RbSr	Type: Int	Start: 57	Length: 6
Name: NdSm	Type: Int	Start: 64	Length: 6
Name: SingleZirc	Type: Int	Start: 71	Length: 6
Name: Agedata	Type: Char	Start: 78	Length: 1

Table 3.11 *Chronobase Data Table*

contain information on the time of formation of a unit relative to:

- a.) The tectonic event responsible for its genesis, indicated as pre-, syn- or post-tectonic.
- b.) The Namaqua Event (ca. 1200Ma - Moore *et al.* 1990) indicated as pre-, syn- or postnam.

Data for this table comes almost exclusively from map legends, or accompanying theses, where the units were classified according to their tectonic ages. The data for the Namtectage field is

---

[1] *Refer to Chapter 5 for an example of terrane analysis using the Divbase data table.*

derived from the absolute ages and is there mainly to simplify database access and queries. Absolute ages were collected from the literature (Moore et al. 1990, Armstrong *et al.* 1988, Reid *et al.* 1987, Barton 1983, SACS 1980, Clifford *et al.* 1975, Clifford *et al.* 1981) and applied to units according to the Correlbase table. This limits the accuracy of the age database to the validity of the correlations made in the Correlbase table, but since data for the Correlbase table was drawn from documents accompanying the maps, and correlations were therefore made by the cartographers themselves, this table is still functional and useful.

Mapbase Data Table

This table was created mainly with the view to quantifying the correlation of units across map boundaries. It contains only the 'map' field with the name of the map from which the spatial data and elements were gathered. This field should correspond with values for the 'Source' fields in the lithological data tables. The table is used exclusively in a database manipulation routine, discussed in Chapter 4.

Chapter 4

The Collated Lithological Map of the Central Namaqua Province

4.1 Introduction

The spatial and attribute data base, discussed in the previous chapter, constitutes the collated digital map database for the Central Namaqua Province. This database can now be analysed to produce a collated, lithological paper map of the CNP. The first section of this chapter discusses the process involved in creating a lithological map from the established database, while the second is a discussion of some of the correlation problems revealed through the process of collating the map.

4.2 Producing the Lithological Map of the Central Namaqua Province

Collation of the lithological map provides an example of the database manipulation capabilities of a GIS, and illustrates the potential of a digital map database for the Namaqua Province. The process involves analysing the lithological database so that it is possible to correlate units across the whole area, especially where map boundaries act as dividing lines between different views and interpretations amongst researchers.

Map boundaries likely to cause most uncertainty are those not covered by the maps of Strydom *et al.* (1986) and Colliston *et al.* (1990), as they are fairly uncorrelated areas and do not contain all three layers of lithological data, namely the Lithbase, UOFSLith and SurvLith data tables. Other problematic boundaries are those between the Onseepkans map of Du Plessis (1989a) and the map by Von Backström (1972), between the map by Maclaren (1988a) and that of Joubert (1973b), the unmapped area between the map by Maclaren (1988a) and that of Du Plessis (1989a), the Orange River boundary between various maps, and the boundary between the map by Toogood (1976a) and the map by Strydom *et al.* (1986) in the Kumkum farm area. The reader is referred to figures 1.2 to 1.5 for illustrations of these map boundaries.

To overcome these problems, a new data table was created by reorganising the existing lithological database. With the aid of this data table it is possible to display units according to their lithology and a probability value, based on information in the lithological database, for the correlation of the units across the CNP. Differences in lithological interpretation or observation, where they exist, will be highlighted by colour differences at map boundaries.

4.2.1 The NammapDB Data Table

The NammapDB table contains a 'lithology' field and a field for the correlation factor (c_value). The lithology field defines the style in which the polygon will be displayed and the correlation value field is an estimate of a unit correlating with similar units in other areas of the map. The correlation probability value is calculated from three variables (fig.4.1a), listed in order of importance:

1. The relative abundance of an observed lithotype within a unit. It is assumed that, in defining the unit, an author lists lithotypes within a unit according to the relative abundances of the lithotypes, with the first listed as the major lithology defining a unit, and so on down to the minor lithotypes.

2. The degree of agreement between observers. If an outcrop is present on several different maps covering the same area and there is agreement between the various authors as to the lithologies within the units comprising the outcrop, the level of agreement will be high.

3. High correlation values should be assigned to cases where the source of the attribute (lithological) information and the source for the spatial element (map element) to which it is attached, is the same, and vice versa. The map by the BRG might describe a lithology in an outcrop which was originally mapped by Joubert, but not recognised by Joubert as containing this lithology. The lithology, for that outcrop, will therefore show a low correlation probability value, as some uncertainty exists as to the exact lithotype assemblage present in the outcrop.

A high correlation value indicates that a particular lithology is abundant in the outcrop, that

several workers who mapped the same outcrop observed this same lithology, and that the lithological information for that outcrop was collected from the same map as the outcrop or unit outline was digitised from (fig.4.1a) . The last variable is important in minimizing the dependence on map compilation by the BRG (Strydom *et al.* 1987), since their map is already an interpretation based on various other maps (including those used in this project).

4.2.2 Building the NammapDB Database

The Spatial Manipulation Language (SML) offered by the TNTmips™ software package makes it possible to calculate the correlation factor automatically for every outcrop in the vector object. For a detailed discussion of the SML program the reader is referred to Appendix A. In brief, a user enters a lithology of interest and a correlation value is then calculated for every polygon in the vector object which contains the lithology in the Lithbase, UOFSLith or SURVLith data records. The algorithm for this process is straightforward.

An algorithm for the process is as follows:

1. Select the vector object.
2. Enter lithology of interest.
3. Process every polygon in the vector object as follows:
    3.1 If the lithology is in the lithological record attached to an outcrop polygon, determine the level in which it is first recognized (i.e. Lith0-Lith5).
    3.2 Determine if the lithology is recognised by more than one author for that polygon, by searching all the lithology records attached to the polygon (Lithbase, UOFSLith and SURVLith).
    3.3 Determine if the record source and the spatial element source corresponds.
    3.4 Calculate, from process 3.1 to 3.3, the correlation factor (fig.4.1a).
    3.5 Output to a new database the polygon id-number, lithology and the correlation factor for each outcrop.

Calculation of the Correlation Value

Map Index for Study Area

Legend

B - UOFS-map
T - Toogood
D - Du Plessis
M - Maclaren
V - Von Backström
J - Joubert

Map by BRG

NammapDB

Lithology = quartzite
c_value = 90

Lithbase

Source = Joubert01
Lith0 = quartzite
Lith1 = qtz_mus_schist

3114

UOFSLith

Source = Strydom01
Lith0 = cd_sill_bt_schist
Lith1 = quartzite

Mapbase

Map = Joubert01

SURVLith

Source = Backstrom1
Lith0 = quartzite
Lith1 = qtz_mus_schist

Calculation:

level =   6
source =   0
correl =   3
_____
9 x 10 = 90

Figure 4.1a *Diagram to illustrate the calculation of a correlation value. The chosen lithology is quartzite and the correlation value is calculated for the outcrop (polygon with identification number 3114). Quartzite is the major lithology for the outcrop as described by Joubert (1973 a and b) and the Geological Survey (1972), but Strydom et al. (1987) observed the major lithology to be cd-sill-bt schist with quartzite as the second most abundant (source = 0; where 0 ≤ source ≤ 2). All the workers did observe quartzite in the outcrop (correl = 3; where 1 ≤ correl ≤ 3) and it is a major component according to the geologist from whose map the polygon was digitised, for that lithology (level = 6; where 1 ≤ level ≤ 6). Therefore the correlation is 90% (the value is given as a percentage since it is a probability).*
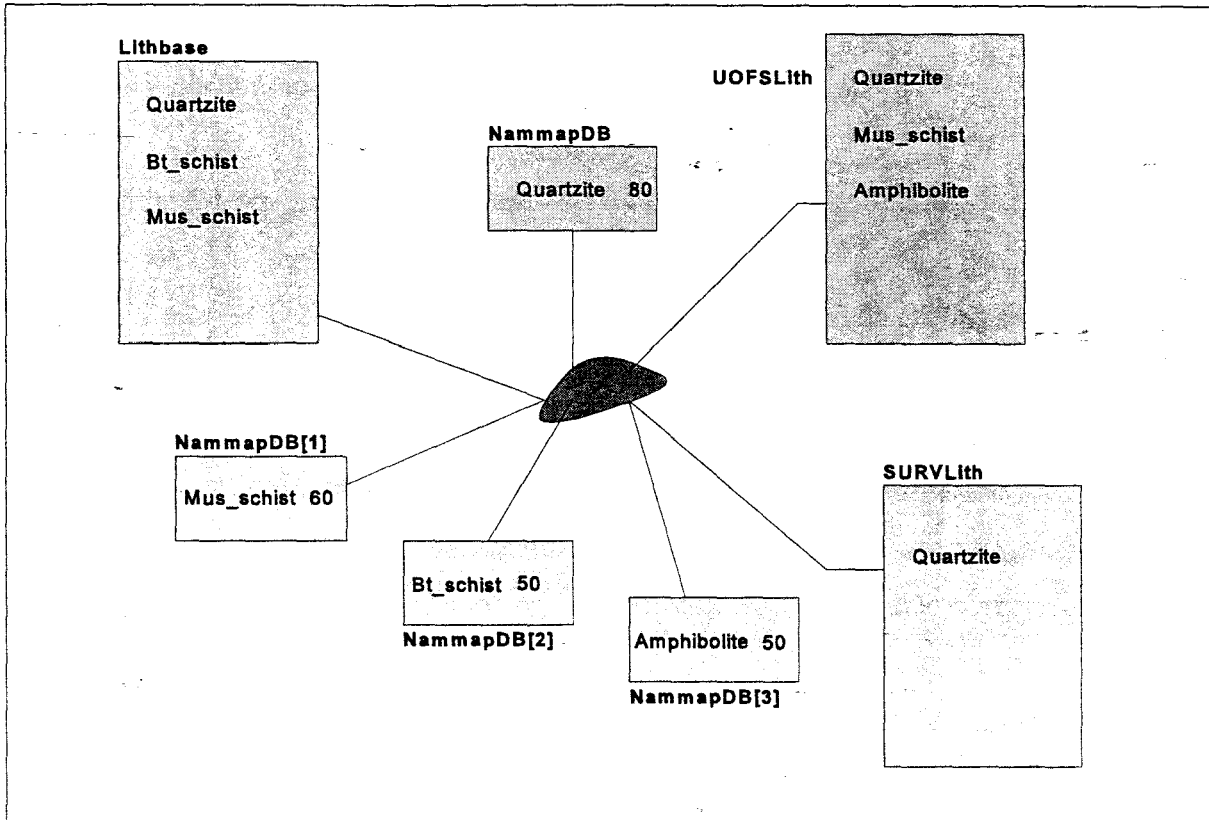
Figure 4.1b *Diagram illustrating the resultant NammapDB database. Every Lithbase, UOFSLith and SURVLith lithology field containing an entry, will generate a NammapDB record for every outcrop polygon.*

The database produced by this program was very large, since the correlation factor is calculated for every lithology associated with every outcrop. Several records were therefore attached to one polygon, with every polygon having at least one unique record attached to it. This resulted in an ASCII database containing over sixteen thousand records (since there are seven thousand polygons in the vector object). This duplication of data slowed down access to the database to such a point that it was impractical to use the database (displaying a map according to this database took a few hours).

Database records, therefore, had to be sorted so that duplicate records could be deleted. This was done by grouping records according to lithology and correlation value. All records showing, for instance, pegmatite with a correlation value of 80% were grouped together and one record was retained to represent all outcrops for which this combination was determined. An element number list of all the polygons to which the duplicate records were attached, was also compiled. By selecting polygons according to the element number list, the single retained record was

attached to the appropriate polygons (many-to-one relation). The number of records was reduced to less than one hundred in this manner.

4.2.3 Displaying the Lithological Map

Maps are displayed in TNTmips™ by selecting polygons and then displaying them with a style determined by the values in the database. In the case of the collated map, all the polygons existing in the database, for which NammapDB entries had been determined, were selected and then displayed in a style according to the value in the lithology field of the selected record. Whether an outcrop (polygon) has more than one NammapDB record attached to it will depend on the original lithological description of the outcrop and on the number of maps covering the area. If the outcrop was described as a unit consisting of several lithologies, it should have at least as many NammapDB records attached to it as there are lithologies in the unit. If every author of a map observed different combinations of lithologies within a unit for a particular outcrop, even more records will be generated by the SML program for that outcrop. The SML program separates the unit lithologies stored in the lithological tables (Lithbase, UOFSLith and SURVLith) into separate records for each lithology present in a unit and attaches a value to each in order to categorize them for every outcrop (fig.4.1b)

Most of the maps used in this project classify outcrops and units according to the most prominent lithology found in the outcrop unit. The map by the UOFS (Strydom *et al.* 1987) is an attempt to classify the outcrops according to stratigraphic units and this creates a high level of duplication in the legend. Several units are so similar that it is difficult to comprehend the reasoning behind Strydom *et al.*'s definition of these as separate stratigraphic units (refer to chapter 1). As a first attempt in establishing a collated lithological map from the lithological database, it was decided to display correlations using only the major lithologies by selecting and displaying polygons according to the lithology with the highest correlation value.

Lithological Map

Displaying this map involved selecting all the polygons with a NammapDB.c_value higher than 1 (cover sequences were given a correlation value of 1 to distinguish them from the Namaqua

sequences), and then displaying each polygon according to the lithology with the highest correlation value for that outcrop. The process is algorithmically simple, but the query language implementation thereof is more complex (Appendix C).

Every selected polygon then passes through the style query process (Appendix C) where the colours for the polygon boundary line and the interior of the polygon are decided. The Variable Declaration Block in the query simplifies the process of changing the colour of a particular lithology, so that it is necessary to change the colour in only one place for it to be reflected throughout the query. In the Lithology Detection Block all the NammapDB records attached to the polygon are inspected to determine which record has the highest value in the correlation field. There are nine major 'if-then'-expressions from which the NammapDB record with the highest correlation value is chosen. By manually inspecting the database it was established that there were no more than nine NammapDB (NammapDB to NammapDB[8]) records attached to any polygon so that the nine 'if-then'-expressions will access all the records. The string value in the lithology field of the record with the highest correlation value is then stored in the lithholder$ string variable for processing in the Display Style Assignment Block. A colour is associated with each lithology in the variable declaration block, and the polygon is then filled with the colour determined for the lithology in the lithholder$ variable. As an example: A polygon is selected and the highest correlation value is found in the seventh NammapDB (NammapDB[6]) record attached to the polygon. The DBMS accesses the record and stores the value in the lithology field of that record in a temporary variable - lithholder$. In the event that the value of lithholder$ is 'quartzo-feldspathic-gneiss', the polygon is filled with an orange colour (the value in the colour variable, qfgn$) and has a black border.

Correlation Map

In studying the lithological map (Annexure 1 at the back of the thesis) it is essential to also keep in mind the correlation probability associated with each outcrop polygon. The correlation value gives an indication of whether there are other possible lithologies that should be considered when correlating outcrops across an area of uncertainty. Two major lithologies are often juxtaposed at map boundaries on the lithological map. If the correlation value of one lithology is relatively

low, it may be an indication that all the geologists who mapped the area did not agree on the most dominant lithology, and that other lithologies are also possible as dominant lithologies.

It is possible to add the correlation values to the lithological map in the form of symbols or patterns, but it was decided to produce a second map containing only correlation information (Annexure 2). This minimizes the data density on the lithological map, while the correlation map can be used as a reference map to check on the probability factor for specific outcrops.

Displaying the correlation map is similar to the process used for the lithological map, but in this case a black and white pattern is used to distinguish polygons with different correlation values. The style query is much the same as that for the lithological map, but since there are only eight correlation values per polygon to check for, it is shorter (Appendix D).

Every polygon with a correlation value above one is selected. The Selection Block is the same as the Lithology Selection Block of Query 4.1 (Appendix C), except that the correlation value is stored in the variable c. In the Display Style Assignment Block the polygon is displayed according to the value in variable c. The patterns assigned to the variables in the Variable Declaration Block were prepared in a pattern design process which is part of the style editor in TNTmips™ version 5.00.

4.3 Discussion on Correlation Problems encountered during Collation of the Lithological Map

4.3.1 Introduction

A scale of 1:200000 was selected for the map (Annexure 1), as this reflected a balance between map sheet size and detail. The Transverse Mercator projection, with a central meridian at E 20°00' longitude, was used and the map printed in geographical coordinates. Tic marks for the grid are at 30' intervals for the area S 28°05' E 18°20' to S 29°40' E 20°20'. There is no topocadastral information on the map, since this is unnecessary for the purposes envisaged for the map. A number of farm names have been added to identify areas of special interest discussed

in the text.

4.3.2 The Legend

The legend contains information on the lithologies present on the map. Only lithologies represented by the highest correlation values are shown on the map, which is a synthesis of the information available in the NammapDB database table, and other lithological databases present in the GIS. Of the thirty lithologies present in the NammapDB database, only nineteen are shown. This reduction is due to the omission of what are usually only minor components of unit assemblages, for example, garnet-biotite-schist, cordierite-anthophylite-biotite schist or sapphirine-biotite-schist. Some unit names are also used for a combination of similar rock types. For example, outcrops described in the texts used for collecting attribute data as consisting of gabbro-norite, olivine-gabbro or diorite are grouped in this map as mafic intrusives.

Lithologies are grouped into four main assemblages: Post-tectonic Intrusive rocks, Syntectonic Rocks such as granite gneisses, Supercrustal Rocks (e.g. quartzites, biotite-schists and para-amphibolites) and Basement Rocks (e.g. mafic migmatite gneisses). This is an interpretative classification gleaned from the literature and the various maps, and the classification could not be rigidly applied for all the units encountered in the area. As an example, it is often the case that one geologist described an outcrop as containing granite gneiss, while another observed quartzo-feldspathic gneiss. It is not therefore possible to decide whether this outcrop is granitic or part of the supercrustal sequence, since both granite and quartzo-feldspathic supercrustal gneiss are very similar in mineral composition.

4.3.3 Lithological Description, Distribution and Correlatives[1]

The following section is a description of correlation issues that arose during collation of the lithological map (Appendix 1). Tables at the head of every section are included only as references

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[1] *Refer to fig.4.1a for a key to characters used for the areas corresponding to original maps. In this section the slash '-' character in a lithology/texture description indicates that the lithology is the name of a unit on the lithological map (in the legend, Annexure 1). Quartzo-feldspathic-gneiss and granite-gneiss are names of units on this map, while quartzo-feldspathic gneiss and granite gneiss are lithological descriptions.*

to descriptions of units by the various authors and workers mentioned in the section. Units appearing in these tables are not necessarily correlated by this author, either in the text or on the lithological map, and no lithotectonic grouping is intended by the tables.

A key to the abbreviations used in this section:

> B - area covered Strydom *et al.*'s map (1987)
>
> V - area covered by the Geological Survey map (1972)
>
> T - area covered by Toogood's map (1976a)
>
> J - area covered by Joubert's maps (1973a and b)
>
> M - area covered by Maclaren's map (1988a)
>
> D - area covered by Du Plessis's map (1989a)

4.3.3.1 Quartzo-feldspathic-gneiss

Stratigraphic Name	Lithological Description	Source
Hoogoor Suite	Red-brown leucocratic quartzo-feldspathic gneiss. Lenses of calc-silicate rocks, quartzites, schists and amphibolite. Sillimanite nodules.	SACS (1980)
Hoogoor Gneiss	Red-brown weathering leucocratic quartz-feldspar gneiss.	Strydom *et al.* (1987)
Gaidip Formation	Leucocratic quartzo-feldspathic gneiss with sillimanite nodules.	Strydom *et al.* (1987)
Namies Gneiss	Fine grained feldspathic gneiss.	Strydom *et al.* (1987)
Coboop Granite Pelgrimsrus Granite Houms River Granite Koeipoort Granite Naroep Granite	Leucocratic foliated granite. Red-brown weathering granite and yellow-brown weathering megacrystic granite. Xenoliths of calc-silicate rocks and bt-cd-sill schist and gneiss.	Strydom *et al.* (1987)
Ramansdrif Subsuite	Leucocratic granite changing east- and southward to quartzo-feldspathic gneiss.	Strydom *et al.* (1987)
Hom Formation	Biotite-rich quartzo-feldspathic gneiss with thin layered mafic zones and calc-silicates.	Strydom *et al.* (1987)
Achab Suite	Porphyroblastic felsic and leucogranitoid gneisses with xenoliths of amphibolite, calc-silicate, quartzite and leucogranite.	Strydom *et al.*(1987) and Watkeys (1986)
Austerlitz Formation	Light brown weathering quartzo-feldspathic gneiss. Sillimanite nodules.	Toogood (1976b)

Yas Granite	Light brown weathering leucocratic quartzo-feldspathic gneiss.	Du Plessis (1989b)
Paragneiss		Geological Survey (1972)
Nousees mafic gneiss	Grey gneiss with minor schist and quartzite. Porphyroblastic grey gneiss.	Joubert (1973 a and b)
Haramoep gneiss	Pink gneiss, granite gneiss, leptite.	Joubert (1973 a and b)
Haramoep Gneiss	Foliated bt-bearing augen gneiss. Resembles rocks from the Little Namaqualand Suite	Strydom et al. (1987)
Quartzo-feldspathic rocks	Quartzo-feldspathic gneiss quartzo-feldspathic megacrystic gneiss, leucogneiss, megacrystic leucogneiss, leptite	Maclaren (1988b)

Quartzo-feldspathic gneisses are probably the most widely distributed lithology on the map and are often associated with the supercrustal quartz/schist assemblages (Moore et al. 1990). This unit is generally known as the Hoogoor Suite, which is a collective name for all the undifferentiated leucocratic quartzo-feldspathic gneisses in the Namaqua Province (SACS 1980). These rocks are often porphyroblastic and may contain sillimanite-muscovite nodules. The BRG mapped several units containing quartzo-feldspathic gneiss as a major lithological component: the Hoogoor Gneiss is a red weathering leucocratic quartzo-feldspathic gneiss, while the Namies Gneiss is described as a feldspathic gneiss. They also mapped a leucocratic quartz-feldspar gneiss with sillimanite nodules (Gaidip Formation, Strydom et al. 1987) as a component of the Orange River Group.

Toogood (1976a) mapped the Austerlitz quartzo-feldspathic formation. This formation is most often correlated by the BRG with the Hoogoor Gneiss, but in several cases it is also correlated with their Coboop and Pelgrimsrus Granites. The description of the Hoogoor Gneiss and that of the medium grained phase of the Coboop and Pelgrimsrus Granites are so similar that confusion may arise (Strydom et al. 1987).

In the east of area T a large outcrop of Austerlitz gneiss was mapped by Toogood (1976a) as containing numerous lenses of amphibolite (fig.4.2). On the current map this outcrop can be followed across the Orange River into where Du Plessis (1989a) mapped a quartzo-feldspathic gneiss (Yas Granite) containing numerous lenses of mafic intrusives.

On the Geological Survey map (1972) legend the unit Kh2Gn is simply described as a paragneiss (gneiss derived from sedimentary rock (Bowes 1989)) and Toogood (1976b) tentatively correlates the more biotite-rich horizons of the Austerlitz quartzo-feldspathic formation with this paragneiss. The BRG recognizes some correlation between the paragneiss and the Hoogoor Gneiss, but near the Kheisberg the same unit is correlated with the Ramansdrif Subsuite (subsuite of the Vioolsdrif Suite - Strydom *et al.* 1987) - a leucocratic granite which changes east- and southward to quartzo-feldspathic gneiss. Again it seems more useful to classify it here as Hoogoor Gneiss.

There are very few places along the boundary between B and V where the quartzo-feldspathic-gneiss unit can be followed across the boundary. In the very western part of map V one can perhaps correlate the paragneiss (on V) with the Gaidip Formation on map B. They are both in contact with biotite-gneiss, but from the current map this correlation is perhaps not so obvious. In the area of Pellaberg the paragneiss on map V changes to biotite-gneiss on map J (fig.4.3). Joubert (1973 a and b) described the biotite-gneiss as grey gneiss (Nousees mafic gneiss) and the BRG described the same outcrops as biotite-rich quartzo-feldspathic gneiss with thin layered mafic zones and calc-silicates (Hom-formation, Strydom *et al.* 1987, Colliston *et al.* 1989). The mafic grey gneiss and Hom Formation can therefore be correlated here with the paragneiss unit in area V.
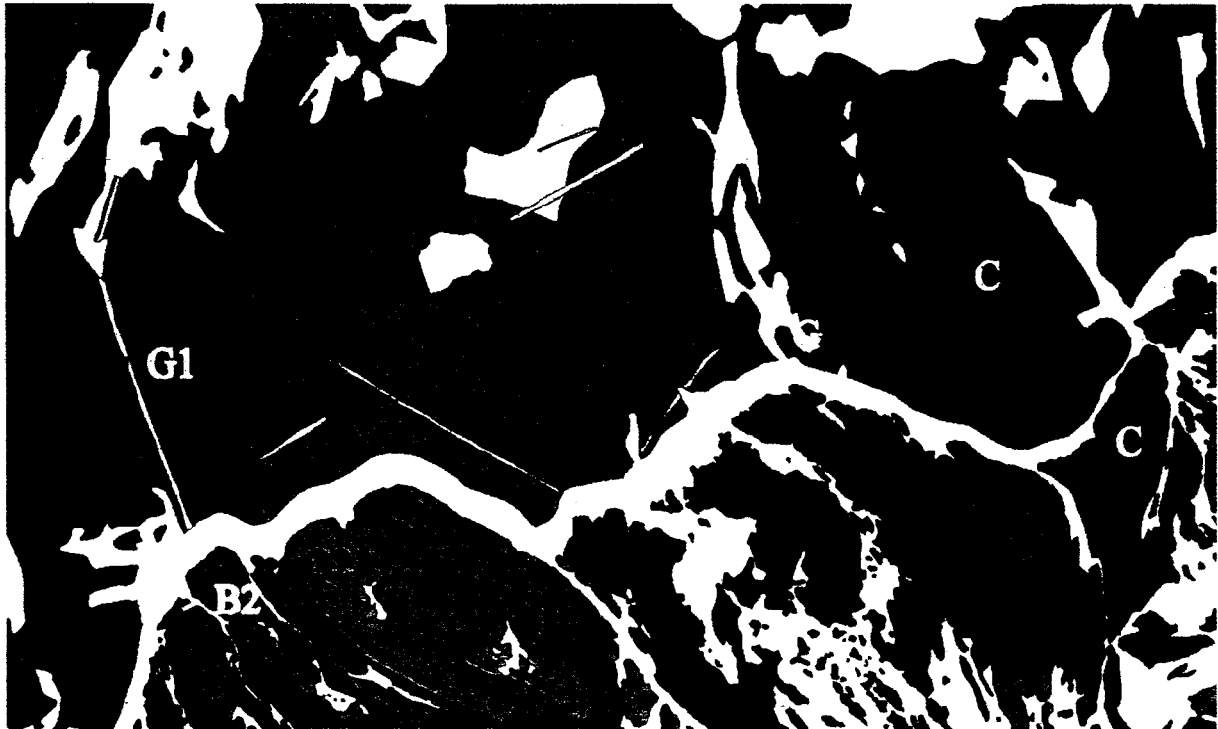
Figure 4.2 The boundary between the maps by Toogood (1976) and Du Plessis (1989). This figure clearly illustrates the correlation between the Austerlitz Formation (Q1) and the Yas Granite (Q2). The extension of the charnockite suite (C) across the Orange River is also clear. B2 is a biotite-gneiss unit (Eendoorn Granite) which can be correlated with the biotite-gneiss at B1 (Grass River Formation) and the granite-gneiss unit G1 (Beenbreek Formation). BH is a biotite-hornblende-gneiss (Schuitdrift Granite).
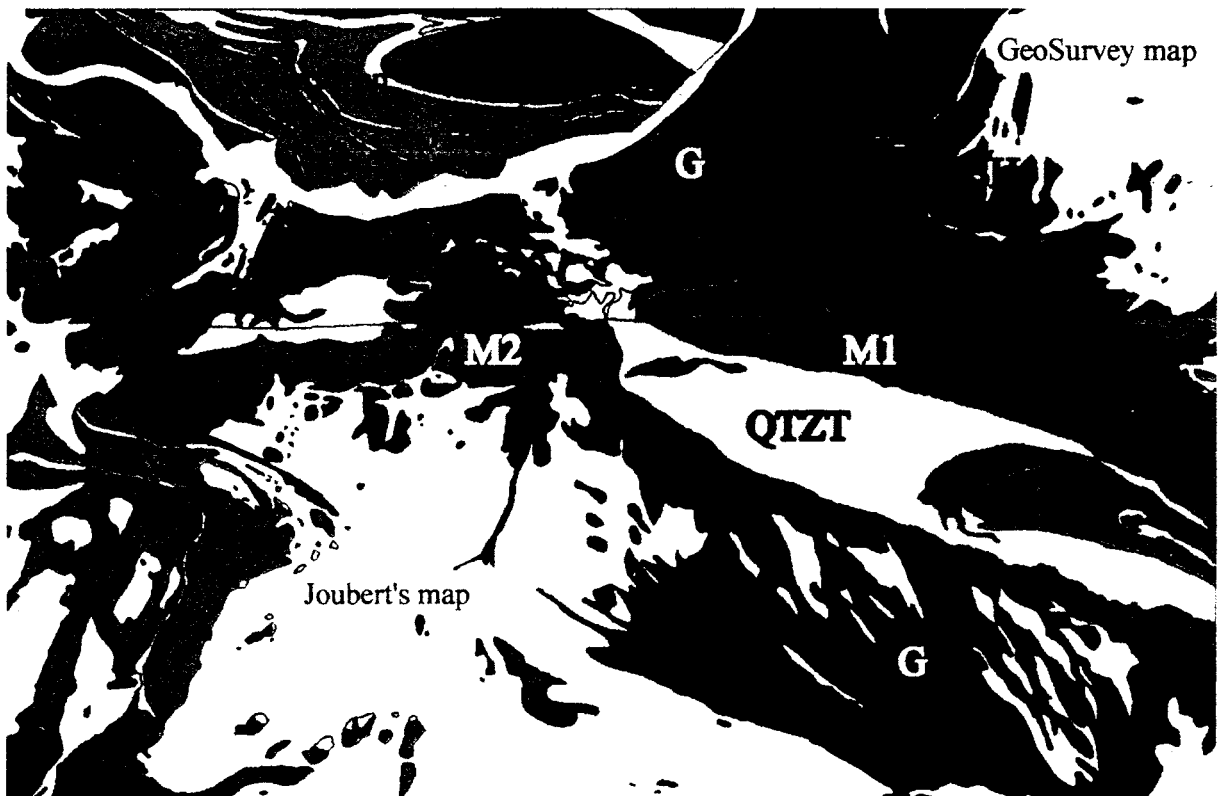
Figure 4.3 The paragneiss (Q) on the map by the Geological Survey (1972) is juxtaposed with the mafic-rock (M1) which is correlated with the Nousees mafic gneiss (Joubert 1973) and the Hom Formation (Strydom et al. 1987). To the west the biotite-gneiss (B) is also in juxtaposition with the mafic-rock unit at M2. This is possible if one considers that the Nousees mafic gneiss unit and the Hom Formation are collective terms for rocks with a mafic composition. H is a hornblende-gneiss outcrop (Pelgrimsrust Formation). BH is biotite-hornblende-gneiss (garnet-bearing biotite and/or amphibole gneiss with amphibolite). Q - quartzofeldspathic gneiss (Austerlitz-formation and paragneiss). G - granite-gneiss (Red Granite and Aroams Gneiss). QTZT - quartzite.

Quartzo-feldspathic gneisses on the map by Joubert (1973 a and b) are all classified as Haramoep Gneiss. The BRG correlated the Haramoep gneiss with the Hoogoor Gneiss in most places (Strydom *et al.* 1987), but other correlative units are the Koeipoort Granite, Naroep Granite, Achab Suite, Namies Gneiss and Haramoep Gneiss. The Koeipoort and Naroep Granites have exactly the same description as that of the Coboop and Pelgrimsrus Granites. Haramoep Gneiss as mapped by the BRG is a foliated augen gneiss with variable amounts of biotite, which differs from the description given by Joubert (1973 a and b) even though it has the same name. The Achab Suite appears south of the Aggeneysberge where Joubert (1973 a and b) mapped it as Haramoep gneiss (Watkeys 1986, Strydom *et al.* 1987)).

The type area for the Haramoep gneiss, named by Joubert (1973 a and b), is the Haramoepberg and it is interesting to see that on the lithological map (Annexure 1) the outcrops are classified as granite-gneiss. The reason for this can be found in the database. The granite-gneiss has a correlation value of 80% (refer to correlation map - Annexure 2) at this locality and inspection of the NammapDB records attached to these polygons reveals that the quartzo-feldspathic-gneiss correlation value is the same. However this record is attached to the outcrop subsequent to the granite-gneiss record. The lithology query (Appendix C) states that the polygon will be displayed according to the lithology defined in the first record attached in the event that correlation values are equal. The reason for identical correlation probabilities for different lithologies at the same localities different unit compositions observed by different workers. The UOFSLith table indicates granite-gneiss because of the main lithology, whilst in the Lithbase table quartzo-feldspathic-gneiss is the major lithology and granite-gneiss is secondary. Whether the polygons should be displayed as granite-gneiss or quartzo-feldspathic-gneiss is therefore difficult to decide, and this problem can only be resolved by re-visiting the outcrops and, if possible, deciding which of the two terms is most appropriate.

Maclaren (1988b) divided the quartzo-feldspathic rocks in area M into three lithologies: quartzo-feldspathic gneiss, leucogneiss and leptite. These three rock types are similar in composition and can be correlated with the Haramoep Gneiss by their common association with quartzite and schist units, as well as by following them across the boundary between areas J and M (especially at Nouzees (fig.4.4) and Pofadder East).

East of Onseepkans Du Plessis (1989b) found the Yas Granite to be the correlative of the Austerlitz Formation of Toogood (1976a). As has been mentioned earlier this unit can be visually correlated on the current map with the quartzo-feldspathic-gneiss on area T.

4.3.3.2 Quartzite/Schist Assemblage

Stratigraphic Name	Lithological Description	Source
Witputs Formation	Layered sequence of quartzite and biotite-sillimanite schist.	Strydom et al. (1987), Colliston et al. (1989)
Wortel Formation	Quartz-biotite-sillimanite schist, quartzite, biotite gneiss, amphibolite, calc-silicate	Strydom et al. (1987), Colliston et al. (1989)
Koeris Formation	Conglomerate, amphibolite, quartz-muscovite-feldspar schist, quartzite	Strydom et al. (1987), Colliston et al. (1989)
T'hammaberg Formation	Muscovite-sillimanite schist, quartzite	Strydom et al. (1987), Colliston et al. (1989)
Undifferentiated metasediments	Sequences of quartzite and schist	Strydom et al. (1987), Colliston et al. (1989)
Gams Member	Quartz-muscovite schist, quartzite, iron-formation, calc-silicates	Strydom et al. (1987), Colliston et al. (1989)
Pella Subgroup	Successions of quartzite, quartz-muscovite schist, quartz-biotite-sillimanite schist, calc-silicates, amphibolite, conglomerate, iron-formation	Strydom et al. (1987)
Koissabes and Abbasas Successions	quartzite and biotite-muscovite schist	Strydom et al. (1987)
Hotson Formation	Quartzite, quartzite/biotite gneiss rythmite, biotite-sillimanite schist, biotite gneiss, conglomerate, iron-formation, calc-silicates.	Prackelt et al. (1992)
Bushmanland Group	Quartzite, quartz-muscovite schist, biotite-sillimanite schist, iron-formation, cherts and amphibolite.	SACS (1980)
Kambreek Formation	Quartz-muscovite schist	Toogood (1976b)
Pella Formation	Quartzite	Toogood (1976b)
Keimas Formation	Calc-silicate gneiss.	Toogood (1976b)
Kaaien Series Quartzite	Quartzite, quartz-sericite schist, calc-silicate gneiss	Geological Survey (1972)
Pella Quartzite	Quartzite, quartz-mica schist, iron-formation	Joubert (1973 a and b)
Namies Schist	Sillimanite-biotite schist, amphibolite, quartzite	Joubert (1973 a and b)
Quartz-muscovite schist	Quartz-muscovite schist and leucogneiss	Joubert (1973 a and b)
Quartzites	Glassy quartzite - orthoquartzite Granular quartzite, calc-silicate Iron-formation	Maclaren (1988b)

According to Moore et al. (1990) the supercrustal sequence consists of two components, the leucogneiss unit and the quartzite/schist assemblage. The quartzite/schist assemblage comprises quartzites, psammitic and pelitic metasediments, iron formation and cherts, and is known as the Bushmanland Group (Moore et al. 1990, SACS et al. 1980).

The BRG, after intensive remapping of the Pella Terrane, has divided the area into numerous smaller allochtonous terranes with each its own supercrustal succession, thereby creating several stratigraphic units with very similar lithological assemblages (Praekelt et al. 1992, Colliston et al. 1989, Moore et al. 1990, SACS 1980). Of significance here are the following formations: Witputs, Wortel, Hotson, Koeris and T'hammaberg. On the map accompanying the paper by Colliston et al. (1989) there is also a unit called Undifferentiated Metasediments which occurs in the Aggeneysberg. The Hotson formation contains the Gamsberg member which contains quartz-muscovite schist, quartzite, calc-silicate and iron formation, and is also home to the economically important sulphide bodies. In essence these formations describe the same lithologies as the Bushmanland Group of SACS (1980).

On the map by Strydom et al. (1987) there is a unit name associated with these assemblages which does not appear on the more recent map (Colliston et al. 1989), namely the Pella Subgroup. Rocks associated with this term outcrop at Pellaberg and correlate with the Pella quartzite mapped here by Joubert (1973 a and b). The subgroup is made up of successions of quartzite and quartz-muscovite schist, quartz-biotite-sillimanite schist, calc-silicate gneiss, amphibolite, conglomerate and iron formation. Again the unit is so similar in description to the others that it is difficult to see the need for a separate unit. The term Pella Subgroup is replaced in the later map (Colliston et al. 1989) by the name Wortel Formation.

In area B there are no outcrops of the quartzite/schist assemblage mentioned, while Toogood (1976a) observed some quartz-muscovite schist in association with quartzites in area T. Toogood (1976a) mapped a quartz-muscovite schist unit (Kambreek Formation) which occurs as thin horizons in the Austerlitz quartzo-feldspathic formation. A quartzite unit (Pella Formation) also

outcrops sporadically, limited mostly to south of the Pofadder Shear Zone (PSZ), although one outcrop was found just north of the shear zone. Toogood (1976b) correlates this unit with the quartzites at Pella (in area J). The calc-silicate unit (Keimas Formation) on T might also be part of this sequence. It is found in thin horizons intercalated with quartzo-feldspathic gneiss (Austerlitz formation), biotite-gneiss (Orangefall formation) and hornblende gneiss (Pelgrimrust formation) north of the Pofadder Shear Zone. On the map by Strydom *et al.* (1987) these units are indicated as lenses of 'quartzite and schist', and calc-silicate rock. One thicker quartz-muscovite schist unit is indicated by the BRG in a colour which this author can only equate with the Koissabes and Abbasas successions on their map legend, which are quartzite and biotite-muscovite schists.

Immediately south of these units, in area V, there are thin quartzite units visible on the collated lithological map (Annexure 1). These are described by the Geological Survey (1972) as units consisting of quartzite, quartz-muscovite schist and calc-silicate gneiss (Kaaien Series quartzite). There are two large outcrops of the quartzite/schist assemblage in area V, at Dabenoris and Pellaberg. On the lithological map it is possible to correlate these with similar outcrops to the south (area J). The map by Strydom *et al.* (1987) indicate similar correlations by designating these outcrops as Pella Subgroup outcrops.

Joubert (1973 a and b) mapped the Pella quartzite unit which consisted of quartzite, quartz-mica schist and iron formation. Other units of the quartzite/schist assemblage are the Namies sillimanite-biotite schist which also contains amphibolite and quartzite, and the quartz-muscovite schist and leucogneiss unit. These units are always in close association with each other and with the Haramoep leucogneiss (Hoogoor Suite). A variety of different names for these units are used by the BRG, separating and joining lithological units into new combinations, but they are lithologically essentially the same, and can be correlated with similar units on map M.

Maclaren (1988b) mapped the same quartzite/schist assemblage, only differentiating between glassy and granular quartzite. The glassy quartzite is an orthoquartzite, while the granular variety grades into calc-silicate gneiss. Iron formation is also present. Calc-silicate gneiss and marble become more prominent in the area, towards the east, and appear to replace quartzite in the

sequence (Annexure 1, also refer to Chapter 5, figure 5.2). Biotite-rich schist is not so prominent in this area, but the quartz-muscovite schist is still present and can be seen in the area of Pellaberg (just north of Nouzees in figure 4.4).

The Pofadder Shear Zone (PSZ) is generally accepted as a terrane boundary at which lithological units terminate (Hartnady *et al.* 1985, Joubert 1986). There are however some thin lenses of quartzite (Pella Formation - Toogood 1976) and calc-silicate gneiss (Keimas Formation - Toogood 1976a) north of the shear zone in area T. In the area mapped by Maclaren (1988a) the exact extent of the PSZ is obscured by lack of outcrop, numerous minor shear zones and fractures, and the influence of the Putsberg Shear Zone which bisects the PSZ in the area (refer to fig.10 and fig.11 in Maclaren 1988b). If the general southeast trend of the PSZ continues in this area (as indicated by Harris 1992), there is definite proof that the quartzite/schist assemblage outcrops north of the shear zone (Annexure 1). These outcrops are narrow lenses in the northeastern half of area M, and they can be followed in a semi-sigmoidal curve across the area to where they join the Pella quartzites (Joubert 1973 a and b) at the PSZ (Annexure 1, fig.5.2). It is significant that the quartzites in this area are also closely associated with calc-silicate gneiss, in a similar way to the quartzites north of the PSZ in area T. There are no outcrops of the quartzite/schist assemblage on map D.

4.3.3.3 Amphibolite-gneiss

Stratigraphic Name	Lithological Description	Source
Amphibolite	Foliated homogenous amphibolite	Colliston *et al.* (1989)
Mafic unit	Foliated and metamorphosed dykes and sills	Strydom *et al.* (1987)
Mafic and ultramafic intrusives	Gabbro, olivine gabbro, olivine norite, pyroxenite, amphibolite, peridotite.	Geological Survey (1972)
Jericho Formation	Amphibolite. Narrow bands of hornblende gneiss.	Toogood (1976b)
Mafic intrusives	Amphibolite, meta norite, meta gabbro	Du Plessis (1989b)
Amphibolite	Amphibolite gneiss	Joubert (1973 a and b)
Para-amphibolite	Banded amphibolite associated with leucogneiss and calc-silicates.	Maclaren (1988b)
Ortho-amphibolites	Not banded. Associated with mafic intrusives	Maclaren (1988b)

The lithological query (Appendix C) handles amphibolite in a separate manner to other mafic rocks, such as gabbro, norite and, what some geologists described as, mafic intrusives and ultramafics. It does not necessarily mean that there is no amphibolite present in the mafic rock assemblage. It is often the case that an author might differentiate between para- and ortho-amphibolite by calling the ortho-amphibolite a mafic rock or mafic intrusive, and the para-amphibolite simply amphibolite (Joubert 1973 a and b). There are not too many units where amphibolite is the main constituent, more often it is a secondary lithology.

On the map by Colliston *et al.* (1989) there is an amphibolite unit, simply described as foliated homogenous amphibolite. Strydom *et al.* (1987) show a mafic dyke and sill unit that, on their map, correlates with amphibolite outcrops described by other authors. On map B there are only a number of mafic rock outcrops (Tantalite Valley Complex, Kum Kum mafic rocks) with amphibolite only mentioned as a minor constituent of these.

The Geological Survey (1972) does not differentiate amphibolite from other mafic rocks. The mafic unit is described as 'mafic and ultramafic intrusives containing gabbro, olivine-gabbro, olivine-norite, pyroxenite, amphibolite and peridotite.' In the area of Onseepkans there are numerous mafic rock lenses in the granite-gneiss and hornblende-biotite-gneiss on the Geological Survey map (1972), which could be related to the amphibolites north of the Orange River in area T.

Toogood (1976b) describes these latter amphibolites (Jericho Formation) as narrow bands of hornblende gneiss with sharp contacts. At Stolzenfels the quartzo-feldspathic-gneiss contains a myriad amphibolite lenses of the Jericho Formation which crosscut the foliation and seem to have an intrusive relationship with the quartzo-feldspathic-gneiss. The amphibolite rocks are possibly related to the larger hornblende-gneiss bodies (Toogood 1976b). The quartzo-feldspathic-gneiss can be followed across the river to the south, and here (map D) it also contains numerous mafic rock lenses, described by Du Plessis (1989b) as mafic intrusives containing amphibolite, meta-norite or meta-gabbro. The frequency of amphibolite outcrop within this

quartzo-feldspathic outcrop is very high. There are also some mafic intrusions in the hornblende-biotite-gneiss (Schuitdrif Granite) in the same area.

Joubert (1973 a and b) has a separate Amphibolite unit, but also includes amphibolite in the mafic intrusive and mafic grey gneiss unit (Nousees) as minor constituents. This Amphibolite unit is associated with the quartzite/schist assemblages and leucogneiss (Haramoep) and are correlated with the Koeris Formation (Strydom *et al.* 1987), described in the section on the quartzite/schist assemblage.

Maclaren (1988b) differentiates between para-amphibolite and ortho-amphibolite. Para-amphibolite in the area that he mapped, is banded and is associated with quartzo-feldspathic and calc-silicate gneiss. The ortho-amphibolite is not banded and is associated with the mafic intrusives. The para-amphibolites on M can be correlated with the Amphibolite unit on J by their association with quartzite /schist and leucogneiss, although there is no direct, visual correlation across the map boundary. One outcrop of para-amphibolite on the map boundary south of Nouzees, is described as a sporadic outcrop and it terminates at the map boundary with no sign of it in area J (Annexure 1, fig.1.3).

At Nouzees there are numerous ortho-amphibolite outcrops associated with the gabbronorite intrusives (Nouzees Gabbronorite Suite) in the area. Across the map boundary Joubert (1973 a and b) mapped grey Nousees mafic gneiss containing schist and amphibolite, and several mafic intrusives (gabbro, norite and amphibolite) within these rocks. On the lithological map these can easily be correlated with the Nouzees Gabbronorite Suite and ortho-amphibolites (fig.4.4).

4.3.3.4 Granite-gneiss

Stratigraphic Name	Lithological Description	Source
Goodhouse Subsuite	Undifferentiated granitoids changing east- and southward to biotite-bearing quartzo-feldspathic gneiss.	Strydom *et al.* (1987)
Houms River Granite Coboop Granite Koeipoort Granite Aroams Granite Naroep Granite Pelgrimsrus Granite	Foliated leucocratic granite consisting of two phases: red-brown weathering granite and a yellow-brown weathering megacrystic granite. Xenoliths of calc-silicate rocks and biotite-cordierite-sillimanite schist and gneiss.	Strydom *et al.* (1987)
Eendoorn Granite	Biotite-bearing augen gneiss. Charnockitic granites. Xenoliths of mafic rocks and granite.	Strydom *et al.* (1987)
Haramoep Gneiss Swartmodder Gneiss Kabis Gneiss	Biotite-bearing foliated augen gneiss, resembling rocks of Little Namaqualand Suite.	Strydom *et al.* (1987)
Houms River Formation	Quartzo-feldspathic gneiss, quartzite, sillimanite-cordierite schist and gneiss.	Beukes and Botha (1976)
Eendoorn Granite	Syntectonic biotite granite	Beukes and Botha (1976)
Red Granite	Red granite changing to pink gneiss in the east	Geological Survey (1972)
Austerlitz Formation	Light brown weathering quartzo-feldspathic gneiss. Sillimanite nodules.	Toogood (1976b)
Naros Granitoid	Weakly foliated granite. Mafic inclusions	Toogood (1976b)
Naros Complex	Zone of stocks and sills of granite surrounding granitoid. Intimately associated with rocks of other formations	Toogood (1976b)
Nautsis Formation	Alkali-feldspar granitic gneiss resembling Austerlitz Formation. No fabric.	Toogood (1976b)
Beenbreek Formation	Foliated megacrystic granite gneiss. Augen gneiss. Grades into garnet-biotite gneiss. Aplite veins.	Toogood (1976b)
Eendoorn Granite	Well foliated megacrystic biotite granite. Aplite veins.	Du Plessis (1989b)
Swartmodder Granite	Homogenous granite	Du Plessis (1989b)
Witwater Granite	Foliated granite. Associated with Eendoorn Granite and Toeslaan Formation.	Du Plessis (1989b)
Aroams Gneiss	Porphyroblastic granite gneiss	Joubert (1973 a and b)
Nousees mafic gneiss	Grey gneiss with minor schist and quartzite. Porphyroblastic grey gneiss	Joubert (1973 a and b)
Achab Suite	Porphyroblastic felsic and leucogranitoid gneisses with xenoliths of amphibolite, calc-silicate, quartzite and leucogranite.	Watkeys (1986), Strydom *et al.* (1987)

Granitoids	Alkali-feldspar granitic gneiss Megacrystic alkali-feldspar granitic gneiss changing to streaky augen gneiss in high strain zones.	Maclaren (1988b)

Area B, south of the PSZ, is almost exclusively covered with granite-gneiss outcrop (fig.4.5). These correlate mostly with the Goodhouse Subsuite according to Strydom et al. (1987), which is described as undifferentiated granitoids changing east- and southwards to biotite-bearing quartzo-feldspathic gneiss. The other granite-gneiss rocks are outcrops of Houms River Granite. Beukes and Botha (1976) described a Houms River Formation as a quartzo-feldspathic gneiss with lenses of quartzite and sillimanite-cordierite schist and gneiss. They correlate this unit with the leucogneiss associated with the quartzite/schist couplet (Hoogoor Suite - SACS 1980). Where Strydom et al. (1987) mapped Vioolsdrif Suite rocks, Beukes and Botha (1976) observed a mixed rock type with biotite-hornblende gneiss, augen gneiss, amphibolite, sillimanite-cordierite gneiss and calc-silicates (Umeis Formation), which is considerably different from the Vioolsdrif Suite. The Houms River Granite is one of the names given to a number of granite gneisses by Strydom et al. (1987). Other granites of significance to the lithological map are: the Coboop, Koeipoort, Aroams, Naroep and Pelgrimsrus. They all have the same description, but occur in different areas and, presumably, different terranes. North of the PSZ Strydom et al. (1987) mapped the Eendoorn Granite, which is a biotite-bearing augen gneiss.

On the map by the Geological Survey (1972) the Red Granite (AG3) unit is described as red granite changing to pink gneiss in the east. Pink gneiss is generally known to describe the leucogneiss or quartzo-feldspathic unit, known as the Hoogoor Suite (Watkeys et al. 1984). In the western half of map V Strydom et al. (1987) correlate the Red Granite with the Goodhouse Subsuite (fig.4.5), but in other areas there is a correlation with the Hoogoor Gneiss (quartzo-feldspathic gneiss). The Red Granite is always associated with Kaaien schists and quartzites in a relationship similar to the quartzite/schist and Haramoep gneiss association to the south, on map J. One would therefore be inclined to correlate AG3, in the area covered by the lithological map, with the Haramoep gneiss (and Hoogoor Suite - SACS 1990) rather than with the Vioolsdrif Suite.

Towards the east on map V the Red Granite is generally correlated by Strydom *et al.* (1987) with their Coboop Granite, but in the area of Onseepkans they mapped a Red Granite outcrop as Hoogoor Gneiss. This outcrop can be followed across the Orange River where it is mapped as Austerlitz quartzo-feldspathic gneiss.

The granite-gneisses mapped by Toogood (1976a) are the Naros Granitoid, Naros Complex, Nautsis Granite and Beenbreek Granite. The Naros Granitoid, according to Toogood (1976b) straddles the Orange River near Naros, but on the lithological map (Annexure 1, fig.4.6) this granite-gneiss unit is juxtaposed with biotite-hornblende-gneiss to the south (map D). Du Plessis (1989a) mapped it as the main body of the Naros Granite, which according to him is a hornblende-biotite gneiss. Toogood (1976b) found its essential constituent minerals to be hornblende, biotite, plagioclase, quartz and microcline. He placed it at the transition between granite and quartz-syenite, which is why it is displayed as a granite-gneiss on the lithological map.

The Nautsis Granite is similar in appearance to the Austerlitz quartzo-feldspathic gneiss but does not show any foliation and was therefore classified as a granite (Toogood 1976b). The BRG mapped it as the Pelgrimsrus Granite (a foliated granite). Near the PSZ some outcrops of Austerlitz Formation were also correlated with the Pelgrimsrus Granite by Strydom *et al.* (1987).

The Beenbreek Granite is a megacrystic granite only found north of the PSZ (on map T) and can be 'unquestionably' correlated with the Eendoorn Granite further west on map B (Toogood 1976b). The Eendoorn granite is described as a biotite-bearing gneiss (SACS 1980, Strydom *et al.* 1987) or a biotite gneiss (Beukes and Botha 1976, Du Plessis 1989b) and is therefore shown on the lithological map as a granite-gneiss in area B and a biotite-gneiss in area D (Annexure 1). The Beenbreek granite is described as a megacrystic granite with biotite present in the matrix, and is therefore displayed as a granite-gneiss, but looking at cross map boundary relationships there is no doubt that the Beenbreek granite can be correlated with the biotite-gneiss in area D (fig.4.2).

Du Plessis (1989b) classifies most of the units on his map as granites due to their composition

and position on the Streckheisen classification diagram. They are differentiated by their metamorphic mineral assemblages on the lithological map (Annexure 1), so that the only granite-gneiss units on map D are correlated with the Swartmodder and Witwater Granites on his map. The Swartmodder Granite is a homogenous, leucocratic rock, classified by Du Plessis (1989b) as belonging to the Hoogoor Suite. The Witwater Granite usually contains garnet and is found in close association with the Eendoorn Granite and the Toeslaan Formation. In the very east of map D the granite-gneiss (Witwater Granite) unit can be followed onto map T, where it is mapped as Beenbreek granite (Eendoorn Granite). The section on the biotite-gneiss provides a more thorough discussion on this combination of units.

In the vicinity Aggeneys and Pofadder, Joubert (1973 a and b) mapped a porphyroblastic granite gneiss and called it the Aroams gneiss. According to SACS (1980) the Aroams and Eendoorn gneisses are part of the Little Namaqualand Suite of augen gneisses. In the northwest of map J the Aroams Gneiss (Joubert) is called the Kabis Gneiss (resembling the Little Namaqualand Suite, Strydom *et al.* (1987)) at one outcrop, and the Naroep Granite (described earlier) at another. In the area of Haramoep (as has been mentioned in the section on the quartzo-feldspathic-gneiss unit) the BRG also recognised two different granite-gneisses, the Haramoep Gneiss and the Koeipoort Granite. Their Aroams Granite covers the granite-gneiss outcrops on the farm Aroams, but the description is the same as for the Koeipoort Granite. At Pellaberg the Aroams Gneiss (Joubert 1973 a and b) is called the Swartmodder Gneiss on the one map (Strydom *et al.* 1987) and Pella Granite on the other (Colliston *et al.* 1989) of the two BRG maps. Both these stratigraphic names describe a biotite-bearing augen gneiss.

Granite-gneiss outcrops found south of the Aggeneysberge, Gamsberg and Namiesberg are classified by Watkeys (1986) as Achab Gneiss, composed of porphyroblastic quartzo-feldspathic gneiss, banded gneiss and leucogranite gneiss. This is essentially the same lithological composition for this unit as indicated on the map by Strydom *et al.* (1987). Joubert (1973 a and b) mapped a porphyroblastic granite gneiss unit south of Namiesberg (which is the reason for this unit being displayed as granite-gneiss on the lithological map, Annexure 1), but pink gneiss in the other areas mentioned above. The other outcrop mentioned by Watkeys (1986) is just north of Namiesberg and here Joubert (1973 a and b) mapped a grey gneiss (essentially a group name

for mafic-gneiss). The BRG indicated Achab Gneiss on their 1987 map (Strydom *et al.* 1987) and undifferentiated gneiss on the map of 1989 (Colliston *et al.* 1989). It is clear that the grey gneisses, as termed by Joubert (1973 a and b), cover a wide spectrum of rocks of different ages and associations, although they are usually mafic in composition (biotite gneiss, biotite-hornblende gneiss, hornblende gneiss, amphibolite).

Further to the east Maclaren (1988b) differentiated between three granitic gneisses: an alkali-feldspar granite gneiss, alkali-feldspar megacrystic granite gneiss and a streaky gneiss. The megacrystic gneiss is biotite-bearing and becomes streaky gneiss in zones of high strain. At the boundary between map J and M, in the area southeast of Pellaberg and in the vicinity of Nouzees these granite gneisses seem to correlate with the biotite-gneiss on J (Annexure 1), although they can also be correlated with the Aroams Gneiss as described by Strydom *et al.* (1987).

4.3.3.5 Biotite Gneiss

Stratigraphic Name	Lithological Description	Source
Umeis Succession	Biotite-gneiss, amphibolite, biotite and hornblende schist, calc-silicate, leucocratic quartzo-feldspathic gneiss, granite gneiss	Strydom *et al.* (1987)
Eendoorn Granite	Biotite-bearing augen gneiss, charnockite, xenoliths of mafic rock	Strydom *et al.* (1987)
Naros Granite	Foliated hornblende-biotite granite	Strydom *et al.* (1987)
Hom Formation	Biotite-rich quartzo-feldspathic gneiss with thin layered mafic zones and calc-silicates.	Strydom *et al.* (1987)
Witputs Formation	Layered quartzite, quartz-biotite-sillimanite schist.	Strydom *et al.* (1987)
T'hammaberg Formation	Muscovite-sillimanite schist and quartzite	Strydom *et al.* (1987)
Guadom Formation	Layered biotite gneiss, hornblende gneiss and schist, calc-silicates, biotite-cordierite-sillimanite-anthophyllite gneiss	Strydom *et al.* (1987)
Eendoorn Granite	Well foliated megacrystic biotite granite.	Du Plessis (1989b)
Naros Granitoid Leucophase	Foliated coarse grained biotite augen gneiss	Du Plessis (1989b)
Naros Granitoid Main Body	Foliated hornblende-biotite granite	Du Plessis (1989b)
Biotite Granite	Biotite granite, granodiorite, grey gneissic granite	Geological Survey (1972)
Kaaien Series Paragneiss	Biotite-rich quartzo-feldspathic gneiss	Geological Survey (1972)

Orangefall Formation	Biotite gneiss, biotite schist, hornblende gneiss, calc-silicate	Toogood (1976b)
Beenbreek Formation	Megacrystic foliated granite, augen gneiss, forming garnet-biotite gneiss in deformed areas	Toogood (1976b)
Grass River Formation	biotite augen gneiss	Toogood (1976b)
Nousees mafic gneiss	grey gneiss, minor schist and quartzite	Joubert (1973 a and b)
Biotite gneiss	migmatitic biotite gneiss and schist	Joubert (1973 a and b)

The biotite-gneiss units on the map by the BRG (Strydom *et al.* 1987) relevant to the collated lithological map, are gneisses from the Umeis Succession. Du Plessis (1989a) mapped two biotite gneiss units, namely the Eendoorn Granite and the leucophase of the Naros Granite. The Eendoorn Granite on his map is described as a well foliated megacrystic biotite gneiss, while the leucophase of the Naros Granite is a foliated, coarse-grained biotite augen gneiss.

According to Toogood (1976b) it is possible to correlate the Beenbreek Formation with the Eendoorn Granite further west. The Beenbreek Formation consists of megacrystic and augen granite gneiss, forming garnet-biotite gneiss in the more deformed areas. There are several instances along the boundary between map T and D where the biotite-gneiss of the Eendoorn Granite (D) is juxtaposed against the granite-gneiss of the Beenbreek Formation on area T (fig.4.2). There is also a case where the biotite-gneiss on D is juxtaposed against augen gneiss of the Grass River Formation on T (fig.4.2). Toogood (1976b) classified all the augen gneiss with an uncertain origin as Grass River gneiss. In the digital database this unit is designated a biotite-gneiss. The BRG classified it as Eendoorn granite (Strydom *et al.* 1987), which, according to Toogood (1976b), is feasible.

Figure 4.4 The farm 'Nouzees', with the Samoep Synforms enclosing the Nouzees Intrusion (NGS and NMG). Maclaren (1988) mappedthe Nouzees Intrusion as the Nouzees Gabbronorite Suite (NGS) and it consists of Olivine Gabbronorite and ortho-amphibolite. Joubert (1973) mapped it as Nouseen mafic gneiss (NMG), which consists of mafic gneiss, amphibolite and mafic intrusives. The collated map shows the Samoep Synform (of which the NGS is the core) and its constituent lithologies clearly. Q - quartzo-feldspathic gneiss. Green polygons north of the Samoep Synform indicate the start of the Wortel Line (WL) of mafic intrusions. NGS is not considered to be part of the Wortel Line (Joubert 1986a).
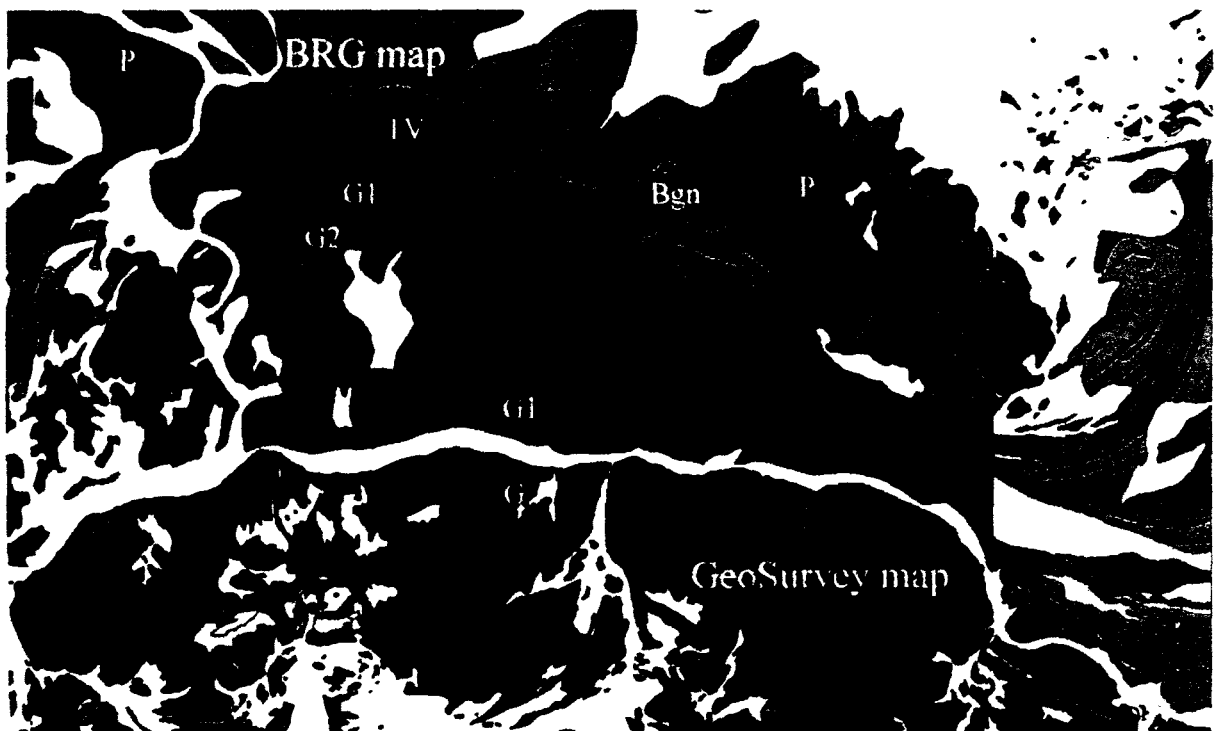
Figure 4.5 Boundary between the maps by the BRG (Strydom et al. 1987) and the Geological Survey (1972). The PSZ approximately follows the line between the green (biotite gneiss - Bgn) and the brown (granite gneiss) units on the BRG map. The granite gneiss unit on the BRG map consists of two components, namely Vioolsdrif Suite granites (G1) and Houms River granites (G2) according to Strydom et al.(1987). G - granite gneiss. TV - Tantalite Valley Complex. Q - quartzo-feldspathic gneiss. P - biotite-cordierite-sillimanite-garnet gneiss.

The Orangefall formation on the map by Toogood (1976a) contains biotite gneiss as a major constituent, and associated with it, biotite schist, hornblende gneiss and calc-silicate boudins, and can therefore be correlated with the Umeis Succession of the BRG. In the extreme east of map T, however, there is a visual correlation across the Orange River between the Eendoorn Granite on map D and the Orangefall biotite-gneiss (Annexure 1). In areas of high deformation the Beenbreek granite grades into a garnet-biotite gneiss and it is often difficult to map accurate contacts with other rock types (Toogood 1976b), giving a possible explanation as to the disparity, namely that in some areas the Orangefall gneiss closely resembles the Beenbreek granite, causing different geologists to classify the units in these specific areas differently. This irregularity is further explained when considering the following: On the map by Toogood (1973) the Orangefall biotite gneiss is usually spatially associated with either the Grass River biotite gneiss or the Beenbreek granite. Beukes and Botha (1976) also noted the close association of a porphyroblastic biotite gneiss within the Umeis Formation with the Eendoorn Granite. The obvious close association and lithological similarities of these units are responsible for the few instances where the Orangefall gneiss is correlated with the Eendoorn granite on the lithological map (Annexure 1).

On the map by the Geological Survey (1972) the only outcrop described by Von Backström as biotite-gneiss is in the northeastern corner of that map, adjacent to the map by Du Plessis (1989a). This unit, AG1, consists of biotite granite, granodiorite and grey gneissic granite. The outcrops adjacent to this one on map D are part of the Naros Granitoid main body, described as hornblende-biotite gneiss (Du Plessis 1989b). On the map by Strydom et al. (1987) unit AG1 is placed in the Naros Granite as a hornblende-biotite gneiss. The Naros leucophase, according to Du Plessis (1989b) is a biotite augen gneiss and it is therefore possible that unit AG1 is an outcrop of the leucophase of the Naros Complex, since AG1 is described as a biotite gneiss. On the other hand, the Orangefall biotite gneiss outcrops just north of the Orange River in area T. There is uncertainty here as to which biotite-gneiss belongs to the Umeis Formation (Orangefall Formation) and which to the Naros Granite.

In the western part of map V, there are small outcrops of biotite-gneiss according to Strydom *et al.*(1987). These units (Guadom Formation) consist of layered biotite gneiss, hornblende gneiss

and schist with lenses of calc-silicate gneiss and biotite-cordierite-sillimanite-anthophyllite gneiss (Strydom *et al.* 1987). The same outcrops are described by Von Backström (1972) as quartz-sericite schist and phyllite of the Kaaien Group. These units were mapped by Toogood as Orangefall biotite gneiss. Most of the other biotite-gneiss outcrops in the area of map V, towards the west, have similar correlations.

At the boundary between V and J (fig.4.3), in the vicinity of Pellaberg, the biotite-gneiss of the Guadom formation (Strydom *et al.* 1987) on V lies in contact with a unit on J, described by Joubert (1973 a and b) as grey gneiss with minor schist and amphibolite (Nousees mafic gneiss), and by Strydom *et al.* (1987) as biotite-bearing quartzo-feldspathic gneiss, with thin layered mafic zones and calc-silicate (Hom Formation) and as felsic gneiss with thin layered mafic zones, cordierite-anthophyllite, biotite-sapphirine and calc-silicate rock, and quartzite by Colliston *et al.* (1989). The descriptions for the Hom and Guadom formations are very similar, and both are correlated with the Nousees mafic gneiss (SACS 1980).

In the southern areas of the lithological map (Pella, Okiep and Garies Terranes) there is a marked decrease in biotite-gneiss occurrence. Joubert (1973 a and b) mapped a number of outcrops in the extreme southwest of the Aggeneys map (fig.4.7, Annexure 1). He described them as migmatitic biotite gneiss and schist. The BRG mapped the same outcrops at Skelmberg as layered quartzite and quartz-biotite-sillimanite schist (Witputs Formation) and an outcrop just south of that as muscovite-sillimanite schist and quartzite (T'hammaberg Formation) which does not correlate with the map by Joubert (1973a).

In the southeast of M there is an outcrop described by Maclaren (1988b) as a biotite-bearing megacrystic alkali-feldspar granitic gneiss, which is displayed on the lithological map as a granite-gneiss unit. Just southeast of Pellaberg, there are a number of biotite-schist outcrops which can be correlated on the current map with mafic grey gneiss on map J.

4.3.3.6 Biotite-hornblende-gneiss and Hornblende-gneiss

Stratigraphic Name	Lithological Description	Source
Biotite hornblende gneiss	Garnet-bearing biotite and/or hornblende gneiss, amphibolite	Geological Survey (1972)
Undifferentiated Gneiss	Undifferentiated migmatitic hornblende and biotite-bearing felsic and mafic gneiss with calc-silicate, schist and quartzite.	Strydom *et al.* (1987)
Naros Granite	Foliated hornblende-biotite granite	Strydom *et al.* (1987)
Orangefall Formation	Biotite gneiss, biotite schist, hornblende gneiss, calc-silicates	Toogood (1976b)
Pelgrimsrust Formation	Hornblende gneiss with horizons of biotite-hornblende gneiss	Toogood (1976b)
Naros Granitoid Main Body	Foliated hornblende-biotite granite	Du Plessis (1989b)
Naros Granitoid Mafic Phase	Hornblende-biotite granite	Du Plessis (1989b)
Schuitdrift Granite	Well foliated, megacrystic biotite-hornblende gneiss, associated with the Eendoorn Granite.	Du Plessis (1989b)
Nousees mafic gneiss	Grey gneiss, minor schist and quartzite	Joubert (1973 a and b)

The only description of biotite-hornblende gneiss as a main constituent of a unit appears on maps south of the Orange River, specifically maps V and M. The Geological Survey (1972) mapped a biotite and/or hornblende gneiss with amphibolite lenses (MGn) at Onseepkans (fig.4.6) that corresponds to a unit on the map by Strydom *et al.* (1987) described as containing undifferentiated migmatitic hornblende- and biotite-bearing felsic and mafic gneiss with calc-silicate rock, schist and quartzite intercalated. Here the schist and phyllite unit (Geological Survey 1972) corresponds to the same unit on the map by Strydom *et al.* (1987). At Onseepkans the biotite-hornblende-gneiss changes to biotite-gneiss and hornblende-gneiss across the Orange River, but the BRG interpretation remains the same. Biotite-gneiss (Orangefall Formation - Toogood (1976b)) has already been discussed. The hornblende-gneiss mapped by Toogood (1976b) is the Pelgrimsrust Formation and, according to him, some horizons contain hornblende-biotite gneiss.

The main body and mafic phase of the Naros Granitoid, as described by Du Plessis (1989b), and the Naros Granite on the map by Strydom *et al.* (1987), are biotite-hornblende gneisses. Du

Plessis (1989a) also mapped a biotite-hornblende augen gneiss (Schuitdrift Granite) south of Stolzenfels, which is very similar to the Eendoorn Granite and might have a genetic relation to it. Towards the south of the lithological map, in the area of maps J and M, the hornblende-biotite-gneiss seems to correlate with the mafic gneiss mapped by Joubert (1973, Annexure 1).

4.3.3.7 Biotite-cordierite-sillimanite-garnet-gneiss

Stratigraphic Name	Lithological Description	Source
Arus Formation	Migmatitic biotite-cordierite-sillimanite-garnet gneiss, quartzo-feldspathic gneiss, calc-silicate boudins, pyroxene-bearing mafic gneiss.	Strydom et al. (1987)
Jerusalem Formation	Cordierite-sillimanite-garnet gneiss	Toogood (1976b)
Orangefall Formation	Biotite gneiss, biotite schist, hornblende gneiss, calc-silicate	Toogood (1976b)
Pelgrimsrust Formation	Hornblende gneiss with horizons of biotite-hornblende gneiss	Toogood (1976b)
Toeslaan Formation	Cordierite-sillimanite-garnet-biotite gneiss, quartzo-feldspathic gneiss, quartzite, calc-silicate.	Du Plessis (1989b)

Strydom et al. (1987) considers biotite-cordierite-sillimanite-garnet gneiss to be the major constituent for the Arus Formation. Also included in the Arus Formation are quartzo-feldspathic gneiss, calc-silicate gneiss and pyroxene-bearing mafic gneiss. Beukes and Botha (1976) observed the same composition for the formation. The distribution of the biotite-cordierite-sillimanite-garnet-gneiss unit is mostly limited to north of the PSZ. Near the Tantalite Valley Complex there are some outcrops just south of the PSZ as indicated by Beukes and Botha (1976) and Strydom et al. (1987) (fig.4.5).

West of Onseepkans, surrounding the large norite/enderbite body, Strydom et al. (1987) indicate a large outcrop of the Arus Formation which corresponds to a combination of units on the map by Toogood (1976a). The Jerusalem Formation on his map is a cordierite-sillimanite-biotite gneiss that he equates with the Arus Formation of Beukes and Botha (1976). Other units correlated with the large Arus Formation outcrop are Orangefall biotite gneiss and Pelgrimsrust hornblende gneiss.
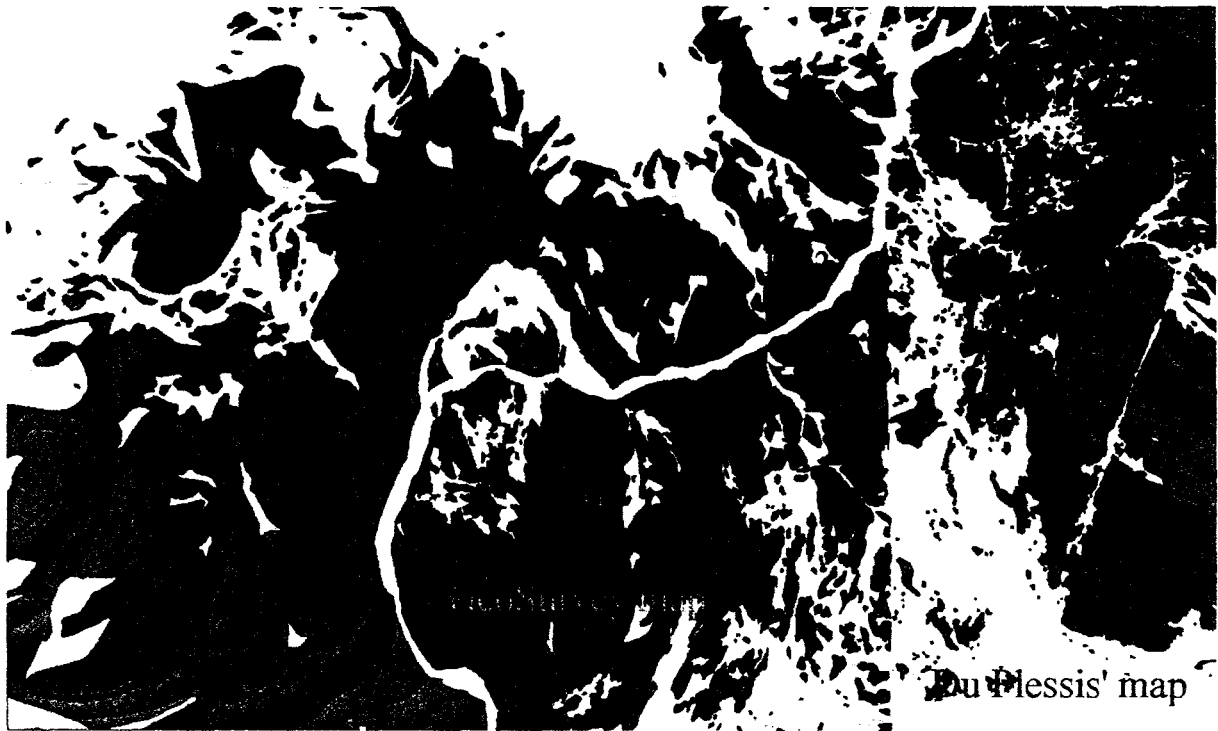
Du Plessis' map

Figure 4.6

Bgn1 on the Geological Survey map (1972) is described by them as a biotite granite. Strydom et al.(1987) mapped it as hornblende-biotite gneiss (Naros Granite). The biotite-hornblende gneiss (BH) opposite this outcrop, was mapped by Du Plessis (1989) as Naros Granite main body. Bgn2 is an outcrop of Naros biotite gneiss (Toogood 1976). According to Du Plessis (1989) the Naros Granitoid contains a leucophase of biotite gneiss, but this outcrops further north (green). Bgn - biotite gneiss. BH - biotite-hornblende gneiss. G - granite gneiss. Q - quartzo-feldspathic gneiss. C - charnockite.

Joubert's maps
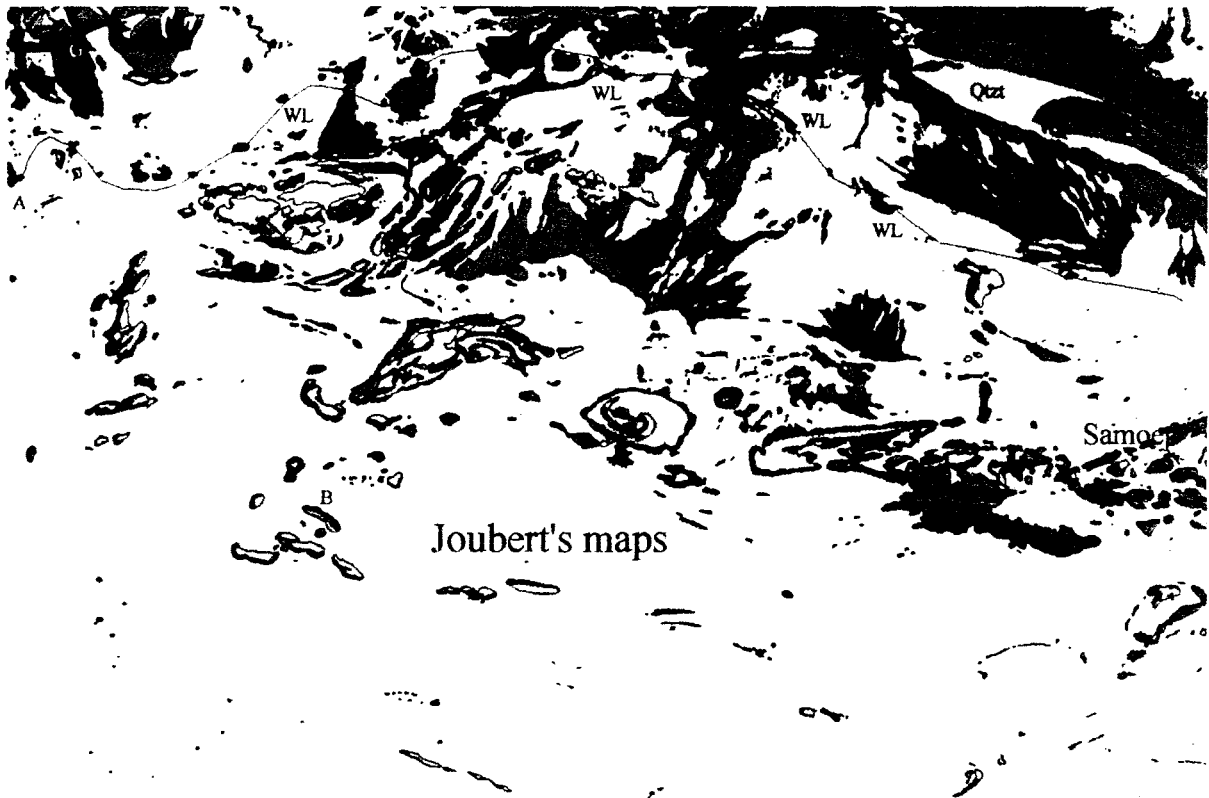
Figure 4.7

Granulite (G - blue) outcrops in the northwest corner of this figure. The Geological Survey (1972) called it grey granulite of unknown origin, while the BRG correlated it with mafic Vioolsdrif Suite rocks (Vuurdood Subsuite - diorite, gabbro). The Wortel Line (WL) of mafic gneiss (green) and intrusives (black) can be followed from just north of the Samoep synform at Nouzees, to the west at A. B - biotite gneiss. Qtzt - quartzite.

The Toeslaan Formation, mapped by Du Plessis (1989a), contains cordierite-sillimanite-garnet-biotite gneiss, with quartzo-feldspathic gneiss, quartzite and calc-silicate gneiss. This corresponds to the Arus Formation, and also to the Jerusalem Formation, since a correlation can be made across the Orange River at Stolzenfels between the Jerusalem and Toeslaan Formations (fig.4.2).

4.3.3.8 Granulite-gneiss and Charnockite

Stratigraphic Name	Lithological Description	Source
Stolzenfels Formation	Vary in composition from norite to enderbite	Toogood (1976b)
Stolzenfels Granite	Enderbite	Du Plessis (1989b)
Mafic Granulite	Similar to amphibolite but contains hypersthene and clinopyroxene. Associated with ortho-amphibolite.	Maclaren (1988b)
Grey Granulite	Grey granulite, amphibole-garnet-epidote rocks, hornblende diorite, amphibolite.	Geological Survey (1972)
Vuurdood Subsuite	Diorite, gabbro/norite, ultramafic rocks and their metamorphic equivalents	Strydom et al. (1989)

'Charnockite is a felsic, melanocratic, holocrystalline, alkali granitic' orthopyroxene-bearing rock (Bowes 1989). The orthopyroxene is usually hypersthene, and the Streckheisen-diagram for the classification of charnockites are the same as for granites, except that hypersthene is used as a prefix to the name, e.g. hypersthene-granite. There are various special names for charnockitic compositions such as enderbite for the more plagioclase-rich charnockites (hypersthene-tonalite), and norite (hypersthene-diorite) for quartz-poor, plagioclase rich charnockites. The paragenesis of the charnockites indicate granulite facies metamorphism, but there is still controversy concerning the petrogenesis of these rocks. Rocks of the charnockite suite are common to Proterozoic granite complexes (Bowes 1989).

Toogood (1976a) mapped a number of outcrops of norite and enderbite as the Stolzenfels Formation. Stolzenfels Formation varies in composition from norite to enderbite and is displayed on the lithological map as charnockite (Annexure 1). In area T the charnockites are closely associated with the granulite facies, Jerusalem cordierite-sillimanite-garnet gneiss

(correlated with the Arus Formation).

South of the Orange River, in area D, Du Plessis (1989b) mapped the extension of the charnockitic rocks (fig.4.2). Charnockites in this area plot more often in the enderbite field than in the norite field (Du Plessis 1989b) and are also closely associated with granulite facies, cordierite-sillimanite-garnet gneiss (Toeslaan Formation).

Further south on map M there are a number of small mafic, granulite bodies east of Pellaberg (Maclaren 1988a). They are interspersed with ortho-amphibolite with a possible co-genetic relationship, and contain hypersthene and clinopyroxene, but no quartz, and are classified as granulites by Maclaren (1988b).

On the lithological map the only other outcrop of granulite or charnockite south of the PSZ can be found in the southwestern corner of area V (Annexure 1, fig.4.5). Here the Geological Survey (1972) observed some outcrops of grey granulite, amphibole-garnet-epidote rocks, hornblende diorite and amphibolite, which the BRG correlated with the Vuurdood Subsuite (the mafic subsuite of the Vioolsdrif Suite) which contains diorite, gabbro/norite, ultramafic rocks and their metamorphic equivalents (Strydom *et al.* 1987).

4.3.3.9 Felsic Rocks

Stratigraphic Name	Lithological Description	Source
Tsams Formation	Metavolcanites, felsic lavas. Changes eastwards to layered felsic and biotite-bearing gneiss and schist	Strydom *et al.*(1987)
Leucocratic granites	Leucocratic granite	Joubert (1973 a and b)
T'Oubep Granodiorite Suite	Leucocratic hornblende-bearing granodiorites without well developed foliation. Calc-silicate xenoliths.	Maclaren (1988b)

Units described by the various workers as felsic, or containing rocks such as granodiorite or tonalite are designated felsic rocks. Felsic rocks have been divided on the lithological map, into felsic intrusives (Fi) and felsic extrusives (Fe). Grouped under felsic intrusives are all the granite

suite rocks with clear intrusive relationships and no well developed foliation. These are the younger intrusive rocks of the Namaqua Province, often called syn to post-tectonic intrusives. It isn't always clear from the literature which units belong to this group. Authors often name units according to the precursor rock of the metamorphic gneisses rather than the metamorphic name, so that the term granite is used for gneiss with a granitic composition (e.g. Du Plessis 1989b).

Other syntectonic felsic rocks described by Toogood have been discussed under other headings and are not displayed as Felsic-rocks. Joubert (1973 a and b) mapped numerous small leucocratic granite outcrops in the Pofadder area, and at Nouzees, where they are intruded into the mafic grey gneiss. Maclaren (1988a) mapped the T'Oubep Granodiorite Suite at T'Oubep (Annexure 1). These rocks are late syntectonic, leucocratic, hornblende-bearing granodiorites without well-developed foliation and containing calc-silicate xenoliths.

Rocks correlated by Strydom *et al.* (1987) with the Tsams Formation are included in the felsic extrusive group, since they include felsic extrusive or volcanoclastic rocks (Strydom *et al.* 1987, SACS 1980). These rocks outcrop in the southwestern corner of map B and on map V, near Pellaberg (Annexure 1).

4.3.3.10 Mafic Rocks

Stratigraphic Name	Lithological Description	Source
Tantalite Valley Complex	Gabbro, anorthosite, quartz-rich gabbro, small bodies of ultramafic intrusives - pyroxenite, peridotite, troctolite	Beukes and Botha (1976)
Kumkum mafic rock	Gabbro, hypersthene gabbro, olivine gabbro, norite and hypersthene norite.	Beukes and Botha (1976)
Kum Kum Formation	Mafic granolite. Foliated norite.	Toogood (1976b)
Mafic and ultramafic rock	Gabbro, olivine gabbro, olivine norite, pyroxenite, amphibolite, peridotite	Geological Survey (1976)
Hom Formation	Biotite-rich quartzo-feldspathic gneiss with thin layered mafic zones and calc-silicates	Strydom *et al.* (1987)
Nousees mafic gneiss	Grey gneiss, minor schist and quartzite.	Joubert (1973 a and b)
Mafic intrusives	Gabbro, norite, amphibolite	Joubert (1973 a and b)

Achab Suite	Porphyroblastic felsic and leucogranitoid gneisses with xenoliths of amphibolite, calc-silicate, quartzite, leucogranite.	Watkeys (1986)
Nousees Gabbronorite Suite	Olivine gabbronorite	Maclaren (1988b)

Included in this unit are all the mafic intrusives in the area. On map B there are several large mafic outcrops. The Tantalite Valley Complex consists mainly of gabbro with anorthosite and quartz-rich gabbro, and small bodies of ultramafic intrusives such as pyroxenite, peridotite and troctolite (Beukes and Botha 1976b). The Kumkum mafic rock consists of gabbro, hypersthene gabbro, olivine gabbro, norite and hypersthene norite according to Beukes and Botha (1976), or mafic granolite (Kum Kum Formation), which is similar in composition to the Stolzenfels norites, according to Toogood (1976b), but contain a crude foliation and mineral banding. The Kum Kum mafic granolite outcrops at the boundary between map B and map T (Annexure 1), and is the only unit on Toogood's map included in this group (Toogood 1976b). Mafic rocks in area D were discussed in the section on the amphibolite unit with which it correlates.

The Geological Survey (1972) mapped mafic and ultramafic rocks, consisting of gabbro, olivine gabbro, olivine norite, pyroxenite, amphibolite and peridotite, in the area V. There is no way of separating these lithologies on their map. The outcrops at Kabis, in the southwestern corner of map V, can be correlated with the mafic rocks of the Hom Formation of Strydom et al. (1987). The Hom formation has been described in the section concerned with felsic extrusives.

Southwards, just northwest of Pellaberg (Annexure 1), there are several mafic outcrops on map V, which can be correlated with the Hom Formation (Strydom et al. 1987) and, on map J, with the mafic intrusives indicated by Joubert (1972). East of Onseepkans, in area V, the biotite-hornblende-gneiss outcrop contains numerous mafic intrusions. This can, perhaps, be correlated with the mafic xenoliths in the Eendoorn Granite as described by Strydom et al. (1987).

In area J the mafic-rock unit corresponds to mafic intrusives (gabbro, norite and amphibolite) mapped by Joubert (1973 a and b). The Nouzees Gabbronorite Suite (fig.4.4, Maclaren 1988a) outcrops within the Samoep Synform. Reid et al. (1979) concluded that the Nouzees Gabbronorite Suite is similar to the other large mafic bodies in the Namaqua Province, such as

at Tantalite Valley and Kumkum. These bodies appear to have a genetic relation with the large shear zones in the Namaqua Province (Joubert 1986a). Pyroxene-bearing diorite occur near T'Oubep (Annexure 1).

The Wortel Line of mafic and ultramafic bodies, as indicated by Joubert (1986a), extends from just north of Nouzees, westwards through the area of the lithological map (Annexure 1) as indicated in figure 4.7, to the Geselskapbank Synform (outside the map area). The Nouzees Gabbronorite Suite was emplaced *circa.* 1400 Ma ago and is not included in the Wortel Line of mafic intrusives, for which an age of 1000Ma is generally accepted (Joubert 1986a).

4.3.3.11 Kimberlite, Dolerite and Pegmatite

Kimberlite pipes have been mapped in the southwest corner of map J, by Joubert (1972), and at Nouzees by Maclaren (1988a). Numerous dolerite dykes and sills, of Karoo Supergroup age, are present in area M. Pegmatites are indicated on the lithological map in all the different areas, but these outcrops are generally small and, as a result of the small scale, difficult to see.

Chapter 5

Customised Maps of the Central Namaqua Province

5.1 Introduction

The collated lithological map of the Central Namaqua Province reflects one layer of information available in the database. It is the answer to an elaborate query which accessed only the lithological tables. Other data tables can also be utilised, on their own or integrated with each other. Lithological and stratigraphical interrelations and patterns can be sought by querying the database appropriately. Maps produced by such queries are called customised maps. This chapter is an introduction to the production of customised maps from the digital map database of the Central Namaqua Province. Three query examples are discussed.

5.2 Queries to the Database

A query is a logical way of accessing information in a database by establishing a set of criteria for the selection and output of data. It is written in the data manipulation language provided by the DBMS. Results of queries can be in any of the geographic forms available to the GIS, depending on the type of spatial database associated with the query and on the type specified in the query. This project is concerned with geological maps and the results of the queries will be in the form of geological maps which will be printed as figures. The format for this chapter will be a number of query examples with accompanying explanations to the queries, results in the form of figures and short discussions of the results. A summary of results concludes the chapter.

It was established in the previous chapter that a query in the TNTmips™ database manipulation language consists of two parts: 1. Element Selection and 2. Element Display Style.

1. Element Selection

Elements to be displayed are selected by a set of criteria, e.g. all outcrops described as having quartzite as a constituent lithology are selected.

2. Element Display Style

Elements chosen in the first part of the query are displayed according to styles specified in this part. For example, if a quartzite outcrop, selected in the first part, also has quartz-muscovite schist as a constituent lithology, the polygon should be displayed with a black border and a yellow interior, otherwise display it with a black border and a light green interior.

5.3 Query Examples[1]

5.3.1 Introduction

In order to use the digital database as a tool to study the geology of the Central Namaqua Province (CNP) it is necessary to review the latest model of the geological history of the area, so that it is possible to recognise meaningful results. Moore (1989) and Moore *et al.* (1990) proposed a model of Proterozoic accretionary tectonics for the Namaqua Province. Results will be discussed with reference to this model.

According to the model, three distinct basement components are recognised, which correspond roughly to the subprovinces proposed by Hartnady *et al.* (1985) for the Namaqua Province, namely the Gordonia, Richtersveld and Bushmanland Subprovinces (fig.1.1). Subduction of oceanic crust at the margin of a supercontinent caused the formation of a magma chamber (at ca. 2000 Ma) from which, due to fractionation of the magma, increasingly felsic lava (from basaltic-andesite to dacite and rhyolite) were extruded onto the surface, forming the Orange River Group. The fractionated magma intruded its own volcanic ejecta crystallizing as plutons comprising the Vioolsdrif Suite of granitoids (Minnit 1992). These two lithologies constitute the basement of the Richtersveld Subprovince. A later suite of leucogranites (ca. 1750 Ma) are believed to be related to the deposition of later supercrustal units. Concurrent to the early intrusive event, a backarc basin was established in which the meta-greywackes, quartzites and calc-silicate units of the Grunau (Umeis and Arus Formations) and Korannaland (Toeslaan Formation) Sequences

---

[1] *Refer to fig.1.1 for the position of the Pofadder Shear Zone and the distribution of tectonic terranes in the Namaqua Province.*

were deposited. These units are intercalated with rocks of the Orange River Group and are therefore of a similar age to rocks of the Orange River Group (ca. 2000Ma).

The Bushmanland microcontinent consisted of Achab porphyroblastic and banded migmatitic grey gneiss, before it collided with the Richtersveld continent margin. Underplating of the microcontinent caused the second phase of acidic intrusions in the Richtersveld area around 1750 Ma. The Wortel Line mafic gneiss and intrusives are believed to be remnants of oceanic crust obducted onto the supercontinent at the Groothoek Thrust (Moore 1989).

This collision event was followed by a period of extensional tectonics, with lithospheric rifting and accompanying acid-dominated volcanism and transgressive siliclastic sedimentation on the microcontinental side of the suture zone (essentially the Groothoek Thrust and Wortel Line). The volcanoclastic and siliclastic sediments were deposited in a peripheral basin forming a shallow marine continental sequence comprising feldspathic sandstone (quartzite with sedimentary structures), psammitic (quartz-muscovite schist) and pelitic (biotite-sillimanite schist) sediments in upward fining cycles. Volcanoclastic sediments are represented by the leucogneisses (Hoogoor Suite), which are interpreted by Watkeys et al. (1988) to be subaerially-deposited acid volcanic tephra.

Around 1600 Ma ago the peripheral basin became more restricted with limited access to open marine environments. Acid-dominated volcanism continued and shales and siliceous cherts (quartzites without sedimentary structures) were deposited. Restricted anaerobic basins also gave rise to manganiferous iron formations and base metal sulphide deposits at the top of the succession. The geochemical composition of the metapelitic rocks indicates derivation from material similar in nature to the underlying leucogneisses (Moore et al. 1990).

In the period from 1500 Ma to 900 Ma subduction resumed to the northwest and southwest of present day Namaqua Province. Effects of this event are encountered in the supercontinent margin, specifically the Gordonia backarc basin sequences, and the microcontinent corresponding to the Bushmanland Subprovince. The effects are less evident in the Richtersveld Subprovince, which is possibly due to the thick batholithic nature of the area, and the more easily

deformed surrounding units of the Gordonia and Bushmanland Subprovinces. Subduction and underplating of continental crust induced formation and emplacement of the syn- and post-tectonic Eendoorn, Aroams, Naros and T'Oubep granitoids. Deformation affected both basement and supercrustal units. Thrust fault tectonics dominated initially, with large scale isoclinal and sheath folding, and reactivation of the large Groothoek Thrust zone. Subsequent deformation events involved lateral shearing and, around 1000 Ma to 900 Ma pegmatites were emplaced along the Orange River.

Features of this model pertinent to the present project are the distribution of the various lithotectonic units, such as basement and supercrustal units, the distribution of units in relation to tectonic terranes, an investigation into the extent of supercrustal units, and the effect of the lateral shearing event. The following three queries will demonstrate the effectiveness of a digital map database for investigating a model for the geological history of a complex terrain.

5.3.2 Distribution of Lithotectonic units in the CNP

Supercrustal units in the CNP are well established as a sequence of leucogneiss at the bottom, followed by fining upwards sequences of quartzite, biotite-sillimanite schist, quartz-muscovite schist and calc-silicate gneiss (Joubert 1986a, 1986b, Moore 1977, 1989, Moore *et al.* 1990, Colliston *et al.* 1989). In some restricted areas, mainly within the area of this project, the top of the sequence is made up of iron-formation, cherts (or pure quartzites), and in some places, such as Gamsberg and Aggeneys, basemetal sulphide deposits.

Basement assemblages have been more difficult to recognize (Moore 1977, 1989, Moore *et al.* 1990, Joubert 1986b, Watkeys 1986), especially in the Bushmanland Subprovince, as the supercrustal units seem to dominate outcrop. Achab suite migmatitic, augen gneisses outcrop in a small number of areas, notably south and north of Namiesberg, south of Aggeneysberge and southwest of Haramoep. Moore (1977) and Watkeys (1986) argue that these rocks represent the basement to the Bushmanland Group of supercrustal rocks, since they have undergone more deformation events than the supercrustal units. The Richtersveld basement consists of Vioolsdrif Suite of granitoids and coeval Orange River Group lavas and volcanoclastics. Migmatites of the

Grunau and Korannaland Sequences in the Gordonia Subprovince are intercalated with Orange River units and are thought to be of a similar age. The estimated age of these migmatites suggest that they are also basement rocks onto which supercrustal rocks (especially leucogneisses) overlap.

Query 5.1 examines the distribution of these lithotectonic units in the CNP.

Query 5.1a Selection Query

Select all polygons.

Query 5.1b Display Style Query

Outcrops are displayed according to their tectonic distribution.

```
1    DrawBorder = 1      # System variable to indicate that a border must be drawn for chosen polygon
2    FillInside = 1      # System variable to indicate that the interior must be filled

3    DrawColor$ = "white"      # System variable to indicate default colour of polygon border
4    FillColor$ = "white"      # System variable to indicate default colour with which the polygon interior should be filled


5    Determining the colour of the selected polygon.

6    If (Tectobase.Basement) then      # if the polygon represents basement lithology it is coloured grey
7           {DrawColor$ = "grey"
8            FillColor$ = "grey"}

9    if (Tectobase.Basement and Tectobase.Migmatite) then      # If it represents basement migmatite it is coloured blue
10          {DrawColor$ = "blue"
11           FillColor$ = "blue"}

12   if (Tectobase.Intrusive) then      # Intrusives are brown (including Vioolsdrif Suite)
13          {DrawColor$ = "brown"
14           FillColor$ = "brown"}

15   if (Tectobase.Extrusive) then      # Extrusives are yellow
16          {DrawColor$ = "yellow"
17           FillColor$ = "yellow"}

18   if (Tectobase.Supercrustal and !(Tectobase.Extrusive)) then      # Supercrustal units (excluding extrusives) are green
19          {DrawColor$ = "green"                                      # '!' represents the logical operator 'not'
20           FillColor$ = "green"}

21   if (Tectobase.Cover) then      # Cover sequences are not displayed
22          {DrawColor$ = "white"
23           FillColor$ = "white"}
```

Query

Query 5.1 is very simple in construction as a consequence of the structure of the Tectobase data table. Boolean fields are easy to use and result in a query that reads well. Lines 18 to 20 determine the colour in which supercrustal units are to be displayed. The **and not** operator in line 18 separates extrusives from other supercrustal units. Extrusives of the Orange River Group, although strictly supercrustal, are classified by Moore *et al.* (1990) as basement.

Legend

■ Supercrustal Units (excluding extrusives)
▨ Extrusives
■ Basement Migmatites
■ Syntectonic Intrusives
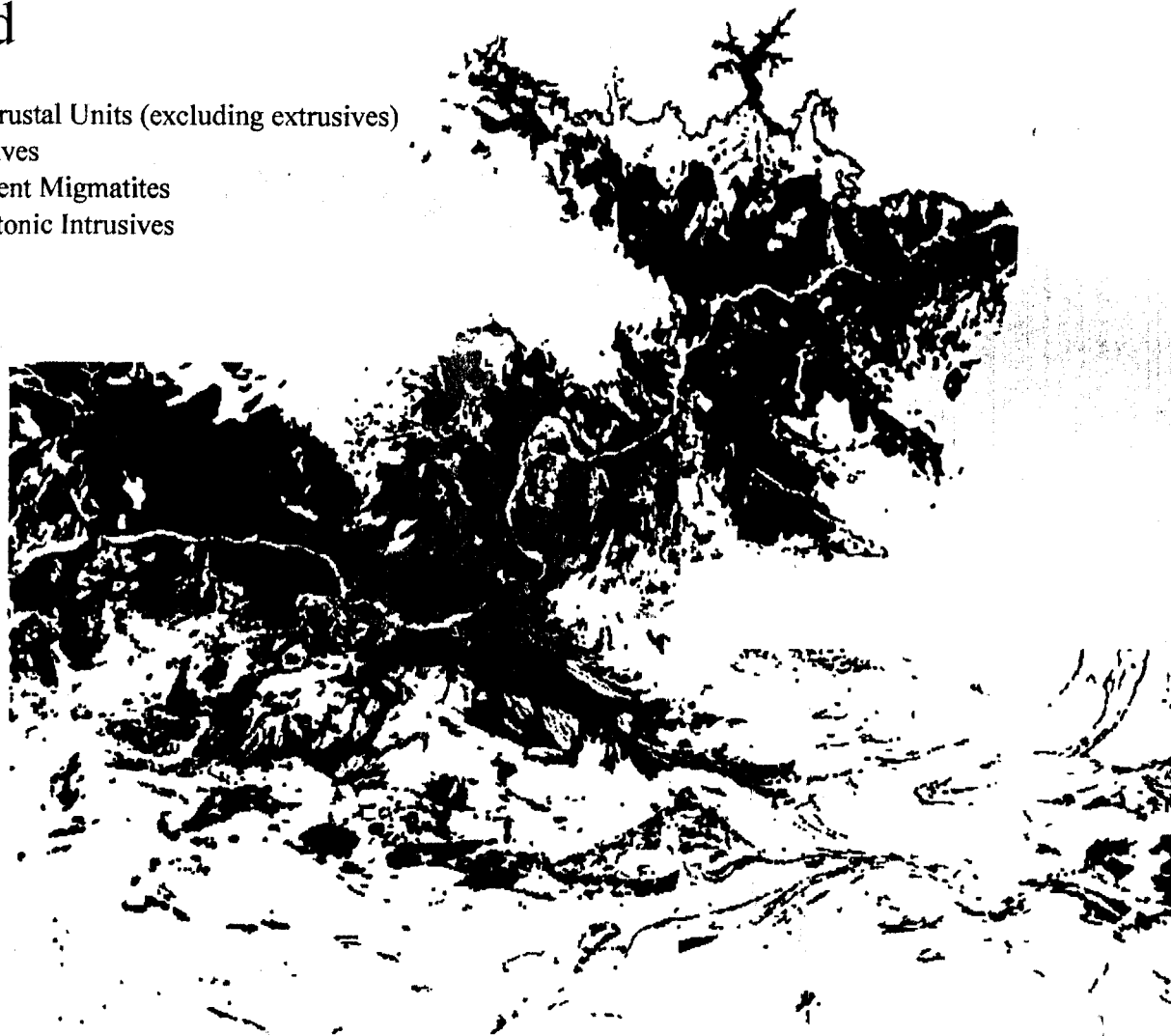
Figure 5.1

Displayed are the main lithotectonic components of the Central Namaqua Province. Supercrustal units (green) consist of metavolcanic and metasedimentary sequences of leucogneiss and quartzite/schist assemblages. These are distributed across the entire area, with the main concentration in the southern half of the map. Supercrustal units north of the Pofadder Shear Zone (PSZ) consist mainly of quartzo-feldspathic gneiss, with minor quartzite and schist horizons. The syntectonic intrusives (brown) include Vioolsdrif Suite granitoids, which together with the Orange River extrusives (yellow), constitute the basement sequence of the Richtersveld Subprovince. Syntectonic intrusives also include augen gneisses, such as Aroams and Eendoorn gneiss, mafic intrusives (Wortel Line, Tantalite Valley and Kumkum), charnockites and late syntectonic granodiorite and tonalite. Basement migmatites (blue) are mostly confined to the Gordonia Subprovince where they comprise the Grunau and Korannaland Sequences, with the Achab Suite of porphyroblastic and banded grey gneisses constituting a basement to the Bushmanland Subprovince.

Results

It is immediately evident from figure 5.1 that supercrustal units are concentrated in the southern half of the study area, while basement lithologies are more prominent in the north. Supercrustal units to the north of the Pofadder Shear Zone (PSZ) consist mainly of quartzo-feldspathic gneiss, while those to the south are sequences of leucogneiss and quartzite-schist assemblages. In some areas north of the shear zone supercrustal units are intercalated with basement gneisses, for example, just north of the PSZ (west of Onseepkans), while in others, such as at Stolzenfels and Nautsis, they appear distinctly intrusive into the basement units.

The change from abundant supercrustal units to basement gneisses coincides with the PSZ. Southwest of the PSZ there are a few outcrops of Achab Suite migmatites and porphyroblastic gneiss, and comprehensive outcrops of supercrustal units. Northeast of the shear zone, basement units are more evident, with thin slivers of supercrustal units. Syntectonic intrusives are also more obvious towards the north, with outcrops much less evident in the south, especially in the southeast where sand cover might be concealing outcrop.

Assuming, from present supercrustal outcrop pattern, as revealed by figure 5.1, that supercrustal units covered the whole study area, it is possible that the abundance of basement migmatite outcrop in the area northeast of the PSZ is a result of upliftment of the crust in the northeast relative to the southwest. Consequently thicker supercrustal units were preserved in the Bushmanland Subprovince southwest of the PSZ, while erosion exposed a deeper crustal section containing basement gneisses and basal units of the supercrustal sequence to the north of the PSZ (fig.5.4a).

5.3.3 Distribution of Quartzite in the CNP

Quartzites in the Central Namaqua Province are mostly classified within the supercrustal Bushmanland Group. Their distribution should indicate the extent of these supercrustal units in the CNP. Geologists mapping the CNP often include quartzites as secondary lithologies in stratigraphic units and these were also searched for in the database. Maclaren (1988) mentioned that the granular quartzites in his area graded into calc-silicate gneiss, and since there are a few

calc-silicate outcrops associated with quartzite in the area mapped by Toogood (1976) north of the Pofadder Shear Zone (PSZ), calc-silicate gneisses, as dominant lithologies[2] within outcrops and units, were included in the query.

Query 5.2a Selection Query

Query to select all outcrops containing quartzite as a constituent lithology and all outcrops containing calc-silicate as a major lithology.

```
# Display polygon for which:
1    Lithbase.Lith0 == "quartzite" or Lithbase[1].Lith0 == "quartzite" or Lithbase[2].Lith0 == "quartzite" or
2    Lithbase.Lith1 == "quartzite" or Lithbase[1].Lith1 == "quartzite" or Lithbase[2].Lith1 == "quartzite" or
3    Lithbase.Lith2 == "quartzite" or Lithbase[1].Lith2 == "quartzite" or Lithbase[2].Lith2 == "quartzite" or
4    Lithbase.Lith3 == "quartzite" or Lithbase[1].Lith3 == "quartzite" or Lithbase[2].Lith3 == "quartzite" or
5    Lithbase.Lith4 == "quartzite" or Lithbase[1].Lith4 == "quartzite" or Lithbase[2].Lith4 == "quartzite" or
6    Lithbase.Lith5 == "quartzite" or Lithbase[1].Lith5 == "quartzite" or Lithbase[2].Lith5 == "quartzite" or
7    Lithbase.Lith0 contains "calc_s" or Lithbase[1].Lith0 contains "calc_s" or Lithbase[2].Lith0 contains "calc_s" or
8    UOFSLith.Lith0 == "quartzite" or UOFSLith.Lith0 contains "calc_s" or UOFSLith.Lith1 == "quartzite" or
9    UOFSLith.Lith2 == "quartzite" or UOFSLith.Lith3 == "quartzite" or UOFSLith.Lith4 == "quartzite" or
10   UOFSLith.Lith5 == "quartzite"
```

Query 5.2b Display Style Query

Query to add particular display parameters to polygons, according to lithology and if the lithology is quartzite, according to the level of prominence within a unit.

```
11   DrawBorder = 1      # System variable to indicate that a border must be drawn for chosen polygon
12   FillInside = 1      # System variable to indicate that the interior must be filled

13   DrawColor$ = "white"      # System variable to indicate colour of polygon border
14   FillColor$ = "white"      # System variable to indicate colour with which the polygon interior should be filled


15   Determining the colour of the polygon:

16   if (Lithbase.Lith5 == "quartzite" or Lithbase[1].Lith5 == "quartzite" or Lithbase[2].Lith5 == "quartzite" or
17   UOFSLith.Lith5 == "quartzite") then
18           {DrawColor$ = "green"
19            FillColor$ = "green"}

20   if (Lithbase.Lith4 == "quartzite" or Lithbase[1].Lith4 == "quartzite" or Lithbase[2].Lith4 == "quartzite" or
21   UOFSLith.Lith4 == "quartzite") then
22           {DrawColor$ = "magenta"
23            FillColor$ = "magenta"}

24   if (Lithbase.Lith3 == "quartzite" or Lithbase[1].Lith3 == "quartzite" or Lithbase[2].Lith3 == "quartzite" or
25   UOFSLith.Lith3 == "quartzite") then
26           {DrawColor$ = "red"
27            FillColor$ = "red"}
```

---

[2] *Chapter 3 Section 3.3.3 discusses the implementation of unit divisions in the Lithbase data table.*

```
28   if (Lithbase.Lith2 == "quartzite" or Lithbase[1].Lith2 == "quartzite" or Lithbase[2].Lith2 == "quartzite" or
29   UOFSLith.Lith2 == "quartzite") then
30           {DrawColor$ = "brown"
31            FillColor$ = "brown"}

32   if (Lithbase.Lith1 == "quartzite" or Lithbase[1].Lith1 == "quartzite" or Lithbase[2].Lith1 == "quartzite" or
33   UOFSLith.Lith1 == "quartzite") then
34           {DrawColor$ = "orange"
35            FillColor$ = "orange"}

36   if (Lithbase.Lith0 == "quartzite" or Lithbase[1].Lith0 == "quartzite" or Lithbase[2].Lith0 == "quartzite" or
37   UOFSLith.Lith0 == "quartzite") then
38           {DrawColor$ = "yellow"
39            FillColor$ = "yellow"}

40   if (Lithbase.Lith0 contains "calc_s" or Lithbase[1].Lith0 contains "calc_s" or Lithbase[2].Lith0 contains "calc_s" or
41   UOFSLith.Lith0 contains "calc_s") then          # 'calc_s' is a subset of the string 'calc_silicate'
42           {DrawColor$ = "cyan"
43            FillColor$ = "cyan"}
```

Query

In the query language the "==" operator (line 1) indicates that an equality comparison is made between the expressions on either side. "Contains" (line 7) is a specific comparison operator applied to subsets of string expressions only, where strings are sets of alphanumeric characters such as "123abc". "Contains" establishes whether one string is a subset of another, which can simplify a query enormously. The expression ("hb_bt_gneiss" contains "hb") is true, because "hb" is a subset of "hb_bt_gneiss". It is therefore possible, for instance, to search for mafic gneisses in the database by searching the database for the subsets "gneiss" **and** "hb". This possibility is investigated in a following example.

Lithbase[n].Lithα (line 1) stores a value in field Lithα (where α = 0 to 5) of table Lithbase record n (where n is the number of the record from the same table attached to the polygon, with n = 0 as the default value). Most polygons have more than one Lithbase record attached to them (only up to three records). If the value in Lithbase[n].Lithα, attached to the selected polygon, is the same as the string value "quartzite" then display it with a certain style.

Only polygons with attached lithology records containing a value of quartzite or calc-silicate are chosen. The selection for quartzites are more detailed since all the levels in the Lithbase and UOFSLith tables need to be searched. Calc-silicate is only selected for if it is a major lithology of the outcrop represented by the polygon.

Selected polygons are then classified by the style query according to the abundance of quartzite in the unit, and according to whether they contain quartzite or calc-silicate as a major constituent. Each class (indicated by if..then statements in lines.16 to 20) is given a colour for the polygon border and interior.

Results

Yellow and light blue indicate polygons with quartzite and calc-silicate rocks as major lithologies respectively (fig.5.2). Orange polygons are also important indicators of supercrustal rock distribution, since Strydom *et al.* (1987) describe several supercrustal units where quartz-mica schists are the major lithologies and quartzites second most abundant in the unit. Such units are still part of the Bushmanland Group.

Quartzite, as the main lithology in units, is most abundant in the area southwest of the PSZ, especially in the Bushmanland Subprovince (fig.5.2). Northeast of the shear zone, quartzite units are mostly absent from areas mapped by Strydom *et al.* (1987), Toogood (1976a) and Du Plessis (1989a), while still appearing in the area mapped by Maclaren (1988a) as narrow horizons which grade into calc-silcate gneiss to the east. There is a marked decrease in unit thickness across the PSZ from areas mapped by Joubert (1973a and b) to the area mapped by Maclaren (1988a).

As secondary lithologies (brown, red and pink polygons), quartzite outcrop is more extensive. Brown units, almost exclusive to the northern half of the map, are quartzo-feldspathic units containing quartzite as minor horizons within them. Red and pink quartzite units are associated with mafic gneiss, correlated mostly with Orange River Group lavas and volcanoclastics and are therefore not indicative of the Bushmanland Group distribution. Quartzites, displayed as red polygons near Aggeneys, Namies and Gamsberg, are minor components of the Achab Suite (Watkeys 1986).

Calc-silicate gneisses appear towards the east of the map, in the area mapped by Maclaren (1988a). There are a number of narrow horizons of calc-silcate gneiss northeast of the PSZ, at Pelladrift (Annexure 1, fig.5.2), associated with quartzo-feldspathic gneisses. The calc-silicate gneisses ocurring towards the center of the map are xenoliths within syntectonic granites

(Strydom *et al.* 1989).

It is evident, from figure 5.2, that quartzite (or supercrustal) units decrease in thickness, and grade into calc-silicate dominated units, from west to east across the CNP. Results of the previous query (fig.5.1) have indicated crustal uplift in the area north of the PSZ, and the observations made from figure 5.2 lends support to this proposal. Figure 5.4b illustrates a mechanism to account for the observed change in unit thickness of the quartzites from west to east across the PSZ. All that remains after erosion of the uplifted block, are the thin basal segments of supercrustal synformal structures, which were similar to those still exposed in the southwestern areas, such as at Namies and Aggeneys.

An increasing component of calc-silicate gneiss towards the east is an indication of increasing exposure of units at the base of the supercrustal sequence, since calc-silicates commonly occur near the base of the supercrustal sequences in the Namaqua Province (Moore 1989). There is evidence of lenses of marble and scapolite-, garnet- and diopside-rich rocks occurring in the eastern extremities of his study area, which may be an indication of increased metamorphic grade. North of the PSZ at Onseepkans, Toogood (1976) mapped narrow bands of calc-silicate gneiss and quartzite (fig.5.2). He also observed calc-silicate boudins within the basement biotite gneisses (Moore *et al.* 1990), which he described as 'tectonically disrupted remains of formerly continuous layers' (Toogood *op.cit.*). Basement gneisses in the Bushmanland Subprovince also contain calc-silicate lenses. In summary: calc-silicate gneiss and marble are associated with the basal units of the supercrustal rocks and also occur in the basement gneiss. Their presence in the outcrop pattern may therefore imply the exposure of deeper crustal levels in areas northeast of the PSZ.

It has been mentioned that quartzite outcrops are not widespread in the areas mapped by Toogood, Du Plessis and Strydom *et al.*, while still relatively abundant in the area mapped by Maclaren. Harris (1992) discusses a mechanism (illustrated in fig.5.4c), whereby the crust northeast of the PSZ was incrementally uplifted along thrust zones, which clarifies this observation. This offers an explanation for the lack of evidence for large vertical components of movement along the PSZ in the area mapped by Maclaren (1988b). Toogood (1976b) proposed

a component of vertical movement along the PSZ in the northern areas of the Gordonia Subprovince on metamorphic evidence, indicated in figure 5.4c.

According to Moore *et al.* (1990), the siliclastic metasedimentary sequences of the supercrustal rocks (Bushmanland Subprovince) are derived from the metavolcanic leucogneiss units, which occur below the metasedimentary units, at the base of the supercrustal sequence. The quartzite-bearing leucogneisses (brown units in fig.5.2) just north of the PSZ show intrusive relationships and are believed to be the proximal equivalents of the Bushmanland Subprovince leucogneiss extrusives. The quartzite-bearing leucogneisses are very extensive north of the PSZ and it is possible that they served as source rocks for the siliceous metasedimentary sequences in the Bushmanland Subprovince to the south, especially if uplift of the Gordonia Subprovince crust occurred (fig.5.4a).
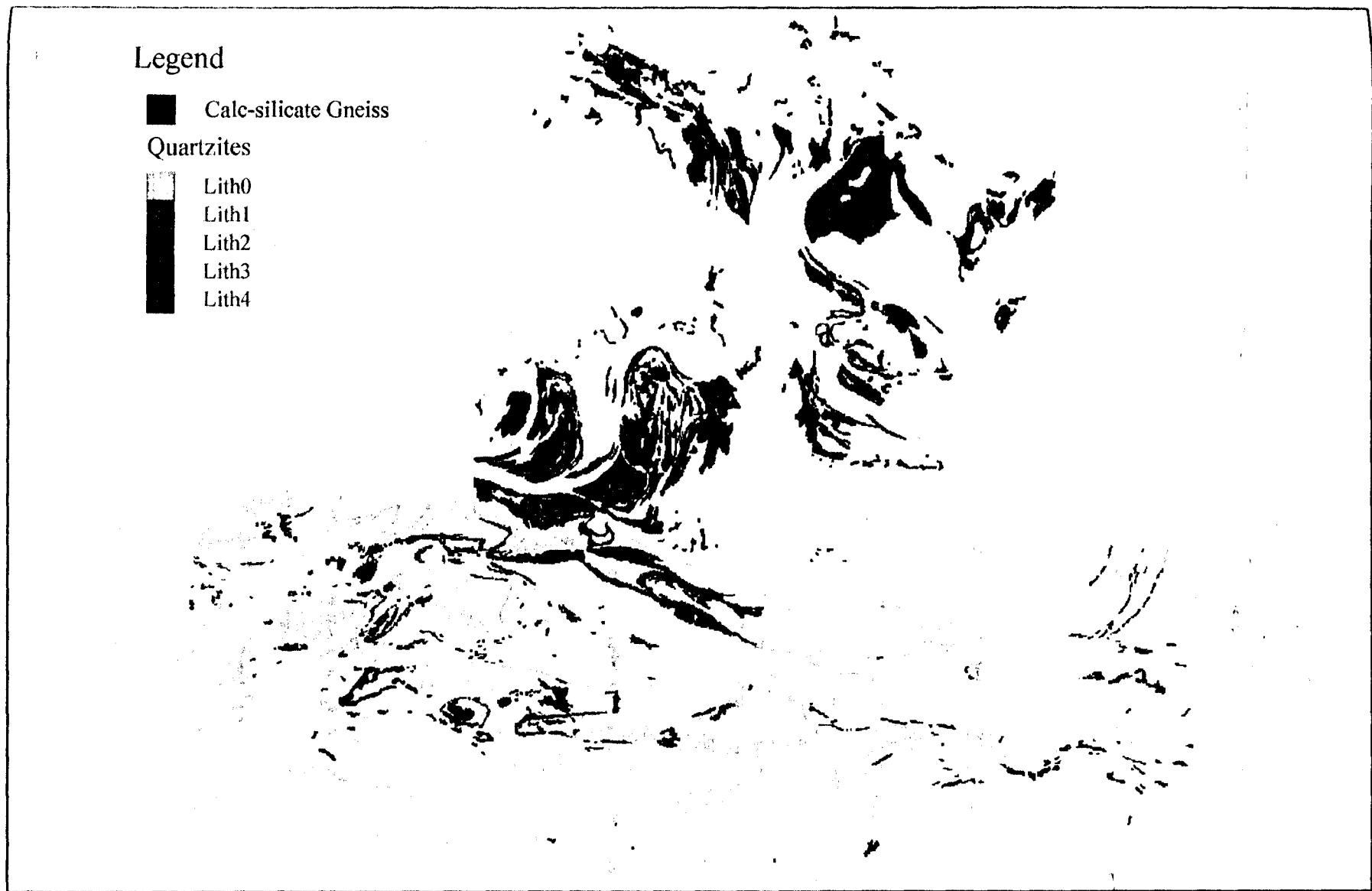
Figure 5.2 This map highlights the distribution of all units containing quartzite as a constituent, as well as units containing calc-silicate gneiss (light blue) as a major constituent. The quartzites are displayed in various colours according to the abundance of quartzite in the unit (abundance decreases from Lith0 to Lith4).

5.3.4 Investigation of the Pella Terrane

On studying the lithological map discussed in chapter 4 (Annexure 1), it appears that the rock types in the Pella Terrane change dramatically across the Pofadder Shear Zone from granite gneiss in the west to more mafic (hornblende and hornblende-biotite) gneiss in the east. The following query will investigate this possibility by isolating mafic gneiss in the Pella Terrane from other rocks within that terrane.

Query 5.3a Selection Query

Select all polygons.

Query 5.3b Display Style Query

Display all selected polygons (outcrops) with a black border and interior, unless they contain supercrustal rocks (yellow), are in the Pella terrane (grey), are mafic gneiss and in the Pella Terrane (orange), or are mafic gneiss and within the Gordonia Subprovince (red).

```
1    DrawBorder = 1
2    FillInside = 1
3    DrawColor$ = "100 100 100"  # Default display style for polygons - white border (100 Red + 100 Blue + 100 Green = White)
4    FillColor$ = "100 100 100"  # white interior
5    mafic = 0; pella = 0; gordonia = 0       # Boolean variables (1=true, 0=false)

6    if (Tectobase.Supercrustal) then        # Tectobase.Supercrustal is a Boolean field (true or false values only)
7            {DrawColor$ = "yellow"
8             FillColor$ = "yellow"}

9    if (Lithbase.Lith0 contains "hb" or Lithbase[1].Lith0 contains "hb" or Lithbase[2].Lith0 contains "hb" or
10   Lithbase.Lith0 contains "mafic_gneiss" or Lithbase[1].Lith0 contains "mafic_gneiss" or
11   Lithbase[2].Lith0 contains "mafic_gneiss" or UOFSLith.Lith0 contains "hb" or
12   UOFSLith.Lith0 contains "mafic_gneiss" orSURVLith.Lith0 contains "hb" or
13   SURVLith.Lith0 contains "mafic_gneiss") then mafic = 1     # If selected outcrop does contain mafic gneiss - mafic is true

14   if (Divbase.Terrane == "Pella") then pella = 1      # If selected outcrop is in the Pella Terrane then pella is true

15   if (Divbase.Subprovince == "Gordonia") then gordonia = 1   # If selected outcrop is in the Gordonia Subprovince then
16                                                              gordonia # is true.

17   if (pella == 1 and !(Tectobase.Supercrustal)) then        # All units other than supercrustal Pella Terrane
18            {DrawColor$ = "grey"
19             FillColor$ = "grey"}

20   if (mafic == 1 and pella == 1) then               # Mafic units in Pella Terrane
21            {DrawColor$ = "orange"
22             FillColor$ = "orange"}

23   if (gordonia == 1 and !(Tectobase.Supercrustal)) then       # All units other than supercrustal in Gordonia Subprovince
```

```
24          {DrawColor$ = "blue"
25           FillColor$ = "blue"}

26  if (mafic == 1 and gordonia == 1) then        # Mafic units in Gordonia Province
27          {DrawColor$ = "red"
28           FillColor$ = "red"}
```

Query

All polygons are selected for display. A number of Boolean variables are declared in line 5 - mafic, pella and Gordonia. These have values of one if true or zero if false and are there to make the query more readable. The default colour for polygons is white (line 3 and 4). Supercrustal units are yellow (lines 6 to 8). All units in the Pella Terrane are grey (line 17 to 19), unless they are mafic gneiss or supercrustal. Mafic gneiss within the Pella Terrane is coloured orange (line 20 to 22) and within the Gordonia Subprovince red (line 26 to 28). Units other than mafic gneiss and supercrustals in the Gordonia Province are coloured blue (line 23 to 25). The Gordonia Subprovince in the area covered by the digital database is equivalent to the Aus Terrane, since that is the only terrane in the Subprovince within the study area (fig.1.1, Hartnady *et al.* 1985). The order of the colour assignment expressions is important for the colour scheme. If mafic gneiss in the Pella Terrane were assigned a colour before all other rocks in the terrane were given a colour, the resultant colour for mafic rocks in the terrane would also have been grey, since 'mafic rocks' is a subset of the set 'all units in the Pella Terrane'. The colour scheme above provides the opportunity to compare the distribution pattern of mafic gneiss in the Pella Terrane with that in the Gordonia Subprovince.

Results

Blue polygons in figure 5.3 represent mainly biotite gneiss from the Umeis Formation and Eendoorn Granite, but also include a number of mafic intrusives (Tantalite Valley) and biotite-cordierite-sillimanite-garnet gneiss (Arus Formation)[3]. The mafic, migmatitic gneiss of the Gordonia Subprovince (Aus Terrane) is indicated in red. The supercrustal units in the Gordonia Subprovince, indicated in green, constitute mainly quartzo-feldspathic gneiss of the Hoogoor

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[3] *The main function of this database query is to isolate basement hornblende and biotite-hornblende gneisses from other units in the Pella Terrane by displaying it in a different colour from the rest, so that it can happen that supercrustal and intrusive units are displayed in the same colour.*

Suite. In the Pella Terrane, to the west of the PSZ, grey represents mainly Viooolsdrif Suite granite gneiss, while east of the PSZ grey indicates biotite gneiss (Eendoorn Granite), charnockite, bt-cordierite-sillimanite-garnet gneiss (Toeslaan Formation) and granite gneiss (Swartmodder and Witwater granites). Supercrustal units in the Pella Terrane are displayed in yellow. The mafic gneiss (orange) in the western parts of the Pella Terrane form part of the Wortel Line on the boundary between the Pella and Okiep Terranes. Only supercrustal units (brown) are indicated for the Bushmanland Subprovince.

As a result of this query it is possible to suggest a review of the Pella Terrane boundaries, specifically where they extend across the PSZ. It appears from figure 5.3 that the Pella Terrane, east of the PSZ belongs to the Gordonia Subprovince, as part of the Aus Terrane, rather than to the Richtersveld.

It is clear from the map that overlap of supercrustal units occurs onto the different terranes, for example, at Stolzenfels in the northeast of the study area, north of Houms River (refer to Annexure 1 for localities) in the northwest and in places along the southeastern boundary of the Pella Terrane. Basement gneisses are more critical in defining terranes in the Namaqua Province, since supercrustal units can accumulate after accretion and therefore overlap onto different allochtonous terranes. If a basement gneiss sequence straddle a terrane boundary, it would indicate that no discontinuity, in the form of a fault, exists between the proposed terranes. The two opposed areas cannot therefore be allochtonous since they share the same tectonic history, at least as far back as the formation of the basement units (Schermer *et al.* 1984).

Basement overlap can be seen at Stolzenfels, further west along the Orange River, at Nous and at Onseepkans and Pelladrift (refer to Annexure 1 for localities), where orange and red units (mafic gneiss) straddle the boundary between the Pella and Aus Terranes. The exact position of the boundary in these areas are therefore uncertain and should be investigated further.

Figure 5.3 highlights the change in the broad lithological composition of the Pella Terrane from west to east across the PSZ. West of the PSZ the terrane consists mainly of granite intrusives with narrow bands of supercrustal rocks overlying them, while to the east of the shear zone there

is a marked increase in the mafic gneiss component. Here mafic gneiss is intercalated with supercrustal units, which is similar to the association of mafic and supercrustal units in the Gordonia Subprovince, in the area mapped by Toogood (1976), particularly just north of the PSZ. In the area mapped by Du Plessis (1989) mafic gneiss units are less abundant, which is also true of the area mapped by Toogood (1976), around Stolzenfels.

The Wortel Line of mafic intursives and gneiss, outcropping along the southern boundary of the Pella Terrane, terminates at Nouzees, not far from the PSZ (Joubert 1986a). According to Moore (1989) this is possibly the remains of a suture zone, formed when the Bushmanland microcontinent accreted to the Richtersveld-Gordonia continental margin *circa* 1750 Ma. There are only a few other outcrops of mafic gneiss in the Terrane, just south of Dabenoris, and, from figure 5.3, they appear to be small intrusive bodies[4].

The southern boundary of the Pella Terrane can therefore be followed on figure 5.3, from the west, along the Wortel Line to where it terminates against the PSZ. From there the boundary is not obvious from the lithological distribution in figure (5.3). The northern boundary is less clear from a lithological viewpoint. A possible boundary line exists along the PSZ, from where the Houms River leucogneisses (yellow supercrustal units) terminate against the PSZ, southeastward to the Orange River. From here the boundary should continue along the PSZ to the termination point of the Wortel Line. This suggestion is based solely on lithological evidence revealed by the query.

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[4] *Strydom et al. 1987, mapped these as Hom Formation while the Geological Survey mapped it as granitic gneiss. The reader is referred to Chapter 4 of this document for a description of these units.*

Legend

■ Supercrustal units in the Bushmanland Subprovince
Supercrustal units in the Pella Terrane
Mafic rocks in the Pella Terrane
Other rocks in the Pella Terrane
Supercrustal units in the Aus Terrane
Mafic gneiss in the Aus Terrane
Other rocks in the Aus Terrane
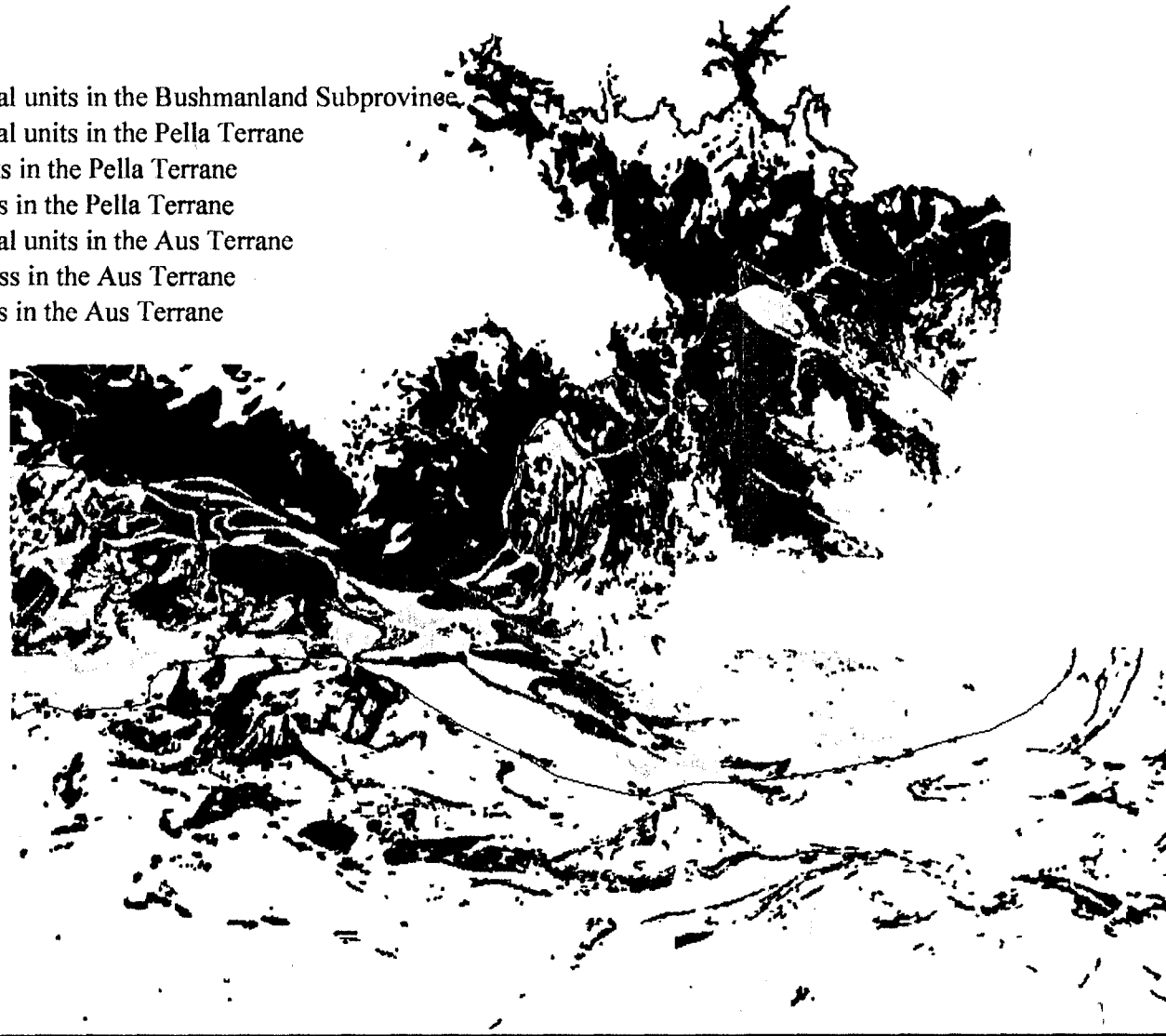
Figure 5.3

Result of tectonic terrane analysis using lithological information only. Black lines indicate subprovince and terrane boundaries. The Pella Terrane (grey, yellow and orange units) consists mainly of Vioolsdrif Suite granites (grey) and supercrustal units (yellow), but on a lithological map there is definite change at the Pofadder Shear Zone (PSZ), from granite gneiss in the east to mafic gneiss (orange) in the west. This change can be clearly observed on the map above. The Aus Terrane (blue, red and green), in this area, consists mainly of syntectonic augen gneiss (blue), mafic gneiss (red) and leucogneiss (green). Grey units to the east of the PSZ are mainly syntectonic augen gneiss. The Wortel Line of mafic gneiss (orange) can be followed along the southern boundary of the Pella Terrane.
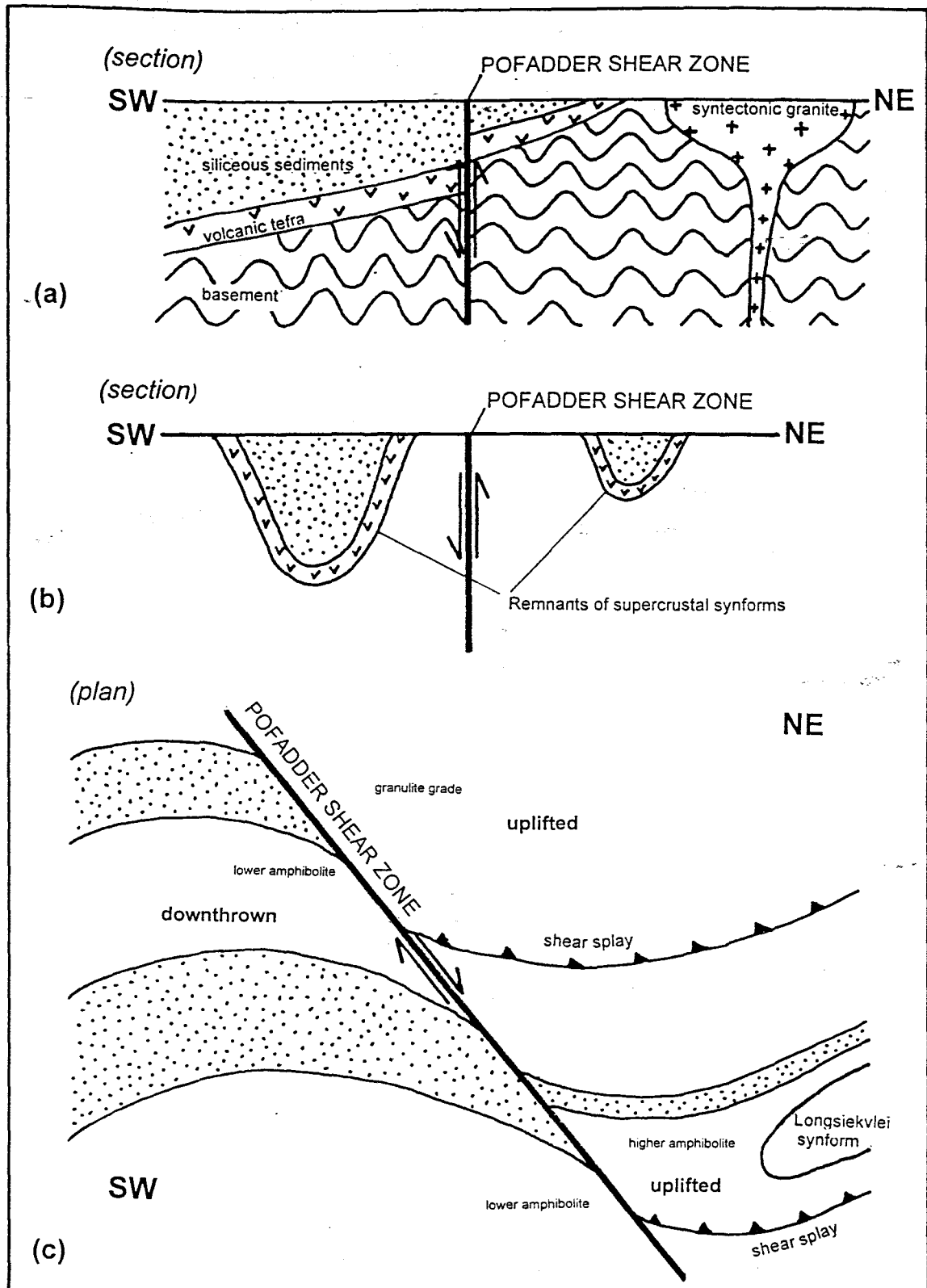
Figure 5.4 *Sketch diagram of possible vertical movement on the Pofadder Shear Zone, as discussed in the text.*

5.3.5 Summary of Results

The preceding three query examples revealed a number of interesting distribution patterns of lithologies and lithotectonic units:

- The composition of supercrustal units varies from quartzite-schist dominated in the south to quartzite-bearing leucogneiss and calc-silicate rich sequences in the north (fig.5.2), indicating a possible source in the Gordonia Subprovince for the siliceous metasediments in the Bushmanland Subprovince.

- Supercrustal sequences dominate in the south, while basement sequences are more abundant in the north (fig.5.1 and 5.3). This may indicate deeper crustal levels exposed in the north (fig.5.4a)

- There is a dramatic change in supercrustal unit thickness from west to east, within the Bushmanland Subprovince (fig.5.2), which suggests deeper synformal sequences to the west relative to preserved basal slivers of the synformal sequences in the east (fig.5.4b).

- The Pella Terrane changes in broad lithological composition from east to west: abundant mafic gneiss outcrops in the east and very few in the west (fig.5.3). This, combined with evidence of basement sequence overlap at terrane boundaries proposed by Hartnady *et al.* (1985), provide support for redefining the boundaries of the Pella Terrane.

Chapter 6

Conclusions

6.1 Introduction

The present study has been concerned with the first two phases of development of a Geographic Information System (GIS) as described by Maguire (1991):

- Creation of a digital database.
- Analysis of the data.

The spatial and attribute databases of the Central Namaqua Province GIS currently contain geological information, gleaned from seven geological maps and various bulletins, reports, theses and papers concerned with the geology of the Central Namaqua Province. Manipulation and analysis of the database produced a lithological map of the area, which provides a unique collated view of a large portion of the Namaqua Province. It is a demonstration of the suitability of GIS technology for enhancing and improving the study of geological phenomena.

The spatial database contains georeferenced vector polygons, which represent outcrop boundaries and lithological unit contacts, digitised from seven paper maps (Chapter 1). Attribute data currently include lithological, textural, paragenetic, tectonic, stratigraphic and correlative information pertaining to the outcrops, in a number of data tables. The primary aim of the study was to merge the spatial data and collate available attribute data from this database, thereby producing a unified lithological, digital map database of the CNP, and to further illustrate the effectiveness of this database by means of a number of selective displays and customised maps. Customised maps provide potential new interpretations of geological features, and are tools for investigating applicability of old theories.

6.2 The Digital Map Database

Advantages

The project has set out to demonstrate that a digital map database for the geology of the Namaqua Province will overcome the limitations inherent in the current paper map system. A summary of advantages follows.

The digital map database is flexible and can be edited and updated easily. Expansion or alteration of spatial and attribute databases is a matter of changing existing data tables or spatial elements in a vector edit window, or adding new elements and data tables. Vector objects with structural or other geological information can be overlayed on the existing lithological vector object, or information can be added directly to the lithological vector object. Any existing digital, spatial data for the area, such as digital elevation models, geophysical data or satellite imagery, can be georeferenced to a common projection and overlayed onto the outcrop map or vice versa.

The customised maps discussed in chapter 5 illustrate how successful a digital map database is at nullifying the scale versus detail situation referred to in chapter 1. The entire database is accessible, but the user may be selective in accessing only relevant data which may be displayed on screen or printed to paper. There is no longer the need to display all the information at once on a single paper map. Map legends are optional with a digital map, unless it is to be printed to paper, since the whole attribute database can be inspected on an element for element basis within the display window of the GIS. Colour differences in the various original maps are nullified by the query process, since the units can be displayed according to the user's choice of colours. The collated map (Annexure 1) and other customised maps (Chapter 5) are examples of this process.

Accuracy of digital map databases is still of concern, but since it is elementary to alter a digital map, the problem has been substantially reduced. With the accurate digital topocadastral maps and satellite images available today, it is simply a matter of georeferencing the digital geological map to a topocadastral map or satellite image and thereafter inconsistencies and distortions can be rectified through mathematical manipulation routines. This procedure was applied to the digitised map by Toogood (Chapter 3), and although the result was not entirely satisfactory, the problem did not reside in the capabilities of the GIS, but rather in the time and money available

to the project. With relevant satellite data of the area (such as SPOT satellite images), the accuracy of the map can be improved.

Map analysis functions, such as finding distances between points, dimensions of map elements, areas and more complex routines, are inherent in any GIS. The integration or overlaying of various data sets is the process that defines a GIS (Cowen, 1988). This was elucidated in the process of overlaying the vector map onto a scanned satellite image so that the vector object could be georeferenced to the satellite image for rectification. This is only a very simple example of what is possible. This project required little map analysis in the form of overlaying, and emphasis was more on attribute database management and analysis.

The project has clearly illustrated the advantages of a digital map database over a paper map system. Mining companies have shown an interest in the database, which confirms recognition of the potential of digital map databases to commercial enterprises.

Limitations of the current database

The size of the spatial database makes it important to consider the hardware used for the GIS. On a microcomputer any process accessing the spatial database takes time. Microcomputer speed is increasing rapidly with every new processor, but the price range of the faster processors can still be a limiting factor. Current software routines are not capable of increasing the access and display speed if the hardware is slow. The spatial database contains more than fifteen thousand lines and most microcomputer based GIS software packages are not capable of managing more than five thousand lines (*e.g.* PC Arc/Info).

Any attribute database is limited by the structure of its database, and a clear understanding of the purpose of the database is necessary in the design phase. Designing a database for a specific purpose, can limit its suitability for other purposes. It is therefore essential to establish as general a database as possible in the initial phase, so that it is feasible to use this database as a basis for further development. In the case of the CNP database the design of the database focussed heavily on the process of collation of existing paper maps, at the risk of neglecting other areas of importance to the study of the Namaqua Province, such as structure and metamorphism. The

lithological database (specifically the Lithbase and Chronobase data tables) combined with the spatial database, however, form a general, objective basis for further development. Adding structural and metamorphic layers of information to the established database should not require too much time and effort.

The level of detail in the spatial database is a definite limitation. Even though the database is very comprehensive, this author often felt that more detailed mapping would have revealed relationships between lithologies that were not visible at the current detail level. The original maps depicted assemblages of lithologies as units, and it would be more useful, perhaps, to have individual lithologies indicated. This will only be realised when workers are able to map areas with the aid of computers so that they are not limited by the size of the map. Notes and detailed mapping can then also be added at the appropriate locality on the digital map. It is often difficult to decide, when entering values into the database, what the original worker meant by certain descriptions, such as 'Red Granite changing towards the east to pink gneiss' (Geological Survey 1972). It is not clear where the data record value should be changed from 'Red Granite' to 'pink gneiss'.

As was mentioned in chapter 3, the map by Toogood has brought the accuracy of the spatial database into question, so that any overlay procedures utilising extraneous data sets (e.g. geophysical data) are bound to be unsatisfactory. The only way to improve the accuracy is to georeference all the data sets to a common satellite image which covers the whole area. This process will create a georeference object for each data set. The data sets can then be made to fit the coordinate grid specified by the new georeference objects, which will be the same for all of them.

All capabilities are limited to what is possible with the software. This limitation is not a reflection on any particular software, but on most GIS software. The science of GIS incorporates a very wide range of disciplines. The software needs to consider applications in all of the disciplines and is usually only capable of generalised routines. Any extra routines have to be written by the user, which is not a simple task without an elaborate software development environment. Some GIS software packages cater more for raster processing, while others lean

more towards vector processing. TNTmips™ strikes a remarkable balance between the two, and any limitations discovered along the way have been rectified in more recent versions, or could be circumvented with prompt aid from the technical team at MicroImages™.

Seemingly less important are spelling and typographic errors in the attribute database which can produce unlikely results and are not easily detected. There is no sure method to eliminate these errors, and the only answer is not to accept the result of a query without cross checking for validity. Again, it is easy to rectify these errors once they are discovered. Validation of the database is an important part of the job of a GIS practitioner.

6.3 The Collated Lithological Map

A collated, lithological paper map was produced with the aid of the established database and the Geographical Information System technology available to the author. The bulk of the process involved writing a customised routine to sort the lithological database and calculate the validity of a correlation, thereby avoiding subjective correlation. Interpretative differences at old map boundaries are therefore not completely eliminated, but colour differences at map boundaries caused by uncertain correlations highlight areas where further investigation is needed. The reader is referred to chapter 4 for a detailed discussion of these areas.

The map contains the outcrop boundaries and lithological unit contacts for a large part of the Namaqua Province. Nineteen out of a possible thirty-four lithologies in the database are represented on the map. Only the major, or characteristic, lithological components of units are displayed. The supercrustal and basement sequences, and syntectonic intrusives are tentatively indicated in the legend.

General Observations

The number of major lithological divisions on the map are reduced from the myriad found on the map by Strydom *et al.* (1987) to nineteen - slightly more than on the maps by Joubert (1973), despite the fact that the map covers at least a sixth of the Namaqua Province at the detail level

of a map drawn at a scale of one in a hundred thousand. Map boundaries are mostly eliminated by removing differences in colour coding and the stratigraphic interpretation of a number of authors. Colour differences remaining at some map boundaries indicate areas where further investigation is necessary. Some map boundary discrepancies are all but impossible to remove without losing the objective integrity of the map, such as differences in outcrop definitions (fig. 4.6) and lithological classification (biotite gneiss to one geologist is a biotite-rich granite gneiss to another - refer to Chapter 4 Section 4.3.3.4 for a discussion).

The map illustrates the spatial distribution of only one thematic variable. All stratigraphic, structural, topographic and cadastral detail that often obscures important lithological associations and relationships, are variables which can now be added and integrated. The lithological and correlation value maps are initial steps in a digital map analysis of the Namaqua Province. The collated map will aid in the establishment of a stratigraphic sequence, by highlighting areas of interpretational differences among the authors.

Some lithological distribution patterns were recognized from the lithological map:

Supercrustal Sequence

Distribution of supercrustal quartzite-schist and leucogneiss units are clearly visible. Quartzite-schist lithologies are mostly limited to south of the Pofadder Shear Zone (PSZ) in most of the area, but quartzo-feldspathic gneisses are ubiquitous throughout the area, overlapping several terrane boundaries (as defined by Hartnady *et al.* 1985). Supercrustal units decrease in thickness from west to east in the Bushmanland Subprovince, with a marked change crossing the PSZ. Quartzite is replaced by calc-silicate in the eastern area of the Bushmanland Subprovince on the map. For the first time it is possible to study the distribution of supercrustal units across the PSZ, in the southeastern parts of the Bushmanland Subsuite. It is also possible to study the variation in the effect of the shear zone on these and other units, across a very substantial section of the PSZ.

Granite and Biotite Gneisses

Assuming that all the mappers agree on the definition of granite and biotite gneiss, there is a

change from granite gneisses south to biotite-rich gneisses north of the PSZ. This could just be a difference in definition of biotite gneisses, since Eendoorn granites are often described as biotite-rich gneisses. The other important biotite gneiss component in the north is that of the Umeis gneiss (a Grunau Sequence formation), which is classified as basement rock rather than a syntectonic intrusive (Moore *et al.* 1990). There is however a definite association of the Umeis biotite gneiss with Eendoorn granites in their distribution pattern. Granite gneiss south of the PSZ are mostly concentrated in the Richtersveld Subprovince, with a number of intrusives apparent in the Gordonia Subprovince.

Granulites and other high grade metamorphic rocks

Another association that appears is that of the biotite-cordierite-sillimanite-garnet gneiss with mafic and charnockitic intrusives. This can be observed in the areas mapped by Strydom *et al.* (1987) (area B in fig.4.1), Toogood (1976a) and Du Plessis (1989a). This spatial relationship between metapelites and mafic intrusives lends credibility to Maclaren's theory that granulite facies metamorphism in the areas north of the Pofadder Shear Zone is the effect of local contact metamorphism (Maclaren 1988). There is still, however, uncertainty as to the origin of the charnockites, and evidence exists for a sedimentary origin (Joubert 1986a, Schultz 1978).

Mafic gneisses and intrusives

Mafic gneiss include the biotite-hornblende and hornblende gneisses which are mostly restricted to the Gordonia Subprovince. Mafic gneiss in the Richtersveld and Bushmanland Subprovinces seem to correlate with rocks of the Orange River Group of mafic and felsic volcanoclastics. In the Samoep Synform mafic gneiss can be correlated with the Nouzees Gabbronorite Suite.

6.4 Customised maps

The lithological map investigated only one aspect of the attribute database and three customised maps or selective displays were produced to demonstrate techniques of database query and display, and the potential use for these techniques in studying the Namaqua Province.

The first customised map displayed the distribution of supercrustal units, basement migmatites

and syntectonic granites. Distribution patterns for these three variables indicate a large supercrustal component in the Bushmanland Subprovince, with a migmatite outcrop in the Aus and eastern Pella Terranes.

Customised maps, displaying lithological and lithotectonic unit distribution in the CNP, lend support to the suggestion by Toogood (1976) of a vertical component of movement on the Pofadder Shear Zone. Several distribution patterns were examined using queries to the attribute database.

- Basement migmatites, supercrustal units and syntectonic granites were displayed to investigate the relations among these lithotectonic units. Basement outcrops are concentrated in the areas northeast of the PSZ, while supercrustal units are mostly limited to the Bushmanland Subprovince, where there are very few basement occurrences. This suggests a deeper level of crust exposed in the northeast.

- The second map examined the quartzite distribution in the CNP, by displaying all outcrops containing quartzite. Calc-silicate gneiss was also displayed to investigate the possibility that quartzites grade into calc-silicate gneiss towards the eastern margins of the study area. This map revealed a reduction in quartzite unit thickness, and a definite change from quarzite to calc-silicate gneiss towards the east, which lends support to the suggestion of a deeper crustal level exposed northeast of the PSZ.

- A simple example of the use of selective displays in terrane analysis was given in the last map where basement mafic gneisses were displayed according to their terrane distributions. A change in the composition of basement lithologies of the Pella Terrane is evident across the PSZ. To the west of the shear zone these lithologies consist mainly of granitic gneiss, while to the east their is a definite mafic gneiss component. This distribution pattern strongly suggests a revision of the positions of the Pella Terrane boundaries.

6.5 Expansion of the Digital Database

The current project has demonstrated the importance and potential of a digital map database combined with modern GIS technology in studying the geological history of the Central Namaqua Province. It is hoped that the project has initialised a shift away from paper geological maps to digital map databases of the Namaqua Province, which will eventually include all available geological, geochemical, geophysical and geomorphological information. The digital database should ideally be made available to all scientists studying Namaqua Province geology.

In the short term it is necessary for the spatial database to cover the Namaqua Province at a detail level at least comparable to the current database. It is also essential to enter structural data from maps used for this project, into the database. Areas of uncertain unit correlations, displayed on the lithological map, should be investigated and, if possible, clarified.

Medium term projects should include adding detailed maps of areas such as Gamsberg, Aggeneys and Namies to the database, where a wealth of information is available due to mining activities. Geochemical and geophysical information can be added.

A map database containing all existing spatial and attribute data for the Namaqua Province, should be the goal for the long term. Such a database will consist of a spatial database incorporating detailed mapping of the whole Namaqua Province, and an attribute database gleaned from geological literature concerning the Namaqua Province.

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Appendix A

Spatial Manipulation Language (SML) Program to Create NammapDB Data Table

A.1 Program List

```
                              1. Global Variable Declaration

1    lb = 0
2    sb = 0
3    dbase = 0
4    sourceval = 0
5    correlfactor = 0
6    unibase$ = "d:/henry/dbasetxt/nammap.txt"
7    counter = 1


                              2. Function Declaration Block
8

9    func getlithlevel(num)

10   begin
11   lname$ = Namvec.poly[num].Lithbase.Lith0$
12   if ((lname$ contains lithology1$) or (lname$ contains lithology2$) or
13   (lname$ contains lithology3$) or (lname$ contains lithology4$)) then
14         begin
15            lb = 1; llevel = 6
16            return llevel
17         end

18   lname$ = Namvec.poly[num].Lithbase.Lith1$
19   if ((lname$ contains lithology1$) or (lname$ contains lithology2$) or
20   (lname$ contains lithology3$) or (lname$ contains lithology4$)) then
21         begin
22            lb = 1; llevel = 5
23            return llevel
24         begin

25   lname$ = Namvec.poly[num].Lithbase.Lith2$
26   if ((lname$ contains lithology1$) or (lname$ contains lithology2$) or
27   (lname$ contains lithology3$) or (lname$ contains lithology4$)) then
28         begin
29            lb = 1; llevel = 4
```

```
30          return llevel
31          begin

32  lname$ = Namvec.poly[num].Lithbase.Lith3$
33  if ((lname$ contains lithology1$) or (lname$ contains lithology2$) or
34  (lname$ contains lithology3$) or (lname$ contains lithology4$)) then
35          begin
36             lb = 1; llevel = 3
37             return llevel
38           _ end

39  lname$ = Namvec.poly[num].Lithbase.Lith4$
40  if ((lname$ contains lithology1$) or (lname$ contains lithology2$) or
41  (lname$ contains lithology3$) or (lname$ contains lithology4$)) then
42          begin
43             lb = 1; llevel = 2
44             return llevel
45           end

46  lname$ = Namvec.poly[num].Lithbase.Lith5$
47  if ((lname$ contains lithology1$) or (lname$ contains lithology2$) or
48  (lname$ contains lithology3$) or (lname$ contains lithology4$)) then
49          begin
50             lb = 1; llevel = 1
51             return llevel
52           end
53  lb = 0
54  llevel = 0
55  return llevel

56  end


57  func getSurvLevel(num)

58  begin
59  sname$ = Namvec.poly[num].SURVLith.Lith0$
60  if ((sname$ contains lithology1$) or (sname$ contains lithology2$) or
61  (sname$ contains lithology3$) or (sname$ contains lithology4$)) then
62          begin
63             sb = 1; slevel = 6
64             return slevel
65             begin

66  sname$ = Namvec.poly[num].SURVLith.Lith1$
67  if ((sname$ contains lithology1$) or (sname$ contains lithology2$) or
68  (sname$ contains lithology3$) or (sname$ contains lithology4$)) then
69             begin
```

```
70          sb = 1; slevel = 5
71          return slevel
72          end

73   sname$ = Namvec.poly[num].SURVLith.Lith2$
74   if ((sname$ contains lithology1$) or (sname$ contains lithology2$) or
75   (sname$ contains lithology3$) or (sname$ contains lithology4$)) then
76          begin
77          sb = 1; slevel = 4
78          return slevel
79          end

80   sname$ = Namvec.poly[num].SURVLith.Lith3$
81   if ((sname$ contains lithology1$) or (sname$ contains lithology2$) or
82   (sname$ contains lithology3$) or (sname$ contains lithology4$)) then
83          begin
84          sb = 1; slevel = 3
85          return slevel
86          end

87   sname$ = Namvec.poly[num].SURVLith.Lith4$
88   if ((sname$ contains lithology1$) or (sname$ contains lithology2$) or
89   (sname$ contains lithology3$) or (sname$ contains lithology4$)) then
90          begin
91          sb = 1; slevel = 2
92          return slevel
93          end

94   sname$ = Namvec.poly[num].SURVLith.Lith5$
95   if ((sname$ contains lithology1$) or (sname$ contains lithology2$) or
96   (sname$ contains lithology3$) or (sname$ contains lithology4$)) then
97          begin
98          sb = 1; slevel = 1
99          return slevel
100         end
101  sb = 0
102  slevel = 0
103  return slevel

104  end

105  func getUOFSLevel(num)

106  begin
107  uname$ = Namvec.poly[num].UOFSLith.Lith0$
108  if ((uname$ contains lithology1$) or (uname$ contains lithology2$) or
109  (uname$ contains lithology3$) or (uname$ contains lithology4$)) then
```

```
110        begin
111          ub = 1; ulevel = 6
112          return ulevel
113        end

114   uname$ = Namvec.poly[num].UOFSLith.Lith1$
115   if ((uname$ contains lithology1$) or (uname$ contains lithology2$) or
116   (uname$ contains lithology3$) or (uname$ contains lithology4$)) then
117        begin
118          ub = 1; ulevel = 5
119          return ulevel
120        end

121   uname$ = Namvec.poly[num].UOFSLith.Lith2$
122   if ((uname$ contains lithology1$) or (uname$ contains lithology2$) or
123   (uname$ contains lithology3$) or (uname$ contains lithology4$)) then
124        begin
125          ub = 1; ulevel = 4
126          return ulevel
127        end

128   uname$ = Namvec.poly[num].UOFSLith.Lith3$
129   if ((uname$ contains lithology1$) or (uname$ contains lithology2$) or
130   (uname$ contains lithology3$) or (uname$ contains lithology4$)) then
131        begin
132          ub = 1; ulevel = 3
133          return ulevel
134        end

135   uname$ = Namvec.poly[num].UOFSLith.Lith4$
136   if ((uname$ contains lithology1$) or (uname$ contains lithology2$) or
137   (uname$ contains lithology3$) or (uname$ contains lithology4$)) then
138        begin
139          ub = 1; ulevel = 2
140          return ulevel
141        end

142   uname$ = Namvec.poly[num].UOFSLith.Lith5$
143   if ((uname$ contains lithology1$) or (uname$ contains lithology2$) or
144   (uname$ contains lithology3$) or (uname$ contains lithology4$)) then
145        begin
146          ub = 1; ulevel = 1
147          return ulevel
148        end
149   ub = 0
150   ulevel = 0
151   return ulevel
```

```
152   end

153   func getlevel(level1,level2,level3)

154   begin
155   position = 0
156   if (lb<>1 and ub<>1 and sb<>1) then
157           begin
158            position=0
159            return position
160            end
161   else

162           begin
163            if ((level1>=level2) and (level1>=level3)) then
164                    begin
165                     position=level1
166                     dbase=1
167                     return position
168                     end
169            if ((level2 >= level1) and (level2 >= level3)) then
170                    begin
171                     position=level2
172                     dbase=2
173                     return position
174                     end
175            if ((level3 >= level1) and (level3 >= level2)) then
176                    begin
177                     position=level3
178                     dbase=3
179                     return position
180                     end
181            end
182   end

183   func getcorrel(base1,base2,base3)

184   begin
185   correlation=0
186   if((base1==1) and (base2==1) and (base3==1)) then
187           begin
188            correlation=3
189            return correlation
190            end
191   else
192           begin
193            if ((base1==1) and (base2==1)) then
```

```
194                    begin
195                        correlation=2
196                        return correlation
197                        end
198              else
199                        begin
200                        correlation=1
201                        return correlation
202                        end
203         _ end  #else
204    end




205    proc findsource(num)


206    begin


207    convar1$=Namvec.poly[num].Lithbase.Source$
208    convar2$=Namvec.poly[num].UOFSLith.Source$
209    convar3$="Backstrom1"
210    source$=""


211    if (dbase==1) then source$=convar1$
212    if (dbase==2) then source$=convar2$
213    if (dbase==3) then source$=convar3$
214    if (source$==map$) then sourceval=1
215                              else sourceval=0
216    end
```

Main Program Block

```
218    GetInputVector(Namvec)
219    unibasefile = fopen(unibase$,"a+")
220    outcrops = NumVectorPolys(Namvec)
221    print("Enter Lithotype1:")
222    lithology1$ = input$()
223    print("Enter Lithotype2:")
224    lithology2$ = input$()
225    print("Enter Lithotype3:")
226    lithology3$ = input$()
227    print("Enter Lithotype4:")
228    lithology4$ = input$()
229    print("Enter main lithology for id-field: ")
230    id$ = input$()
```

```
231   while (counter <= outcrops)
232          begin
233            polyX = Namvec.poly[counter].POLYSTATS.CentX
234            polyY = Namvec.poly[counter].POLYSTATS.CentY
235            map$ = Namvec.poly[counter].Mapbase.map$
236            llevel = getLithLevel(counter)
237            ulevel = getUOFSLevel(counter)
238            slevel = getSurvLevel(counter)
239            level = getlevel(llevel,ulevel,slevel)
240            if (level>0) then
241                 begin
242                   correl=getcorrel(lb,ub,sb)
243                   findsource(counter)
244                   correlfactor=(correl+sourceval+level)*10
245                   fprint(unibasefile,counter,polyX,polyY,id$,correlfactor)
246                 end
247            print(counter)
248            counter=counter+1
249          end
250   fclose(unibasefile)

                        End of Program List
```

A.2 Discussion

Main Program

The program starts with the Global Variable Declaration Block (line 1-8), where all variables which can be accessed and changed globally (in the main program and subroutines) are declared. The main program block (line 219-250) consists of calls to the subprograms, calculation of the final correlation value and the output section where an ASCII database is created. A vector object is selected by the user (line 219) and a text file with the name specified in the unibase$ variable is opened for writing and appending purposes (line 220). The number of polygons in the selected vector object is stored in the outcrops variable (line 221). The user enters four lithologies for which correlation values are to be calculated (line 222-229). This makes it possible to calculate values for units of lithologies instead of single lithologies, or to search the database for variable spelling of lithologies. It can also make it easier to search for metamorphic units where the paragenetic minerals listed in the name are in varying order, for instance, bt-cd-sill gneiss. Line 230 and 231 give the user the opportunity to enter the name of the unit as it is to be used in the

resultant database.

The 'while' loop processes every polygon (line 232-250). Xy-coordinates of the centroid of every polygon in the vector object is stored in the POLYSTATS database as CentX and CentY. In line 234 and 235 the coordinate points are stored in variables polyX and PolyY. For the calculation of the correlation value it is necessary to know in which original map the polygon was located (line 236) and this is stored in the Mapbase data table. Line 237 to 239 reference subroutines where the prominence of a lithology within the polygon/outcrop is detected (whether it is a major lithology or secondary). The getlevel (line 240) function determines in which data table the lithology has the highest level, or in other words, which worker recognized the lithology as the more prominent in the outcrop.

Only if the lithology is present in the outcrop are lines 241 to 247 executed, otherwise the counter is incremented and the next outcrop selected (line 248-250). The getcorrel function (line 243) determines the level of agreement among workers who mapped the outcrop, on the presence of the lithology in the outcrop. In the findsource procedure (line 244) it is determined whether the source of the lithology information associated with the polygon is the same as the source for the polygon. The correlation value is calculated from the three variables: correl, sourceval and level in line 245 and then printed (line 246) with other necessary information to the ASCII-file opened in line 220.

Subroutines

The getlithlevel, getSurvLevel and getUOFSLevel functions are the same, but different data tables are accessed. Only the getlithlevel will be discussed.

getlithlevel

This function compares the lithology entered by the user in lines 222-229 with every Lith field in the Lithbase data table and so determines what the level of prominence is for the given lithology within the outcrop. Lines 11 to 17 accesses Lith0 and if the lithology in Lith0 is the same as the given lithology the function is exited with a level of six and a pointer (lb) to the database table in which this level was attained (line 15 and 16). If the lithology is not in level six,

the same is done for the lower levels. If the lithology is not recognised in Lithbase, lb and level variables are zeroed.

getlevel

The database table in which the given lithology attained the highest level (Lith0 to Lith5), is determined by the getlevel function (line 153 to 182) for use in the findsource function. It also determines the highest level overall for the given lithology. If the lithology is absent from all the data tables for the specific outcrop, the function is left with the level equal to zero (line 156-160). Otherwise the highest level in the three data tables are determined and in which data table this was the case (line 161-181).

getcorrel

If the lithology was recognised in the outcrop by all three workers, a value of three is indicated for correl (refer to line243) in lines 186 to 190. If only two workers observed the lithology in the outcrop correl is two otherwise the function is exited and correl is one (line 191-204).

findsource

The source of the spatial database for the specific polygon is compared with the source of the attribute database attached to it. If they are the same, the sourcevalue variable is one otherwise it equals zero. In lines 207 to 209 the source to the lithological data attached to the polygon is determined from the appropriate data table fields and stored in variables. All information in the SURVLith data table are from the same source namely the Geological Survey map (1972), compiled by Von Backström (line 209). If the data table for which the given lithology is most prominent for the outcrop, is Lithbase then the source attribute data can be sought in the variable containing the source value from Lithbase (line 211). Line 214 compares the appropriate values.

Appendix B

Data Tables

Chronbase Data Table

Namtectage	Tectage	PbPb	PbU	RbSr	NdSm	SingleZirc	Agedata
prenam		1300	0	0	0	0	yes
prenam		0	2000	2000	0	0	yes
prenam		0	0	0	1700	0	yes
prenam		0	1996	0	0	0	yes
prenam		0	0	1800	0	0	yes
prenam		0	0	1731	0	0	yes
prenam		0	0	1900	0	0	yes
midnam	syntectonic	1115	1100	1100	0	0	yes
prenam		2000	2000	0	0	2000	yes
prenam		0	0	0	1650	0	yes
prenam	pretectonic	0	0	0	0	0	no
prenam	pretectonic	0	0	0	0	0	no
postnam		980	0	1000	0	0	yes

Correlbase Data Table

SACS	PRU	UOFS	GeoSurvey	Other
Geselskapbank_formation	Grunau_sequence	Arus_formation	Kheis_system	Toeslaan_formation
Hoogoor_suite	Hoogoor_suite	Undifferentiated_gneiss	Red_granite	Yas_granite
Pella_subgroup	Pella_quartzite	Wortel_formation	Kaiing_series	
Namies_formation	Namies_schist	Wortel_formation		
Pella_subgroup	Pella_subgroup	Wortel_formation		
Pella_subgroup	Pella_subgroup	Witputs_formation		
Namies_formation	Namies_schist	Witputs_formation		
Pella_subgroup	Pella_subgroup	Hotson_formation		
Namies_formation	Namies_schist	Hotson_formation		
Pella_subgroup	Pella_subgroup	Thammaberg_formation		
Aroams_gneiss	Aroams_gneiss	Aroams_granite		
Hom_subgroup	Nousees_mafic_gneiss	Hom_formation	Kaiing_series	Haib_group
Aroams_gneiss	Aroams_gneiss	Pella_granite		
Hom_subgroup	Nousees_mafic_gneiss	Achab_suite		Undifferentiated_gneiss
Hoogoor_suite	Hoogoor_suite	Achab_suite		Haramoep_gneiss
Hom_subgroup	Nousees_mafic_gneiss	Koeipoort_gneiss	Red_granite	Undifferentiated_gneiss
Hoogoor_suite	Hoogoor_suite	Coboop_gneiss	Red_gneiss	Undifferentiated_gneiss
	Amphibolite	Koeris_formation		
Guadom_formation		Guadom_formation	Kaiing_series	
	Kambreek_formation	Abbasas_succession	Kaiing_series	
	Pelgrimsrust_formation	Umeis_succession		Grey_gneiss
	Orangefall_formation	Umeis_succession		Grey_gneiss
	Hoogoor_suite	Pelgrimsrus_gneiss		Austerlitz_formation
	Nautsis_formation	Pelgrimsrus_gneiss		
	Kumkum_mafic_granolite	Kumkum_mafic_rock		gabbro
Keimoes_suite	Naros_granitoid	Naros_granitoid	Naros_granitoid	
		Kabis_gneiss	Namaqualand_granite_gneiss	
Hoogoor_suite	Hoogoor_suite	Kabis_gneiss	Red_granite	
		Kabis_gneiss	Kaiing_series	
Vioolsdrif_suite		Vuurdood_subsuite		
Vioolsdrif_suite	Austerlitz_formation	Goodhouse_subsuite		Hoogoor_suite
Tsams_formation		Tsams_formation	Kaiing_series	
Vioolsdrif_suite	Vioolsdrif_suite	Ramansdrif_subsuite	Red_granite	Hoogoor_suite
		Swartmodder_granite		
		Gaidip_formation		
Hoogoor_suite	Hoogoor_suite	Houmsriver_gneiss	Red_granite	Pink_gneiss

Divbase Data Table

Subprovinc	Terrane	Zone
Gordonia	Aus	
Richtersveld	Pella	
Bushmanland	Okiep	
Bushmanland	Garies	
Gordonia	Kakamas	

SACSbase Data Table

Suite	Subsuite	Sequence	Group	Subgroup	Formation	Member
			Bushmanland	Pella		
			Bushmanland	Aggeneys	Namies	
			Bushmanland	Guadom		
			Bushmanland	Hom		
		Korannaland		Toeslaan		
			Orange_river	Haib	Tsams	
Viooisdrif						
Little_Namaqualand						
Hoogoor						
T'oubep						

Lithbase Data Table

Source	Name	Lith0	Text0	Mineral0	Lith1	Text1	Mineral1	Lith2	Text2	Mineral2
Joubert01	Pella_quartzite	quartzite	gneiss		qtz_bt_sill_schist	schist	qtz_bt_sill~garn	iron_formation	gneiss	magnetite
Strydom01	Witputs_formation	quartzite	gneiss		qtz_bt_schist	schist	qtz_bt_sill~garn			
Strydom01	Wortel_formation	qtz_bt_sill_schist	schist	qtz_bt_sill	quartzite	gneiss		bt_gneiss	gneiss	bt
Strydom01	Ou_eendop_formation	bt_sill_schist	schist	bt_sill	mus_sill_bt_schist	porphyr_schist	mus_sill_bt	quartzite	gneiss	fspar
SACS18	Holson_formation	quartzite	gneiss		bt_sill_schist	schist	bt_sill	quartzo_feldspathic	gneiss	bt_sill
Strydom01	Thammaberg_formation	quartzite	gneiss		mus_sill_bt_schist	schist	mus_sill_bt			
Colliston1	Hom_formation	felsic	gneiss		mafic	gneiss		cd_anth_schist	schist	cd_anth
Joubert01	Namies_schist	sill_bt_schist	schist	qtz_bt_sill	amphibolite	gneiss		quartzite	gneiss	
Joubert01	Calc_silicate	calc_silicate	gneiss							
Colliston1	Calc_silicate_rock	qtz_fspar_amph_gneiss	gneiss	qtz_fspar_amph~garn~magn						
Joubert01	Aroams_gneiss	granite	porphyroblast_gneiss							
Colliston1	Undifferentiated_gneiss	qtzo_fspathic_gneiss	gneiss	qtz_fspar~bt~hbl						
Colliston1	Aroams_granite	bt_granite	megacrystic_gneiss							
Colliston1	Pella_granite	granite	augen gneiss	bt_hbl						
Joubert01	Haramoep_gneiss	qtzo_fspathic_gneiss	gneiss		granite	gneiss		leptite	gneiss	
Strydom01	Hoogoor_gneiss	qtzo_fspathic_gneiss	gneiss							
Strydom01	Namies_gneiss	fspathic_gneiss	gneiss							
Strydom01	Achab_suite	Leucogranitoid_gneiss	porphyroblast_gneiss		amphibolite	gneiss		calc_silicate	gneiss	
Strydom01	Koeipoort_granite	granite_gneiss	gneiss	bt_magn	granite_gneiss	megacrystic_gneiss	bt_magn	calc_silicate	gneiss	
Strydom01	Haramoep_gneiss	granite	augen_gneiss	bt						
Strydom01	Naroep_gneiss	granite_gneiss	gneiss	bt_magn	granite_gneiss	megacrystic_gneiss	bt_magn	calc_silicate	gneiss	
Colliston1	Vioolsdrif_suite	qtzo_fspathic_gneiss	gneiss							
Joubert01	Quartz_muscovite_schist	qtz_mus_schist	schist	qtz_mus	leucogneiss	gneiss				
Strydom01	Coboop_gneiss	granite	gneiss	bt_magn	granite	megacrystic_gneiss	bt_magn	calc_silicate	gneiss	
Colliston1	Koeris_formation	conglomerate	gneiss		amphibolite	gneiss		qtz_mus_fspar_gneiss	gneiss	qtz_mus_fspar
Maclaren01	Pelitic_gneiss	qtz_cd_sill_gneiss	gneiss	qtz_cd_sill~garn~bt						
Maclaren01	Para_amphibolite_gneiss	amphibolite	gneiss	plag_hb_qtz						
Maclaren01	Quartzo_feldspathic_gneis	qtzo_fspathic_gneiss	gneiss	qtz_kspar_plag~mag~bt						
Maclaren01	Quartzo_feldspathic_gneis	qtzo_fspathic_gneiss	megacrystic_gneiss	qtz_kspar_plag~mag~bt						
Maclaren01	Leucogneiss	qtzo_fspathic_gneiss	gneiss	qtz_kspar_plag~mag~bt						
Maclaren01	Leucogneiss	qtzo_fspathic_gneiss	megacrystic_gneiss	qtz_kspar_plag~mag~bt						
Maclaren01	Leptite	qtzo_fspathic_gneiss	gneiss	qtz_plag~mag						
Maclaren01	Calc_silicate_gneiss	calc_silicate	gneiss	qtz_plag_hb~gar~kspar~di						
Maclaren01	Calc_sil_conglomerate	calc_silicate	conglomerate_gneiss	qtz_plag_hb						
Maclaren01	Biotite_schist	biotite_schist	schist	qtz_bt_mus~plag~mag						
Maclaren01	Mus_qtz_schist	qtz_mus_schist	schist	qtz_mus~magn						
Maclaren01	Glassy_quartzite	quartzite	gneiss	qtz~mus	qtzo_fspathic_gneiss	gneiss				
Maclaren01	Granular_quartzite	quartzite	gneiss	qtz	calc_silicate	gneiss				

Lithbase Data Table

Source	Name	Lith0	Text0	Mineral0	Lith1	Text1	Mineral1	Lith2	Text2	Mineral2
Maclaren01	Iron_formation	iron_formation	gneiss	qtz_magn~plag						
Maclaren01	Mafic_granulite	granulite	gneiss	plag_hb_hy_cpx	amphibolite	gneiss				
Maclaren01	Olivine_gabbronorite	olivine_gabbronorite	gneiss	plag_cpx_opx~ol						
Maclaren01	Amphibolites	amphibolite	gneiss	plag_hb						
Maclaren01	Granite_gneiss	granite	gneiss	kspar_qtz_plag	granite	megacrystic_gneiss	kspar_qtz_plag~bt			
Maclaren01	Granodiorite_tonalite	granodiorite_tonalite		qtz_plag_kspar						
Maclaren01	Diorite	diorite		plag_kspar_hbl~cpx~opx						
Maclaren01	Dolerite	dolerite		cpx_plag_ol						
Maclaren01	Kimberlite	kimberlite								
DuPlessis1	Yasgranite	Qtzo_fspathic_gneiss	gneiss	qtz_kspar_plag~bt~magn	amphibolite	gneiss				
DuPlessis1	Stolzenfels_enderbite	enderbite	gneiss	plag_qtz_hb_opx_bt_cpx						
DuPlessis1	Swartmodder_granite	granite_gneiss	gneiss	qtz_kspar_plag						
DuPlessis1	Schuitdrift_granite	bt_hb_gneiss	augen_gneiss	qtz_kspar_plag_hb~bt						
DuPlessis1	Eendoorn_granite	biotite_gneiss	megacrystic_gneiss	qtz_kspar_plag_bt~garn						
DuPlessis1	Daberas_granodiorite	granodiorite	gneiss	plag_qtz_kspar_bt_hb~hy						
DuPlessis1	Naros_granitoid_main_body	hb_bt_gneiss	gneiss	kspar_plag_qtz_bt~hb						
DuPlessis1	Naros_granitoid_mafic_phs	hb_bt_granite	gneiss	plag_kspar_qtz~hy~bt~hb						
DuPlessis1	Naros_granitoid_leucophse	biotite_gneiss	augengneiss	kspar_qtz_plag~bt~hb						
DuPlessis1	Witwater_granite	granite_gneiss	gneiss	qtz_kspar_plag~garn~bt						
DuPlessis1	Toeslaan_formation	cd_sill_garn_bt_gneiss	gneiss	cd_sill_garn_bt	qtzo_feldspathic_gneiss	gneiss		quartzite	gneiss	
Toogood1	Austerlitz_formation	qtzo_fspathic_gneiss	gneiss	qtz_kspar_plag~bt	sill_schist	schist		quartzite	gneiss	
Toogood1	Orangefall_formation	biotite_gneiss	gneiss	qtz_kspar_plag_bt	bt_cd_sill_schist	schist	bt_cd_sill	hb_gneiss	gneiss	
Toogood1	Jerusalem_formation	cd_sill_garn_gneiss	gneiss	qtz_kspar_bt_sill~garn~cd						
Toogood1	Kambreek_formation	qtz_mus_schist	schist	qtz_mus_bt						
Toogood1	Pella_formation	quartzite	gneiss							
Toogood1	Pelgrimsrust_formation	hb_gneiss	gneiss	qtz_plag_hb~bt	hb_schist	schist	qtz_plag_hb~bt	cl_epi_schist	schist	cl_epi
Toogood1	Keimas_formation	calc_silicate	gneiss	qtz_plag_cpx						
Toogood1	Beenbreek_formation	granite	megacrystic_gneiss	qtz_plag_kspar_bt	granite	megacrystic		aplite		
Toogood1	Grass_river_formation	qtzo_fspathic_gneiss	augen_gneiss	qtz_plag_kspar_bt						
Toogood1	Naros_formation	granite		kspar_qtz_plag_bt~hb	granite_gneiss	gneiss	kspar_qtz_plag_bt~hb			
Toogood1	Nautsis_formation	alkali_fspar_granite	granular							
Toogood1	Stolzenfels_formation	norite			enderbite					
Toogood1	Kumkum_formation	mafic_granolite	gneiss							
Toogood1	Jericho_formation	amphibolite	gneiss	plag_qtz_hb						
Strydom01	Guadom_formation	biotite_gneiss	gneiss		hb_gneiss			bt_cd_sill_schist	schist	bt_cd_sill~antoph
Strydom01	Abbasas_succession	Quartzite	gneiss		mus_bt_schist	schist	mus_bt	bt_quartzite	gneiss	
Strydom01	Undifferentiated_gneiss	bt_hb_gneiss	gneiss		biotite_schist	schist		calc_silicate	gneiss	
Strydom01	Quartzite_schist	quartzite	gneiss		qtz_mus_schist	schist	qtz_mus			

Lithbase Data Table

Source	Name	Lith0	Text0	Mineral0	Lith1	Text1	Mineral1	Lith2	Text2	Mineral2
Strydom01	Umeis_succession	biotite_gneiss	gneiss	qtz_fspar_bt	amphibolite	gneiss		bt_hb_schist	schist	
Strydom01	Arus_formation	bt_sill_cd_garn_gneiss	gneiss	bt_sill_cd_garn	qtzo_fspathic_gneiss	gneiss		calc_silicate	gneiss	
Strydom01	Pelgrimsrus_gneiss	granite_gneiss	gneiss		granite_gneiss	megacrystic_gneiss		calc_silicate	gneiss	
Strydom01	Kumkum_mafic_rock	gabbro			norite					
Strydom01	Eendoorn_suite	bioite_gneiss	augen_gneiss	bt	charnockite	gneiss		mafic_rock		
Strydom01	Mafic_dykes_sills	amphibolite	gneiss							
Strydom01	Naros_granite	hb_bt_granite_gneiss	gneiss							
Strydom01	Kabis_gneiss	granite_gneiss	augen_gneiss	bt						
Backstrom1	MGr	granulite	gneiss		amph_garn_epi_gneiss	gneiss	amph_garn_epi	hb_diorite		
Strydom01	Vuurdood_subsuite	diorite			gabbronorite			amphibolite	gneiss	
Strydom01	Goodhouse_subsuite	qtzo_fspathic_gneiss	gneiss							
Strydom01	Tsams_formation	felsic_gneiss	gneiss		felsic_schist	schist		biotite_gneiss	gneiss	
Strydom01	Pella_subgroup	quartzite	gneiss		qtz_bt_mus_sill_schist	schist	qtz_bt_mus_sill	amphibolite	gneiss	
Strydom01	Ramansdrif_subsuite	granite_gneiss	gneiss		qtzo_fspathic_gneiss	gneiss				
Strydom01	Wortel_mafic_unit	mafic_plutonic_rocks			ultra_mafic_rocks					
Strydom01	Swartmodder_gneiss	granite_gneiss	augen_gneiss	bt						
Backstrom1	Red_granite	granite_gneiss	gneiss		granite					
Backstrom1	Namaqualand_granite_gneis	granite_gneiss	gneiss							
Backstrom1	Kh2Gr(brown)	granite_gneiss	gneiss							
Backstrom1	Kh2Gn	qtzo_fspathic_gneiss	gneiss							
Backstrom1	Kh2Sc	schist	schist		phyllite	phyllite				
Backstrom1	Kh2Q	quartzite	gneiss		qtz_sericite_schist	schist		calc_silicate	gneiss	
Backstrom1	Kh2Gl	meta_sediments								
Backstrom1	Mafic_intrusives	gabbro			olivine_gabbro			olivine_norite		
Backstrom1	Kh3L	basic_lava								
Backstrom1	MGn	bt_hb_gneiss	gneiss		biotite_gneiss	gneiss		hb_gneiss	gneiss	
Backstrom1	AG1	bt_granite_gneiss	gneiss		granite_gneiss	gneiss				
Strydom01	Tantalite_valley	mafic_rocks			ultra_mafic_rocks					
Strydom01	Kumkum_mafic_rock	gabbro			norite					
Strydom01	Gaidip_formation	qtzo_fspathic_gneiss	gneiss	sill	qtzo_fspathic_schist	schist				
Strydom01	Bleskop_suite	pegmatite								
Strydom01	Houmsriver_granite	granite_gneiss	gneiss		granite_gneiss	megacrystic_gneiss		calc_silicate	gneiss	
Joubert01	Amphibolite	amphibolite	gneiss							
Joubert01	Biotite_gneiss	biotite_gneiss	gneiss		biotite_schist	schist				
Joubert01	Nousees_mafic_gneiss	mafic_gneiss	gneiss		mafic_schist	schist		amphibolite	gneiss	
Toogood1	Mylonite_zones	mylonite								
Toogood1	Skimmelberg_pegmatite	pegmatite								
Joubert01	Mafic_intrusives	mafic_rock								

Lithbase Data Table

Source	Name	Lith0	Text0	Mineral0	Lith1	Text1	Mineral1	Lith2	Text2	Mineral2
Maclaren01	Pegmatite	pegmatite								
Joubert01	Pegmatite	pegmatite								
DuPlessis1	Pegmatite	pegmatite								
Maclaren01	Quartz_vein	quartz_vein								

Lithbase Data Table

Lith3	Text3	Mineral3	Lith4	Text4	Mineral4	Lith5	Text5	Mineral5
amphibolite	gneiss		calc_slicate	gneiss		iron_formation	gneiss	magnetite
bt_gneiss	gneiss	bt	iron_formation	gneiss				
conglomerate	schist		iron_formation	gneiss				
calc_silicate	gneiss		quartzite	gneiss		bt_sapph_gneiss	gneiss	bt_sapph
quartzite	gneiss		magnetite_quartzite	gneiss	magn	leucogranite	gneiss	
bt_cd_sill_schist	schist							
bt_cd_sill_schist	schist	bt_cd_sill						
bt_cd_sill_schist	schist	bt_cd_sill						
quartzite	gneiss							

Lithbase Data Table

Lith3	Text3	Mineral3	Lith4	Text4	Mineral4	Lith5	Text5	Mineral5
calc_silicate	gneiss		calc_silicate	marble				
calc_silicate	gneiss							
amphibolite	gneiss							
garn_bt_gneiss	augen_gneiss							
calc_silicate	gneiss							
quartzite	gneiss							

Lithbase Data Table

Lith3	Text3	Mineral3	Lith4	Text4	Mineral4	Lith5	Text5	Mineral5
calc_silicate	gneiss		qtzo_fspathic_gneiss	gneiss		granite_gneiss	gneiss	'
mafic_gneiss	gneiss	px						
bt_cd_sill_schist	schist							
granite								
amphibolite	gneiss							
biotite_schist	schist							
calc_silicate	gneiss		qtzo_fspathic_gneiss	gneiss		conglomerate	gneiss	
pyroxenite			amphibolite			peridotite		
amphibolite	gneiss							
bt_cd_sill_schist	schist	bt_cd_sill						
mafic_gneiss	porphyroblast_gneiss							

Lithbase Data Table

Lith3	Text3	Mineral3	Lith4	Text4	Mineral4	Lith5	Text5	Mineral5

Originfo Table

strat	description
Pella_quartzite	quartzite
Kimberlite_mc	
Haramoep_gneiss	Quartzo_feldspathic
Unknown	
Namies_schist	sill_bt_schist
Pegmatite	
Amphibolite	amphibolite
Calc_silicate	calc_silicate
Mafic_intrusive	mafic
Aroams_gneiss	Granite_gneiss
Cover	superficial
Granite	leucocratic
Nousees_gneiss	mafic_gneiss
Qtz_mus_schist	
Quartz_vein	
Quartzite	glassy
Quartzite	granular
Calc_silicate	gneiss
OrthAmphibolite	
Leucogneiss	
Qrtzo_feldspath	gneiss
orthAmphibolite	cluster
Granite_gneiss	red_alkali_feldspar
Karoo-dol_mc	dolerite
Streaky_gneiss	
ParaAmphibolite	
Cover	pan_deposits
Calc_silicate	marble
Iron_formation	
Mus_qtz_schist	
mQrtzo_fspath	megacrystic_gneiss
Granite_mgneiss	red_alkali_feldspar
Biotite_schist	
mLeucogneiss	megacrystic
Ol_gabbronorite	mafic
Granite_mc	granodiorite_tonalit
Cover	Dwyka_float
Leptite	
Amphibolite	cluster
Diorite	pyroxene_bearing
Calc_silicate	conglomerate
Pelitic_gneiss	pelitic
Cover	Dwyka_tillite
Cover	Dwyka_shale
Cover	Dwyka_gravel
Eendoorn	m_bt_granite
Swartmodder	leucogranite
Toeslaan_fm	mixed
Naros_granite	main_body
Witwater	leucogranite
Toeslaan_fm	calc_silicate_lenses
Aplite_veins	
Stolzenfels	charnockite
Mafic_intrusive	amphibolite
Nous	quartz_diorite
Schuitdrift	bt_hbl_augengranite
Daberas	granodiorite
Naros_granite_M	mafic_phase
Yas_granite	leucogranite

Originfo Table

strat	description
Naros_granite_L	Leuco_phase
Dolerite_dyke	
Austerlitz	Qtzo_feldsp_gneiss
Kambreek	qtz_mus_schist
Orangefall	biotite_gneiss
Pelgrimsrust	hornblende_gneiss
Pelgrimsrust	hornblende_agmatite
Mylonite_zones	
Keimas	calc_silicate_gneiss
Pella	quartzite
Jerusalem	cd_sill_gar_gneiss
Kumkum	mafic_granolite
Beenbreek	mgranite_aplite
Beenbreek	megacrystic_granite
Orangefall	gneiss+calcsil_lense
Grassriver	augen_gneiss
Nautsis	alk_feldsp_granite
Jericho	amphibolite
Naros_complex	
Naros_granitoid	
Beenbreek	mgranite_aplite_fol
Cover	Nama_group_quartzite
Tsams_fm	metavolcanites
Goodhouse_gran	granitoids
Houmsriver	leucogranite
Goodhouse_undif	undiff_granitoids
Eendoorn_suite	augen_gneiss
Hoogoor_gneiss	leuco_qtzo_feldsp_gn
Bleskop_suite	pegmatites
Gaidip_fm	leuco_qtzo_feldsp_gn
Guadom_fm	biotite_gneiss
Vuurdood	mafic_ultra_mafic
Arus_fm	migmatite_mixed
Umeis_fm	migmatite_mixed
Tantalite_vally	mafic_ultra_mafic
Kumkum	mafic_rock
Ultramafic	
Namaqualand	granite_gneiss
Red_granite	
Kh2Gr	granitization
Kh2Gn	paragneiss
Kh2Sc	schist_fillite
Kh2Q	Quartzite
Granulite	amphibolite
Kh2Gl	meta_sediments
Mafic_rocks	
Kh3L	basic_lavas
Bt_hbl_gneiss	garnet_bearing
Biotite_granite	grey_gneissic_granit
Hom_fm	qtzo_feldspathic_gn
Skimmelberg	pegmatite
Stolzenfels_T	charnockite
calc_silicate_j	
mafic_granulite	orthoAmphibolite
biotite_gneiss	schist

Appendix C

Style query to display a map according to the lithologies with the highest correlation values

Variable Declaration Block

```
amph$ = "0 33 0"    # colour - 0 Red+33 Green+0 Blue = Light Green
bgn$ = "33 66 0"
bhgn$ = "100 33 33"
bhsc$ = "66 66 0"
bsc$ = "100 33 0"
csil$ = "0 100 100"
casc$ = "66 66 66"
csbsc$ = "66 33 66"
csqgn$ = "0 66 66"
char$ = "0 0 66"
dior$ = "100 0 0"
dol$ = "66 0 100"
felsic$ = "100 0 0"
gabbro$ = "0 0 0"
gbgn$ = "100 33 0"
gran$ = "66 33 33"
glite$ = "33 0 100"
hgn$ = "100 66 66"
ifm$ = "66 100 33"
qtz$ = "100 100 0"
kimb$ = "33 66 100"
leucogn$ = "66 33 33"
mafic$ = "0 0 0"
mqsc$ = "33 33 0"
mylonite$ = "0 66 66"
pegm$ = "100 33 100"
qfgn$ = "100 66 0"
sapbsc$ = "0 66 0"
sbsc$ = "66 33 100"
smsc$ = "66 66 100"
```

```
n=0                    # Boolean variable to test if a lithology has already been selected
DrawBorder = 1         # System variable (one of the query language variables) = 0 if the border is not to be drawn
Fillinside = 1         # System variable = 1if the polygon is to be filled with a colour
UseStyle = 0           # System variable = 1if a particular predefined style is to be used on polygon display
```

Lithology Detection Block

1. If the c_value in the first record, attached to the selected polygon, is the highest then display the polygon according to the value in the lithology field of the same record. The 'larger or equal to' -operator is used in the 'if'-expression as there are instances where two records have the same c_value. The first instance is then chosen and the other ignored.

```
if ((NammapDB.c_value >= NammapDB[2].c_value) and (NammapDB.c_value >= NammapDB[1].c_value)
        and (NammapDB.c_value >= NammapDB[3].c_value) and (NammapDB.c_value >= NammapDB[4].c_value)
        and (NammapDB.c_value >= NammapDB[5].c_value) and (NammapDB.c_value >= NammapDB[6].c_value)
        and (NammapDB.c_value >= NammapDB[7].c_value) and (NammapDB.c_value >= NammapDB[8].c_value)) then
        {n = 1; lithholder$ = NammapDB.lithology$}      # lithholder now contains the selected lithology
```

2. The same as (1.), but check if the c_value field of the second record is the highest and whether the previous record has not been chosen already (check if n still equals zero). The variable n has to be checked since a 'larger or equal to'-operator is used in the 'if'-expression.

```
if (((NammapDB[1].c_value >= NammapDB[2].c_value) and (NammapDB[1].c_value >= NammapDB.c_value)
        and (NammapDB[1].c_value >= NammapDB[3].c_value) and (NammapDB[1].c_value >= NammapDB[4].c_value)
        and (NammapDB[1].c_value >= NammapDB[5].c_value) and (NammapDB[1].c_value >= NammapDB[6].c_value)
        and (NammapDB[1].c_value >= NammapDB[7].c_value) and (NammapDB[1].c_value >= NammapDB[8].c_value)) and
```

```
       n == 0) then
       {n = 1; lithholder$ = NammapDB[1].lithology$}
```

3. Check third record attached to same polygon.

```
if (((NammapDB[2].c_value >= NammapDB[1].c_value) and (NammapDB[2].c_value >= NammapDB.c_value)
       and (NammapDB[2].c_value >= NammapDB[3].c_value) and (NammapDB[2].c_value >= NammapDB[4].c_value)
```

(Query 4.1 cont'd)

```
       and (NammapDB[2].c_value >= NammapDB[5].c_value) and (NammapDB[2].c_value >= NammapDB[6].c_value)
       and (NammapDB[2].c_value >= NammapDB[7].c_value) and (NammapDB[2].c_value >= NammapDB[8].c_value)) and
       n == 0) then
       {n = 1; lithholder$ = NammapDB[2].lithology$}
```

4. Check fourth record of same polygon.

```
if (((NammapDB[3].c_value >= NammapDB[2].c_value) and (NammapDB[3].c_value >= NammapDB.c_value)
       and (NammapDB[3].c_value >= NammapDB[1].c_value) and (NammapDB[3].c_value >= NammapDB[4].c_value)
       and (NammapDB[3].c_value >= NammapDB[5].c_value) and (NammapDB[3].c_value >= NammapDB[6].c_value)
       and (NammapDB[3].c_value >= NammapDB[7].c_value) and (NammapDB[3].c_value >= NammapDB[8].c_value)) and
       n == 0) then
       { n = 1; lithholder$ = NammapDB[3].lithology$}
```

5. Check fifth record of same polygon.

```
if (((NammapDB[4].c_value >= NammapDB[2].c_value) and (NammapDB[4].c_value >= NammapDB.c_value)
       and (NammapDB[4].c_value >= NammapDB[3].c_value) and (NammapDB[4].c_value >= NammapDB[1].c_value)
       and (NammapDB[4].c_value >= NammapDB[5].c_value) and (NammapDB[4].c_value >= NammapDB[6].c_value)
       and (NammapDB[4].c_value >= NammapDB[7].c_value) and (NammapDB[4].c_value >= NammapDB[8].c_value)) and
       n == 0) then
       {n = 1; lithholder$ = NammapDB[4].lithology$}
```

6. Check sixth record of same polygon.

```
if (((NammapDB[5].c_value >= NammapDB[2].c_value) and (NammapDB[5].c_value >= NammapDB.c_value)
       and (NammapDB[5].c_value >= NammapDB[3].c_value) and (NammapDB[5].c_value >= NammapDB[4].c_value)
       and (NammapDB[5].c_value >= NammapDB[1].c_value) and (NammapDB[5].c_value >= NammapDB[6].c_value)
       and (NammapDB[5].c_value >= NammapDB[7].c_value) and (NammapDB[5].c_value >= NammapDB[8].c_value)) and
       n == 0) then
       {n = 1; lithholder$ = NammapDB[5].lithology$}
```

7. Check seventh record attached to same polygon.

```
if (((NammapDB[6].c_value >= NammapDB[2].c_value) and (NammapDB[6].c_value >= NammapDB.c_value)
       and (NammapDB[6].c_value >= NammapDB[3].c_value) and (NammapDB[6].c_value >= NammapDB[4].c_value)
       and (NammapDB[6].c_value >= NammapDB[5].c_value) and (NammapDB[6].c_value >= NammapDB[1].c_value)
       and (NammapDB[6].c_value >= NammapDB[7].c_value) and (NammapDB[6].c_value >= NammapDB[8].c_value)) and
       n == 0) then
       {n = 1; lithholder$ = NammapDB[6].lithology$}
```

8. Check eighth record attached to same polygon

```
if (((NammapDB[7].c_value >= NammapDB[2].c_value) and (NammapDB[7].c_value >= NammapDB.c_value)
       and (NammapDB[7].c_value >= NammapDB[3].c_value) and (NammapDB[7].c_value >= NammapDB[4].c_value)
       and (NammapDB[7].c_value >= NammapDB[5].c_value) and (NammapDB[7].c_value >= NammapDB[6].c_value)
       and (NammapDB[7].c_value >= NammapDB[1].c_value) and (NammapDB[7].c_value >= NammapDB[8].c_value)) and
       n == 0) then
       {n = 1; lithholder$ = NammapDB[7].lithology$}
```

9. Check nineth record attached to polygon.

```
if (((NammapDB[8].c_value >= NammapDB[2].c_value) and (NammapDB[8].c_value >= NammapDB.c_value)
       and (NammapDB[8].c_value >= NammapDB[3].c_value) and (NammapDB[8].c_value >= NammapDB[4].c_value)
       and (NammapDB[8].c_value >= NammapDB[5].c_value) and (NammapDB[8].c_value >= NammapDB[6].c_value)
       and (NammapDB[8].c_value >= NammapDB[7].c_value) and (NammapDB[8].c_value >= NammapDB[1].c_value)) and
       n == 0) then
       {n = 1; lithholder$ = NammapDB[8].lithology$}
```

There are no more than nine NammapDB records attached per polygon

Display Style Assignment Block

```
if (lithholder$ == "quartzite") then
                {DrawColor$ = "black"
                FillColor$ = qtz$}          # polygon is filled with colour associated with selected lithology
if (lithholder$ == "amphibolite") then
                {DrawColor$ = "black"
                FillColor$ = amph$}
if (lithholder$ == "bt_gneiss") or (lithholder$ == "bt_granite_gneiss") then

(Query 4.1 cont'd)
                {DrawColor$ = "black"
                FillColor$ = bgn$}
if (lithholder$ == "bt_hb_gneiss") then
                {DrawColor$ = "black"
                FillColor$ = bhgn$}
if (lithholder$ == "bt_hb_schist") then
                {DrawColor$ = "black"
                FillColor$ = bhsc$}
if (lithholder$ == "bt_schist") then
                {DrawColor$ = "black"
                FillColor$ = bsc$}
if (lithholder$ == "calc_silicate_gneiss") then
                {DrawColor$ = "black"
                FillColor$ = csil$}
if (lithholder$ == "cd_anth_schist") then
                {DrawColor$ = "black"
                FillColor$ = casc$}
if (lithholder$ == "cd_sill_bt_schist") then
                {DrawColor$ = "black"
                FillColor$ = csbsc$}
if (lithholder$ == "cd_sill_qtz_gneiss") then
                {DrawColor$ = "black"
                FillColor$ = csqgn$}
if (lithholder$ == "charnockite_enderbite") then
                {DrawColor$ = "black"
                FillColor$ = char$}
if (lithholder$ == "dioritic_rock") then
                {DrawColor$ = "black"
                FillColor$ = dior$}
if (lithholder$ == "dolerite") then
                {DrawColor$ = "black"
                FillColor$ = dol$}
if (lithholder$ == "felsic_rock") then
                {DrawColor$ = "black"
                FillColor$ = felsic$}
if (lithholder$ == "gabbroic_rock") then
                {DrawColor$ = "black"
                FillColor$ = gabbro$}
if (lithholder$ == "garnet_bt__gneiss") then
                {DrawColor$ = "black"
                FillColor$ = gbgn$}
if (lithholder$ == "granitic_gneiss") then
                {DrawColor$ = "black"
                FillColor$ = gran$}
if (lithholder$ == "granulite") then
                {DrawColor$ = "black"
                FillColor$ = glite$}
if (lithholder$ == "hb_gneiss") then
                {DrawColor$ = "black"
                FillColor$ = hbgn$}
if (lithholder$ == "iron_formation") then
                {DrawColor$ = "black"
                FillColor$ = ifm$}
if (lithholder$ == "kimberlite") then
                {DrawColor$ = "black"
                FillColor$ = kimb$}
if (lithholder$ == "leucogneiss") then
                {DrawColor$ = "black"
                FillColor$ = leucogn$}
if (lithholder$ == "mafic_rock") then
```

```
                        {DrawColor$ = "black"
                        FillColor$ = mafic$}
if (lithholder$ ==  "mus_qtz_schist") then
                        {DrawColor$ = "black"
                        FillColor$ = mqsc$}
if (lithholder$ == "mylonite") then
                        {DrawColor$ = "black"
                        FillColor$ = mylonite$}
if (lithholder$ == "pegmatite") then
                        {DrawColor$ = "black"
                        FillColor$ = pegm$}
if (lithholder$ == "quartzo_feldspathic_gneiss") then
                        {DrawColor$ = "black"
                        FillColor$ = qfgn$}
if (lithholder$ == "sapph_bt_schist") then
                        {DrawColor$ = "black"
                        FillColor$ = sapbschist$}
if (lithholder$ == "sill_bt_schist") then
                        {DrawColor$ = "black"
                        FillColor$ = sbsc$}
if (lithholder$ == "sill_mus_schist")) then
                        {DrawColor$ = "black"
                        FillColor$ = smsc$}
```

End of Query

Appendix D

Displays polygons according to the correlation value for the NammapDB record with the highest correlation value. Corresponds to the lithology query - Appendix C

Variable Declaration Block

```
c_20$ = "horbars"              # variables containing predefined pattern information - 'horbars' = horizontal bars
c_30$ = "vertbars"
c_40$ = "circly"
c_50$ = "dotty"
c_60$ = "diagr"
c_70$ = "dashedh"
c_80$ = "diagl"
c_90$ = "diagtr"


n=0                            # Boolean variable - true if a style has already been chosen
DrawBorder = 0                 # System Variable = 0 if no border is to be drawn around polygons
FillInside = 1                 # polygon is to be filled...
FillBitmapPatt = 1             # ...with a predefined bitmap pattern
UseStyle = 0                   # no style to be used
```

Selection Block

1. The same as Query 4.1. See if first NammapDB record attached to the polygon contains the highest correlation value. If true then store the value, so that a pattern can be associated with the polygon.

```
if ((NammapDB.c_value >= NammapDB[2].c_value) and (NammapDB.c_value >= NammapDB[1].c_value)
        and (NammapDB.c_value >= NammapDB[3].c_value) and (NammapDB.c_value >= NammapDB[4].c_value)
        and (NammapDB.c_value >= NammapDB[5].c_value) and (NammapDB.c_value >= NammapDB[6].c_value)
        and (NammapDB.c_value >= NammapDB[7].c_value) and (NammapDB.c_value >= NammapDB[8].c_value)) then
        {n = 1; c = NammapDB.c_value}       # style has been chosen (n is true). c now contains highest correlation
                                            value
```

2. Check second record

```
if ((NammapDB[1].c_value >= NammapDB[2].c_value) and (NammapDB[1].c_value >= NammapDB.c_value)
        and (NammapDB[1].c_value >= NammapDB[3].c_value) and (NammapDB[1].c_value >= NammapDB[4].c_value)
        and (NammapDB[1].c_value >= NammapDB[5].c_value) and (NammapDB[1].c_value >= NammapDB[6].c_value)
        and (NammapDB[1].c_value >= NammapDB[7].c_value) and (NammapDB[1].c_value >= NammapDB[8].c_value)) then
        {n = 1; c = NammapDB[1].c_value}
```

3. Check third record.

```
if (((NammapDB[2].c_value >= NammapDB[1].c_value) and (NammapDB[2].c_value >= NammapDB.c_value)
        and (NammapDB[2].c_value >= NammapDB[3].c_value) and (NammapDB[2].c_value >= NammapDB[4].c_value)
        and (NammapDB[2].c_value >= NammapDB[5].c_value) and (NammapDB[2].c_value >= NammapDB[6].c_value)
        and (NammapDB[2].c_value >= NammapDB[7].c_value) and (NammapDB[2].c_value >= NammapDB[8].c_value)) and
        n == 0) then
        {n = 1; c = NammapDB[2].c_value}
```

4. Check fourth record

```
if (((NammapDB[3].c_value >= NammapDB[2].c_value) and (NammapDB[3].c_value >= NammapDB.c_value)
        and (NammapDB[3].c_value >= NammapDB[1].c_value) and (NammapDB[3].c_value >= NammapDB[4].c_value)
        and (NammapDB[3].c_value >= NammapDB[5].c_value) and (NammapDB[3].c_value >= NammapDB[6].c_value)
        and (NammapDB[3].c_value >= NammapDB[7].c_value) and (NammapDB[3].c_value >= NammapDB[8].c_value)) and
        n == 0) then
        { n = 1; c = NammapDB[3].c_value}
```

5. Check fifth record

```
if (((NammapDB[4].c_value >= NammapDB[2].c_value) and (NammapDB[4].c_value >= NammapDB.c_value)
        and (NammapDB[4].c_value >= NammapDB[3].c_value) and (NammapDB[4].c_value >= NammapDB[1].c_value)
        and (NammapDB[4].c_value >= NammapDB[5].c_value) and (NammapDB[4].c_value >= NammapDB[6].c_value)
        and (NammapDB[4].c_value >= NammapDB[7].c_value) and (NammapDB[4].c_value >= NammapDB[8].c_value)) and
```

```
        n == 0) then
            {n = 1; c = NammapDB[4].c_value}
```

6. Check sixth record

```
if (((NammapDB[5].c_value >= NammapDB[2].c_value) and (NammapDB[5].c_value >= NammapDB.c_value)
        and (NammapDB[5].c_value >= NammapDB[3].c_value) and (NammapDB[5].c_value >= NammapDB[4].c_value)
        and (NammapDB[5].c_value >= NammapDB[1].c_value) and (NammapDB[5].c_value >= NammapDB[6].c_value)
        and (NammapDB[5].c_value >= NammapDB[7].c_value) and (NammapDB[5].c_value >= NammapDB[8].c_value)) and
        n == 0) then
            {n = 1; c = NammapDB[5].c_value}
```

7. Check seventh record.

```
if (((NammapDB[6].c_value >= NammapDB[2].c_value) and (NammapDB[6].c_value >= NammapDB.c_value)
        and (NammapDB[6].c_value >= NammapDB[3].c_value) and (NammapDB[6].c_value >= NammapDB[4].c_value)
        and (NammapDB[6].c_value >= NammapDB[5].c_value) and (NammapDB[6].c_value >= NammapDB[1].c_value)
        and (NammapDB[6].c_value >= NammapDB[7].c_value) and (NammapDB[6].c_value >= NammapDB[8].c_value)) and
        n == 0) then
            {n = 1; c = NammapDB[6].c_value}
```

8. Check eigth record.

```
if (((NammapDB[7].c_value >= NammapDB[2].c_value) and (NammapDB[7].c_value >= NammapDB.c_value)
        and (NammapDB[7].c_value >= NammapDB[3].c_value) and (NammapDB[7].c_value >= NammapDB[4].c_value)
        and (NammapDB[7].c_value >= NammapDB[5].c_value) and (NammapDB[7].c_value >= NammapDB[6].c_value)
        and (NammapDB[7].c_value >= NammapDB[1].c_value) and (NammapDB[7].c_value >= NammapDB[8].c_value)) and
        n == 0) then
            {n = 1; c = NammapDB[7].c_value}
```

9. Check nineth record.

```
if (((NammapDB[8].c_value >= NammapDB[2].c_value) and (NammapDB[8].c_value >= NammapDB.c_value)
        and (NammapDB[8].c_value >= NammapDB[3].c_value) and (NammapDB[8].c_value >= NammapDB[4].c_value)
        and (NammapDB[8].c_value >= NammapDB[5].c_value) and (NammapDB[8].c_value >= NammapDB[6].c_value)
        and (NammapDB[8].c_value >= NammapDB[7].c_value) and (NammapDB[8].c_value >= NammapDB[1].c_value)) and
        n == 0) then
            {n = 1; c = NammapDB[8].c_value}
```

Display Style Assignment Block

```
if (c == 20) then FillPatt$ = c_20$      # if the correlation value for the polygon is 20%, then display polygon filled with
                                              pattern associated with a 20% correlation value.

if (c == 30) then FillPatt$ = c_30$
if (c == 40) then FillPatt$ = c_40$
if (c == 50) then FillPatt$ = c_50$
if (c == 60) then FillPatt$ = c_60$
if (c == 70) then FillPatt$ = c_70$
if (c == 80) then FillPatt$ = c_80$
if (c == 90) then FillPatt$ = c_90$
```

End of Query 4.2