PROVENANCE OF ALLUVIAL DIAMONDS IN SOUTHERN AFRICA: A MORPHOLOGICAL AND MINERAL CHEMISTRY STUDY OF DIAMONDS AND RELATED HEAVY MINERALS FROM THE VAAL-ORANGE SYSTEM AND THE WEST COAST

by

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DECLARATION

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

Signature: Date: 31 January 2012

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PREAMBLE

A collection of coloured diamonds from the Samada kimberlite, Northern Free State Province, Republic of South Africa that formed part of this study.
Scale divisions in millimetres.

"Heavy minerals are unique messengers of coded data, carrying the history of its ancestry" Mange (2002)

A B S T R A C T

The discovery of lucrative diamond deposits along the west coast of Southern Africa about 1200 kilometres from the Kimberley region during the period 1908 to 1927, gave rise to a number of different theories with respect to their possible provenance. These included the transportation of diamonds from unknown sources in southern Namibia by south-flowing rivers, hidden on- and off-shore kimberlites along the coast, and transportation by west-bound rivers from the hinterland. Subsequent research has shown that the latter is the only plausible theory.

The discovery of marine and coastal diamond deposits as far south as the Olifants River estuary showed that the Vaal-Orange drainage in its current form could not have been the only conduit for diamonds to the coast, and the drainage evolution of southern Africa was interpreted as comprising essentially the following two main palaeo-fluvial systems active in the formation of the world's only known diamond mega-placer deposit:

- The Karoo River with its headwaters similar to those of the modern Orange and Vaal Rivers and entering the Atlantic Ocean *via* the present-day Olifants River;
- The Kalahari River that drained southern Botswana and followed the route of the modern-day Molopo River, entering the Atlantic Ocean in the vicinity of the present Orange River mouth.

An important shortcoming of the above model is that it could not account for the fact that diamond distribution along the west coast shows a marked increase in grade and average stone size at the estuaries of all the major rivers draining from the escarpment to the Atlantic between the Olifants and the Orange Rivers. The presence of fluvial diamond deposits along the courses of the Buffels, Swartlintjies, Spoeg, Horees and Groen Rivers confirms that the increased grade and diamond size at their estuaries is not a function of large bays and rougher bottom topography associated with the rivers, although these could have contributed to this phenomenon. This proves that the catchments of the rivers between the Olifants

and Orange Rivers also had access to diamondiferous debris, although they were not in contact with these two major drainages.

A number of researchers proposed that diamonds liberated from pre-Karoo kimberlites were moved from their primary hosts to the south-western parts of the subcontinent by Dwyka glacials.

From the above it is clear that nearly a century after the discovery of diamonds along the west coast of southern Africa consensus regarding their origin had not been reached. The aim of this study was therefore to establish a model explaining the most likely sources and distribution history of the more important alluvial diamond deposits in southern Africa.

The methodology comprised a study of 1878 diamonds collected from 25 alluvial and two kimberlitic sources for comparison with known similar data from 12 kimberlitic populations in southern Africa. The diamond study was supplemented by a study of sedimentary clasts from bulk gravel samples taken along the Middle and Lower Orange River as well as Scanning Electron-microscope (SEM) Analyses of garnet grains and zircon geochronology.

The evidence from the study does not support the postulated existence of a former Karoo River. The surface features of diamonds, notably brown spots indicating – in the context of southern Africa - liberation from pre-Karoo kimberlites, as well as the results of Fourier Transform Infrared analyses revealed that the populations at Kwaggaskop along the Sout River, previously considered an erosion remnant of the Lower Karoo River and those occurring south of Brandvlei and Van Wyksvlei in the valley of the Sak River, previously considered to have been reworked from the Middle Karoo River, differ profoundly from each other. In addition, the surface feature studies and Fourier Transform Infrared Analyses clearly show major distinctions between the diamond populations from the Sout River-Olifants River estuary and those from the Kimberley kimberlite province which was said to have supplied diamonds in large quantities to the Olifants River estuary *via* the postulated Karoo River. Furthermore the idea of a palaeo-Gamoep River playing a significant role in the transportation of diamonds to the west coast is favoured by the presence of brown-spotted diamonds and diamonds with Platelet Preservation Indices revealing severe platelet destruction that could be traced through Bosluispan in the Koa River valley, the Buffels River valley, the Buffels River estuary and to the shallow marine environment north of the Buffels River.

Zircon geochronology confirmed the role of the Orange River in the denudation of the sub-continent.

With respect to the drainage evolution and diamond distribution in southern Africa the results of this study indicate a complex diamond dispersal model that differs in some respects from prevailing theories. It shows that diamonds liberated from pre-Karoo kimberlites in the north-eastern part of the sub-continent were initially moved in a south-westerly direction by pre-Karoo drainages, then by Dwyka glaciers and ice sheets. Ultimately, after liberation from exhumed glacial and fluvial deposits and together with diamonds subsequently liberated from Jurassic and Cretaceous kimberlites, Cretaceous and younger drainages provided the transport toward the Atlantic Ocean where the diamonds were concentrated along shorelines and in bedrock trap sites. Significant quantities did not reach the coast, but were locked up in fluvial sediments in erosion remnants like terraces, karstic depressions and other segments of palaeo-channels along the way.

The presence of diamonds with FTIR characteristics reminiscent of those from Orapa and Jwaneng in the Orange River deposits as well as in a raised marine terrace in southern Namaqualand and in marine deposits north of Concession 12A, also negates the possible existence of a palaeo-Kalahari River, unless it was a very young system that did not interrupt the south-bound dispersal of Botswana diamonds during the Late Oligocene-Early Miocene.

The study also included microscopic examination of a parcel of diamonds from the enigmatic Skeleton Coast deposits, north-western Namibia. These results confirmed the conclusion based on geological and geomorphic grounds that these diamonds cannot be linked to the Oranjemund deposits, while their surface features showed that pre-Karoo sources comprise the most likely provenance for the Skeleton Coast diamonds.

Thus the combination of FTIR analyses and surface feature studies of diamonds, zircon geochronology and SEM analyses of garnets allowed the formulation of a revised model for the distribution of alluvial diamonds and the drainage history of the sub-continent since the Middle Cretaceous, while the study of sedimentary clasts confirmed the repeated occurrence of high energy fluvial conditions – especially evident in the palaeo-Orange River sediments – that contributed to the high percentage of gem stones in the surviving alluvial diamond populations due to the destruction of poor quality diamonds.

OPSOMMING

Die ontdekking van ryk alluviale diamantafsettings aan die suider-Afrikaanse weskus, meer as 1200 kilometer van die Kimberley-omgewing af tussen 1908 en 1927, het 'n aantal teorieë omtrent moontlike provenansgebiede vir hierdie afsettings tot gevolg gehad. Dit het gewissel van die suidwaartse vervoer van diamante vanaf bronne in suidelike Namibië, diamantdraende kimberliete in die kusvlaktes of op die vastelandstoep onder huidige seevlak, tot die vervoer van diamante deur weswaarts-vloeiende riviere vanuit die binneland.

Geen ontdekkings wat eersgenoemde teorie kon ondersteun is in Namibië gemaak nie. Verder, namate meer gevorderde navorsingsresultate aan die lig gekom het, het dit duidelik geword dat kimberliete wat weg van 'n antieke kraton geleë is, grootliks sonder diamante is, en gevolglik het die idee van nabygeleë diamant-draende kimberliete in die kusvlakte of op die seebodem as bron, onaanvaarbaar geword. Grootskaalse wes- tot suidweswaartse vervoer van diamante het gevolglik die enigste aanvaarbare alternatief gebied.

Die ontdekkiing van aan- en aflandige mariene afsettings tot so ver as suid van die Olifantrsrivier het getoon dat die Vaal-Oranjestelsel in sy huidige vorm nie die enigste vervoerkanaal vir diamante na die weskus kon wees nie. Die dreineringsgeskiedenis van suidelike Afrika was gevolglik vertolk aan die hand van twee voorgestelde groot oer-rivierstelsels, naamlik:

- Die Karoorivier met sy bolope naastenby soortgelyk aan dié van die moderne Oranje- en Vaalriviere, en wat langs die huidige Olifantsrivier uitgemond het;
- Die Kalaharirivier wat die suide van Botswana gedreineer het, en min of meer die roete van die huidige Moloporivier gevolg het, met sy monding baie naby aan dié van die moderne Oranjerivier.

'n Belangrike tekortkoming in bogenoemde model is die feit dat dit nie 'n verduideliking bied vir die volgende feit nie: Diamant-produksiedata van die Suid-

Afrikaanse weskus toon 'n skielike toename in graad (karaat per 100 ton) en gemiddelde steengrootte van diamante by die monding van al die belangrike riviere tussen die Olifants- en Oranjeriviere, wat vanaf die platorand na die Atlantiese Oseaan dreineer. Die feit dat fluviale diamantvoorkomste in die valleie van die Bufffels-, Swartlintjies-, Spoeg-, Horees- en Groenriviere aangetref word, bevestig dat hierdie verskynsel nie net aan die teenwoordigheid van kus-inhamme en ruwer vloertopografie wat met die riviermondings geassosiëer is, toegeskryf kan word nie, alhoewel dit wel ‘n bydrae tot hierdie waarneming kon maak. Dit bevestig dat hierdie riviere wel in hul opvang-gebiede ook toegang tot diamanthoudende puin gehad het, sonder enige kontak met die Olifants- of Oranjeriviere.

'n Aantal navorsers het die gedagte geopper dat diamante wat uit voor-Karoo kimberliete vrygestel was, deur bewegende ysplate en/of gletsers vanaf hul provenansgebiede na die suidweste van die subkontinent vervoer is.

Uit die voorafgaande paragrawe is dit duidelik dat, ongeveer 'n eeu ná die ontdekking van diamante langs die suider-Afrikaanse weskus, daar nog nie eenstemmigheid bereik is oor die oorsprong van hierdie diamante nie. Die doel van hierdie studie was gevolglik die daarstelling van ‘n model wat ‘n aanvaarbare verduideliking bied vir die verspreiding en afsetting van sommige voorkomste van spoeldiamante in suidelike Afrika soos tans waargeneem.

Vir hierdie doel is 1878 diamante afkomstig vanuit 25 alluviale en twee kimberlietvoorkomste ondersoek. Die resultate is vergelyk met soortgelyke inligting wat bekend is vir diamantpopulasies vanuit 12 suider-Afrikaanse kimberliete. Die diamantstudie is aangevul met die ondersoek van spoelklippe vanuit gruismonsters wat langs die Middel- en Benede Oranjerivier versamel is asook Skanderings-elektron Mikroskoop-analises (SEM) van granaatkorrels en sirkoon-geokronologie.

Die resultate van hierdie studie ondersteun nie die hipotese van ‘n eertydse Karoorivier nie. Die teenwoordigheid van bruin spikkels op diamante wat – in die konteks van die geologiese geskiedenis van suidelike Afrika – vrystelling vanuit vóór-Karoo kimberliete impliseer, asook die resultate van FTIR-analises dui op 'n komplekse model wat 'n alternatief bied vir bestaande sienswyses. Dit toon dat die diamantpopulasies by Kwaggaskop langs die Soutrivier wat veronderstel was om die Benede Karoorivier te verteenwoordig, en dié wat suid van Brandvlei en Van Wyksvlei in die vallei van die Sakrivier aangetref word en veronderstel was om afkomstig te wees uit die Middel Karoorivier, drasties van mekaar verskil. Dit openbaar ook beduidende verskille tussen die diamantpopulasies van die Olifantsriviermonding en dié van die Kimberley-omgewing waarvandaan die veronderstelde Karoorivier groot hoeveelhede diamante aan die Sout-Olifantsrivier sou gelewer het. Verder verskaf die teenwoordigheid van diamante met bruin spikkels en diamante met eienskappe wat toon dat hul stikstofplaatjies vernietig is, 'n skakel tussen Bosluispan in die vallei van die Koarivier en die seegebied noord van die Buffelsrivier, *via* die Buffelsriviervallei en die Buffelsriviermonding, en hierdie feite ondersteun gevolglik eerder die voorstel dat groot hoeveelhede diamante deur die paleo-Gamoeprivier na die weskus vervoer is.

Die teenwoordigheid van diamante met FTIR-kenmerke soortgelyk aan dié van Orapa en Jwaneng in die Mid-Oranje afsettings, 'n mariene terras in die suide van Namakwaland en in mariene konsessies noord van Seegebied 12A, opponeer ook die gedagte van 'n paleo-Kalaharirivier, tensy laasgenoemde 'n baie jong stelsel was wat nie die suidwaartse beweging van Botswana-diamante gedurende die Laat Oligoseen tot Vroeg Mioseen verhinder het nie.

Die resultate van die sirkoon-geokronologie het die rol van die Oranjerivier in die afplatting van die subkontinent bevestig.

Die volgende model tree uit bogenoemde waarnemings na vore: diamante wat in die noordooste van die subkontinent uit kimberliete met 'n voor-Karoo inplasingsouderdom vrygestel is, is aanvanklik suidweswaarts vervoer deur voor-Karoo riviere. Daarna is die diamante deur gletsers en ysplate gedurende die Dwykatydperk, en uiteindelik ná vrystelling vanuit ontblote glasiale en paleo-fluviale afsettings tesame met diamante wat intussen vanuit Jura- en Krytouderom kimberliete vrygestel is, deur die dreineringstelsels in die Kryt-tydperk en later, verder suidweswaarts vervoer. Sommige het onderweg in fluviale sedimente (terrasse, karstholtes en ander reste van paleokanale) agtergebly, terwyl 'n beduidende hoeveelheid tot in die Atlantiese Oseaan vervoer is waar hulle deur mariene prosesse in ou strandlyne en bodemrots opvangstrukture gekonsentreer is.

Die studie het ook die mikroskopiese ondersoek van 'n pakkie diamante afkomstig vanuit die enigmatiese afsettings aan die noordelike Skedelkus van Namibië ingesluit. Op grond van geologiese en geomorfologiese getuienis word die afleiding gemaak dat die Skedelkusdiamante nie met die Oranjemund-afsettings verbind kan word nie, terwyl die mikroskopiese oppervlakteksture toon dat bronne met 'n voor-Karoo inplasingsouderdom die mees waarskynlike provenans vir hierdie diamante is.

Die kombinasie van FTIR-analises en oppervlaktekstuur-studies van diamante, sirkoon-geokronologie en SEM-analises van granate het die formulering van 'n hersiene model vir die subkontinent se dreineringsgeskiedenis sedert die Middel-Kryttydperk en diamantverspreiding moontlik gemaak terwyl die studie van sedimentêre klaste getoon het dat hoë-energietoestande, waardeur diamante van swak gehalte vernietig sou word, herhaaldelik voorgekom het, veral in die paleo-Oranjerivier. Die afleiding word gemaak dat hierdie aspek 'n bydrae gelewer het tot die hoë persentasie juweelstene in die oorblywende alluviale diamantpopulasies.

LIST OF ABBREVIATIONS

BP	before present
CD	compact disc
CGS	Council for Geoscience, Pretoria, South Africa
CL	cathodoluminescence
cpht	carat per 100 tons of ore
ct	carat
DEM	Digital elevation map
EDX	Energy dispersive x-rays
FA	floodplain alluvium
FTIR	Fourier Transform Infrared
Ga	giga-annum (10^9 years)
HT	high terrace
IAS	International Association of Sedimentologists
LT	lower terrace
m.a.m.s.l.	metres above mean sea level
Ma	milli-annum (10^6 years)
MT	middle terrace
NAD	nitrogen aggregation diagram
NAM SG	Namibian Special Grant (diamond concessions, Orange River)
OU	Older Unit (Graauw Duinen)
PC	palaeo-channel
Psd/psd	particle size distribution
pers. comm.	personal communication
PPI	Platelet Preservation Index
SACS	South African Committee for Stratigraphy
SEM	Scanning Electron-microscope
SHRIMP	Sensitive High Resolution Ion Microprobe
SRTM90	Shuttle Radar Topography Mission
SWR	Swartwater mining section, Baken Mine

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CHAPTER 1. INTRODUCTION AND GENERAL BACKGROUND

1.1 General

This study benefited from visits to scores of mines and mineralized prospects on four continents over a period of more than 40 years. During this time, the way in which different factors worked together to cause an anomalous concentration of valuable elements that ultimately formed an ore body was often observed with awe. This interplay is also clearly illustrated by the diamond deposits of the Vaal-Orange drainage system and the marine as well as on-shore placers along the west coast of southern Africa. Here, the combination of alkaline volcanism, chemical and mechanical erosion, glaciation, diastrophism, climate and sea level fluctuations, regional as well as local geology, geomorphology, fluvial and marine sedimentology, the resistance of diamonds of gem quality to abrasion, and, to a lesser extent, aeolian processes, culminated in the formation of the world's only mega alluvial diamond placer (*i.e.,* containing ≥ 50 million carats of which at least 95% are of gem quality; Bluck *et al.*, 2005). This region has already produced about 200 million carats and the total potential resource has been estimated at 1.5 billion carats (Levinson *et al.,* 1992). In comparison, De Wit (1996) put the historic production from inland alluvial deposits at 18 million carats.

This thesis highlights the role of the Vaal-Orange drainage system in the distribution of diamonds in southern Africa, but also recognises the fact that this system was but one of a number of agents active in the distribution of diamonds.

It was along the valley of the Orange River that the first diamond was found in South Africa, a discovery that initiated the country's diamond industry and forever changed the mining and economic landscape of southern Africa.

The fascinating history of the discovery of diamonds in southern Africa is summarized and fully referenced in Appendix 8.5 (See also Fig.1.1).

The prime motivation for this study was to present an acceptable model that indicates the most likely source regions and transportation routes for the lucrative diamond deposits described above. Despite numerous publications on the subject a comprehensive model is still lacking.

1.2 Previous work

The available literature on diamonds, their host rocks and post-intrusion sedimentological evolution is comprehensive. Of particular interest for this study is the present state of knowledge on the provenance of alluvial diamond deposits in the Vaal-Orange River system and along the west coast of southern Africa.

In his two publications, Reuning explained that the placer diamond deposits at Alexander Bay and near the mouth of the Orange River were derived from a westward flowing drainage system (Reuning 1928; 1931). He supported the views of Lotz (1909) and stated that the Orange River was "the main bringer of diamonds to the coast" even in the face of stiff opposition from Wagner (1914), Wagner and Merensky (1928), who believed the coastal diamonds were derived from submarine kimberlites. Today Reuning's view is accepted by most researchers.

As our knowledge on diamond genesis and kimberlite petrology increased it became obvious that kimberlites located in mobile belts, a substantial distance away from a craton, or along a craton margin with thin lithospheric crust, are devoid of diamonds. Therefore the para-kimberlites of Bushmanland and kimberlites of southern Namibia could not be considered as possible sources for the alluvial diamonds found along the south-western coastal strip of the subcontinent. This was borne out by numerous unsuccessful prospecting attempts on these occurrences (Stocken, 1976; Van der Westhuizen, 1983). More recent research also revealed that none of the Bushmanland pipes are true kimberlite (Verwoerd and De Beer, 2006). With the known diamondiferous kimberlites located on the Kaapvaal and Zimbabwe Cratons of southern Africa, numerous attempts have been made to reconstruct the mode of dispersal of diamonds from these remote primary source regions to the western and south-western perimeter of the country (Dingle and Hendey, 1984; De Wit, 1993, 1996, 1999; De Wit *et al., 2000)*.

The relative young and unconsolidated sediments of the Lower Orange River valley were studied intermittently, as described below. De Villiers and Söhnge (1959) in their memoir on the geology of the Richtersveld observed that quartzite clasts were the most common rocks in the Cenozoic Orange River terraces. They also recognised the presence of pebbles of banded ironstone and jasper that came from beyond the confines of their study area. These were important observations made prior to the discovery of the diamondiferous sediments along the Lower Orange River valley.

Keyser (1972; 1976) described the diamond deposits of the South African west coast.

Fowler (1976, 1982) in his investigation of the Cenozoic sediments along the Lower Orange River valley and adjacent coastal regions introduced a relative-age related nomenclature for the fluvial terraces. The older proto terrace is overlain by a younger meso terrace, the latter being covered by the modern day Orange River gravels. Often, because of river meanders and incision, this order is reversed, with the older deposits occupying remnant terraces at higher elevations. SACS (1980) uses the name Arrisdrif Gravel Formation for the proto deposits.

The Miocene age of the Arrisdrif Gravel Formation was determined by Corvinus and Hendey (1978) based on the identification of vertebrate fossils found in proto-Orange River gravel beds and their observations were confirmed by Pickford *et al.* (1995). Pienaar (1982), Van Wyk and Pienaar (1986), Gresse (2003) and Mouton (1999, 2002) have all demonstrated that the various terraces are genetically linked through a continuous process of channel migration and incision.

After the discovery of economically important diamondiferous gravel deposits along the Lower Orange River, the Orange as a transport link between the diamondiferous kimberlites of the hinterland and the coast was confirmed (Van der Westhuizen, 1997). Earlier work by Hallam (1959, 1964) showed that the Orange was not the only fluvial system that took part in the westward dispersal of diamonds, but all the major drainages along the West Coast as far south as the Olifants River. Some of these rivers have no present link with the regions where the known on-craton diamondiferous kimberlites occur and a number of hypotheses were developed to address this aspect. Dingle and Hendey (1984) proposed that during Late Cretaceous times the

Orange River entered the Atlantic more or less at the same position (28° south) as today, but the Palaeogene Orange/Vaal River (termed the Karoo River) exit was *via* the escarpment crossing situated at 31° south close to the present Olifants River estuary. During the Late Miocene the Orange/Vaal system had switched back to the 28° south exit after stream capture caused the Karoo River to follow the Doornberg lineament in a northerly direction to become the Lower Orange River.

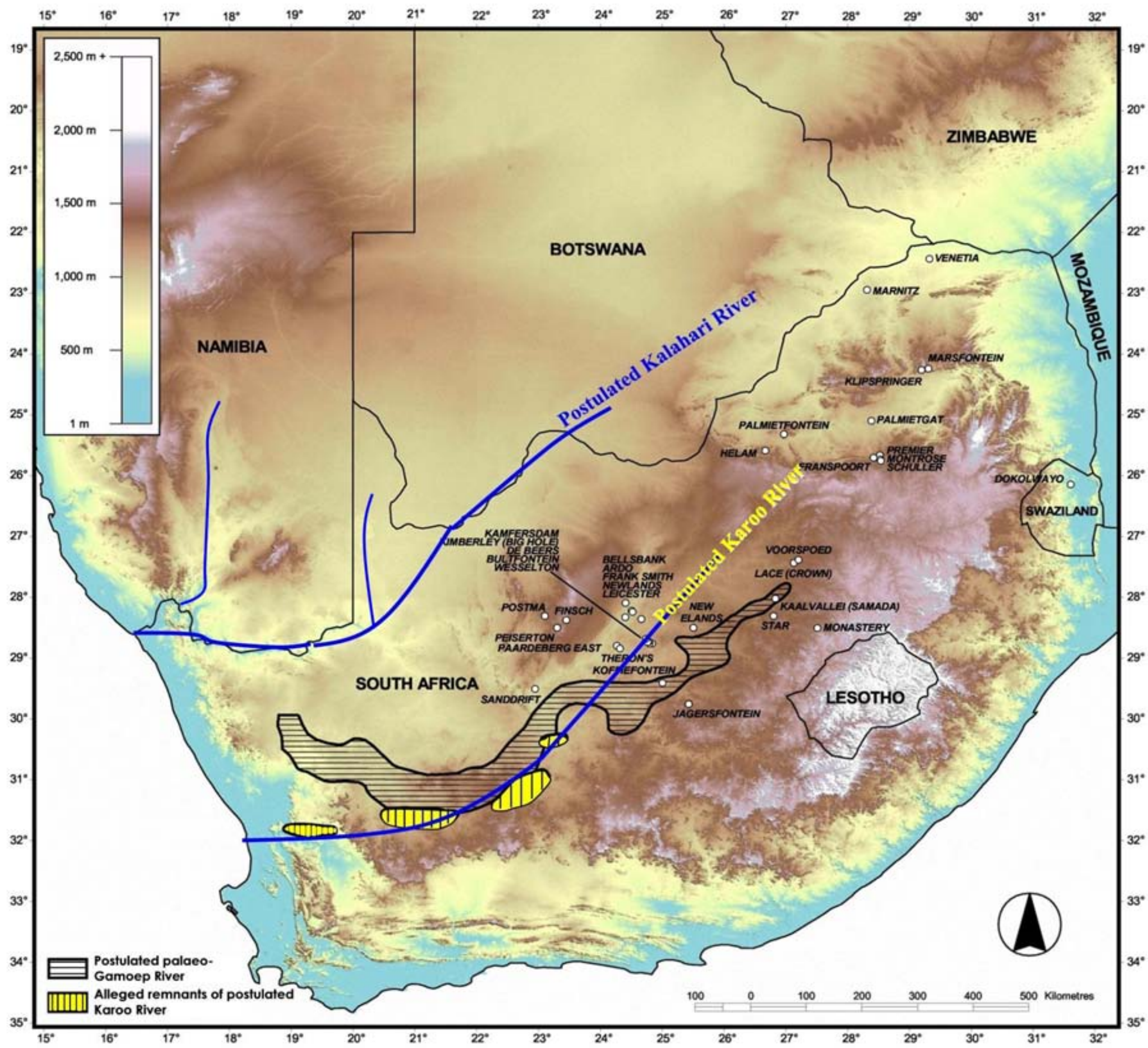


Figure 1.1 Palaeo-drainages as proposed by Dingle & Hendey (1984), De Wit (1993, 1999), De Wit *et al., (*2000), McCarthy *et al.* (1985), Partridge and Maud (1987) and Behr (1989).

Malherbe *et al.* (1986) concluded that the Orange River had a history dating from the pre-Permian to the Quaternary. They also proposed the former existence of an "Early Tertiary" drainage system (the Gamoep River) which originated near Odendaalsrus and reached the sea *via* the Swartlintjies River; this "Tertiary" river was subsequently captured by the channel of the present-day Koa Valley which in turn was captured by the Krom River (explaining the similarity of fish species in both river systems). Malherbe *et al. (op cit.)* saw the re-emergence of the Orange River as the major drainage system during Quaternary times, causing the Hartbees River to capture the Sak River and also influencing the development of the Molopo River.

Maree (1987) pointed to the close proximity of known important alluvial diamond deposits to areas where the Dwyka glacial deposits had been subjected to prolonged periods of weathering. His views that the mode of diamond dispersal included both glacial and fluvial activity was supported by Rouffaer (1988) and Moore and Moore (2004).

De Wit (1993, 1999) addressed the development of the Orange River and a number of other river systems and disagreed with Dingle and Hendey (1984) on their suggested drainage switching of the Orange River. He referred to the occurrence of two major depo-centres along the Atlantic coast of southern Africa which were interpreted as associated with two major drainages (Figure 1.1):

(i) the Karoo River in the south that consisted of the Upper Orange/Vaal River system that linked up with the present Olifants River, and
(ii) the Lower Orange River which drained southern Namibia and Botswana and linked up with the proto-Molopo River and formed the northern drainage system, referred to as the Kalahari River.

Alluvial diamond deposits along the Lower Orange River downstream from Vioolsdrif were well studied by a number of investigators. Hill and Van Der Westhuizen (1995) identified five different morphological sections of which the most extensive of these Cenozoic deposits were restricted to those areas where the river attained a high sinuosity ratio. Ward and Bluck (1997) highlighted some important aspects on the tectonic, geomorphic and climatic evolution of the sub-continent that influenced the development of the Orange-Vaal drainage and in particular the Orange River :

- It has been the most important conduit for transporting sediment from the interior of southern Africa to the Atlantic Ocean since the Early Cretaceous.
- Its character and capacity to carry sediment changed considerably from Late Cretaceous times through the Cenozoic to the present.
- It is currently a superimposed, predominantly braided, misfit system occupying an inherited meandering drainage pattern.
- It occupies a channel which has a gradient far steeper than that possible for a meandering river of its given discharge, indicating that the current slope is not the same as that which prevailed during incision, but was acquired subsequent to incision when the drainage had already been established.
- At the time of incision the river system drained approximately one million km^2.
- The discharge was much higher than that of major floods recorded during the 20th century.
- During the Late Cretaceous the bed load was essentially comprised of sand and a delta was built out on the southwest African continental shelf;
- By the Middle Eocene predominantly siliceous gravel clasts derived from the interior of southern Africa reached the Atlantic Coast *via* the Orange River;
- The uplift and accompanying incision began sometime during the Late Cretaceous;
- During the Miocene the incision was halted and fluvial aggradation prevailed, filling the inherited superimposed pattern of especially the Lower Orange River. The material deposited here (Arrisdrif Gravel Formation, SACS 1980) consisted mostly of sand and fine to coarse gravel, with occasional vertebrate remnants that were subsequently fossilized *in situ;*
- During the Plio-Pleistocene renewed incisions straightened out the lower reaches of the Orange River, leaving a number of cut-off meanders in its wake;
- With the renewed incision came rejuvenated stream activity that flushed out coarse (cobble- and boulder-sized) gravel to the Atlantic Ocean, but not without depositing substantial quantities of coarse gravel along the younger river channel (meso-deposits of Fowler, 1976, 1982).

Jacob *et al.* (1999) and Jacob (2005) reported on the diamondiferous fluvial deposits of the Lower Orange River, especially on the Namibian side. This was followed by a detailed sedimentological study between Vioolsdrif and the Atlantic coast. He concluded that:

- The Orange River incised the landscape by between 600 and 1000 metres but for about 90% of this incision, no sedimentary record is currently preserved in the Orange River valley;
- His study essentially supports Fowler (1976, 1982) who, based on river course, bedrock level, overall geometry and clast assemblage identified two sets of terraces flanking the modern Orange River. The older proto-suite of terraces harbouring pre-Proto (Late Eocene to Mid-Oligocene) and Proto (Early to Mid-Miocene) deposits, are the legacy of a sinuous river course markedly different from the modern river. Incision and aggradation during the Plio-Pleistocene resulted in the younger meso suite of upper, intermediate and lower terraces. Their bedrock elevations are closer, and they follow a course very similar to that of the modern river.
- Based on a comparison of longitudinal bedrock profiles, rates of downstream fining, clast roundness and clast type proportions, the modern river "is a considerably less competent river " than it was in proto and meso times.
- Clast assemblages were dominated by exotic siliceous lithotype deposited during the Eocene. This changed to locally-dominated types by the time the pre-Proto deposits accumulated, reflecting incision through the Karoo Basin and replacing of a Vaal River-derived clast suite by an Upper Orange River suite. This occurred in response to the aridification of the central and western parts of southern Africa.

Research on marine sedimentation on the offshore delta southwest of the mouth of the Olifants River, termed the Cape Canyon was done by Wigley (2005). She found no evidence supporting the existence of a major palaeo Karoo River and concluded that the submarine Cape Canyon was incised during the Plio-Pleistocene and not the Oligocene as previously suggested by Dingle (1971), Siesser and Dingle (1981) and Dingle and Hendey (1984).

All previous studies had investigated aspects related to geomorphology, sedimentology and heavy mineral composition of the diamondiferous placer deposits. The use of diamond characteristics *per sé* however had not been used to contribute to the understanding of their distribution and provenance, except for a single study by Phillips and Harris (2008) that used $^{40}Ar/^{39}Ar$ laser probe analyses of clinopyroxene inclusions. They investigated detrital diamonds from the Buffels River valley and estuary (48) and Oranjemund (68) along the west coast. A link between diamonds derived from kimberlites with a pre-Karoo emplacement age geographically derived from Botswana (Orapa), was indicated.

The present study, aimed at using the characteristics of alluvial diamonds from a variety of localities as indicators of provenance in conjunction with a series of other indicators, was initiated early in 2001. Such a study has not been previously undertaken mainly because of the legal and security constraints on the possession of uncut diamonds. The author's access to a diversity of diamond sources provided the opportunity to study diamond distribution from provenance to present location in a large section of southern Africa.

1.3 Aims and objectives

Despite numerous publications on various aspects of alluvial diamond distribution in southern Africa, the lack of an acceptable and comprehensive model that explains the migration of diamonds from source to present occurrence motivated this research project. Such a study could not be restricted to the west coast only and included as many alluvial diamond occurrences as possible.

To achieve the objective of aerially tracing alluvial diamond distribution in southern Africa a variety of parameters were considered instrumental in achieving this goal.

- A sound understanding of the geomorphological history of the sub-continent would allow identification of palaeo-fluvial systems that could have been active in diamond dispersal. This would be done by field observations and literature studies.

- The lithology of sedimentary clasts in the palaeo-fluvial diamondiferous deposits would be indicative of their provenance and features such as roundness, sphericity and size distribution, of transport distances.

- From a mineralogical perspective diamonds as such were considered the most logical and best mineral to study. Previous work on surface features allowed a source related classification (Lind and Bardwell, 1923; Phaal, 1965; Harris *et al.,* 1973, 1975; Orlov, 1973; Vance *et al.,* 1973; Robinson, 1975, 1979; Raal and Robinson, 1980; Hall and Smith, 1984; Tappert *et al.,* 2006) and combined with Fourier Transform Infra Red (FTIR) analyses, provided information diagnostic of the diamond source.

- To expand the existing literature database on surface and FTIR characteristics of diamonds from kimberlites, additional similar studies were undertaken on two South African kimberlites.

- To assist with provenance identification garnets which are very resistant against abrasion were selected from the heavy mineral population of the diamondiferous placers. Their mineral chemistry is considered a good indicator of their provenance particularly in distinguishing between metamorphic terranes and diamondiferous and non-diamondiferous kimberlite sources.

- Because of their extreme resistance to abrasion, geochronology of zircons in the diamondiferous placers was expected to assist in the identification of regional provenance terrains drained by these fluvial systems. Thus an indirect guide to the provenance of the associated diamonds could be identified.

The integration of results obtained from the above approaches would provide a good indication of diamond migration from source to final destination.

1.4 The Study area

The area selected for this study covers most of the central part of southern Africa and is indicated by the detailed maps (Figs. 1.3 to 1.6).

In this study the following nomenclature applies to the Orange River:

- the **Upper Orange:** from its source in the Maluthi Mountains of Lesotho to the Lesotho/South Africa border,
- the **Middle Orange**: from the Lesotho border to Augrabies and
- the **Lower Orange:** downstream from Augrabies to the West Coast.

In line with international geographical convention reference is not made to the north or south sides of the river but to the right and left banks with the observer looking downstream. This is preferable, since with a sharply meandering river like the Orange the same bank can change from being the eastern, northern, western and southern bank within a couple of kilometres.

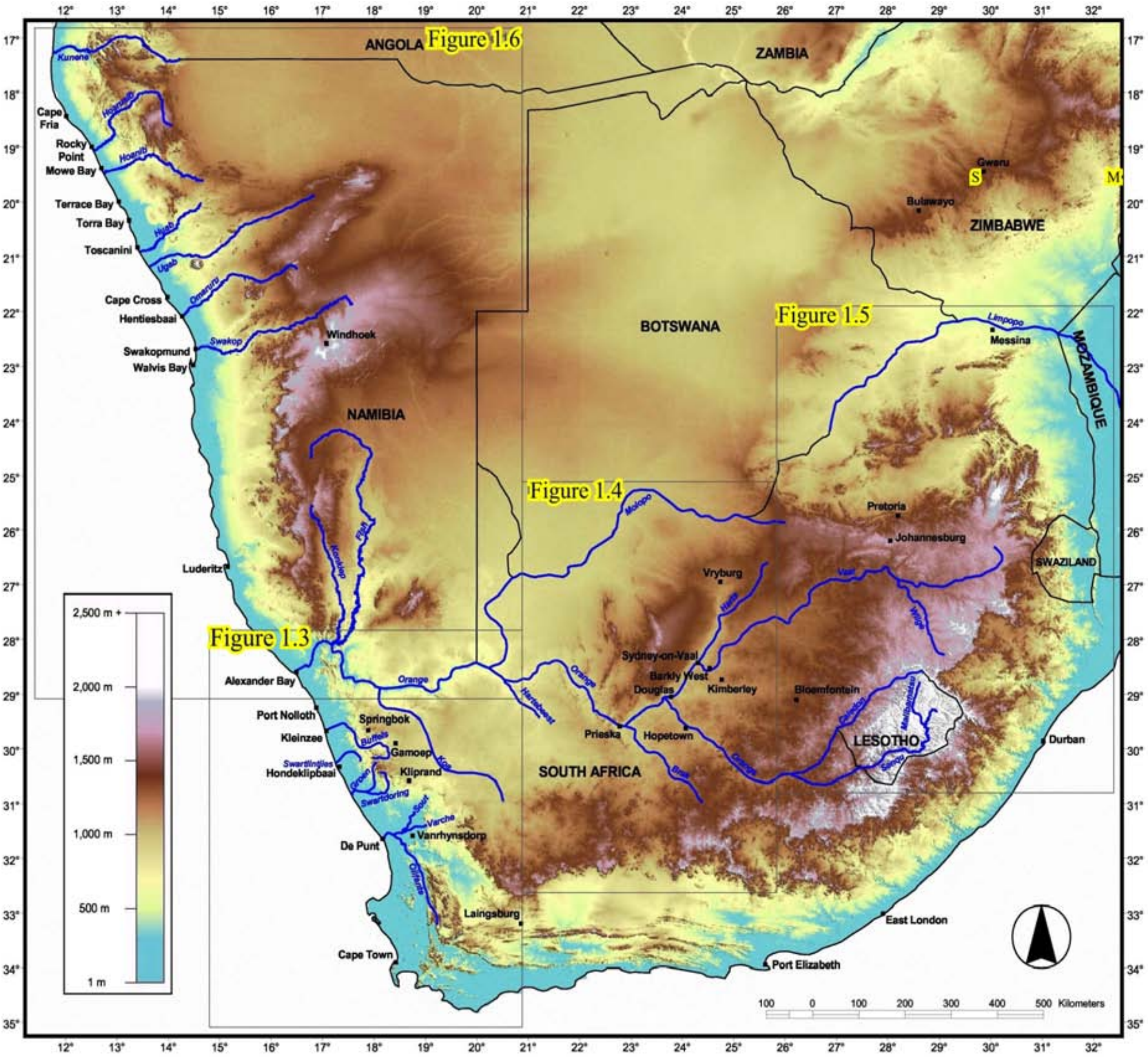


Figure 1.2 Digital elevation map (DEM) of southern Africa, with the major drainages relevant to this study shown as royal blue lines, as well as the outlines of detailed maps. The elevation data was acquired from SRTM90.

Drainages and towns were digitized from published 1:250000 topographical sheets.

Locations of diamond mines and occurrences: Council for Geoscience, Pretoria.

Alluvial diamond fields in Zimbabwe referred to in this thesis are indicated as follows:
S = Somabula, M = Marange/Chiadzwa

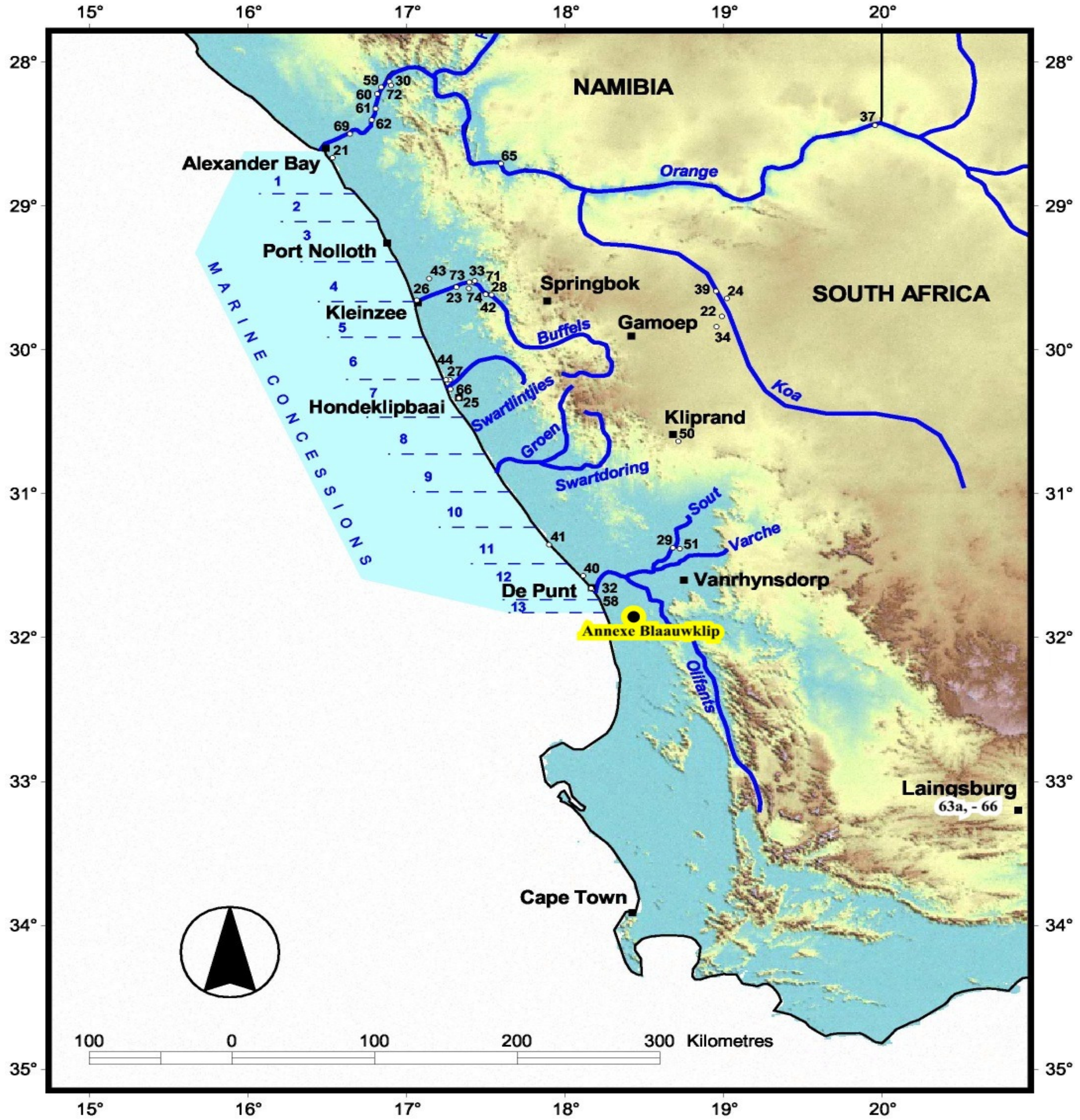


Figure 1.3: Detailed map - Western portion of study area showing major drainages, on-shore sample localities and the marine concessions from where the off-shore diamond samples were collected for the present study.

Sample localities are listed in Tables 1.1 to 1.3. For Legend see Figure 1.2.

The numbers 63a – 66 at Laingsburg refer to sample numbers of this study, while the others are identity numbers allocated by the Council for Geoscience.

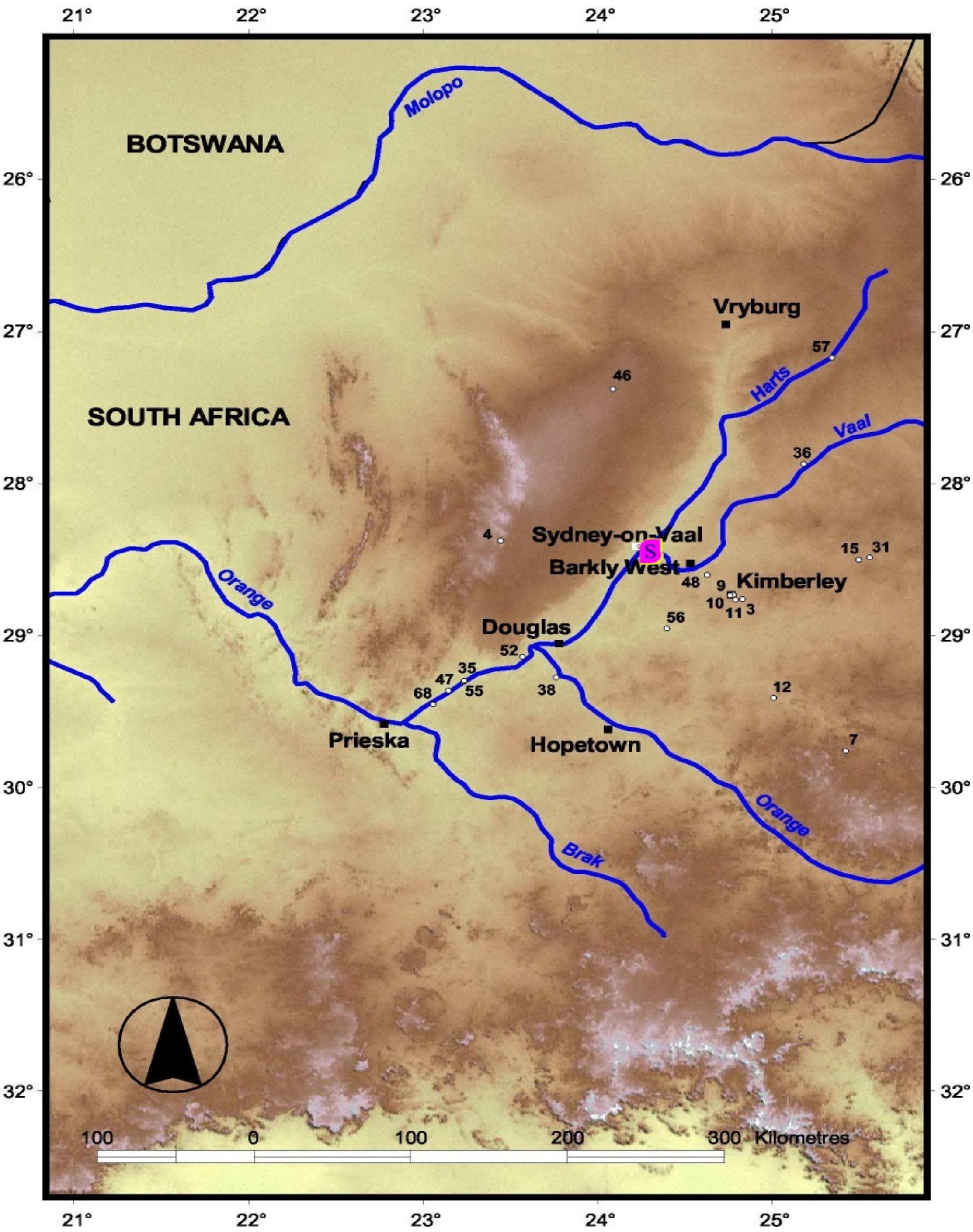


Figure 1.4: Detailed map - Central portion of study area showing major drainages, sample localities, major towns and important geographic localities relevant to this study. Localities listed in Tables 1.1 to 1.3.

("S" = Sydney-on-Vaal) Legend and data source as for Figure 1.2.

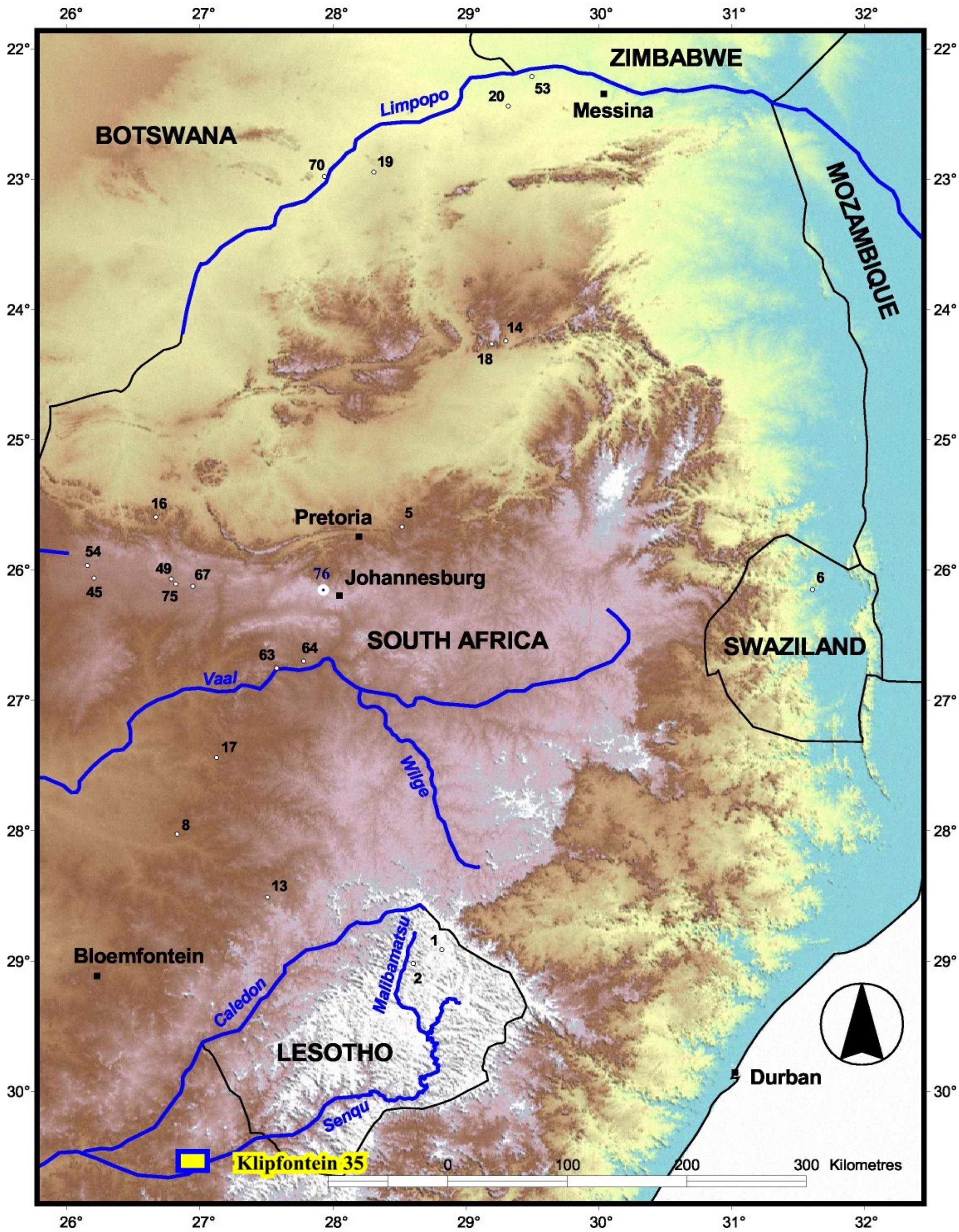


Figure 1.5 Detailed map - North-eastern portion of study area showing major drainages, some sample localities and important geographic localities. Localities listed in Tables 1.1 to 1.3.

Legend and data source as for Figure 1.2.

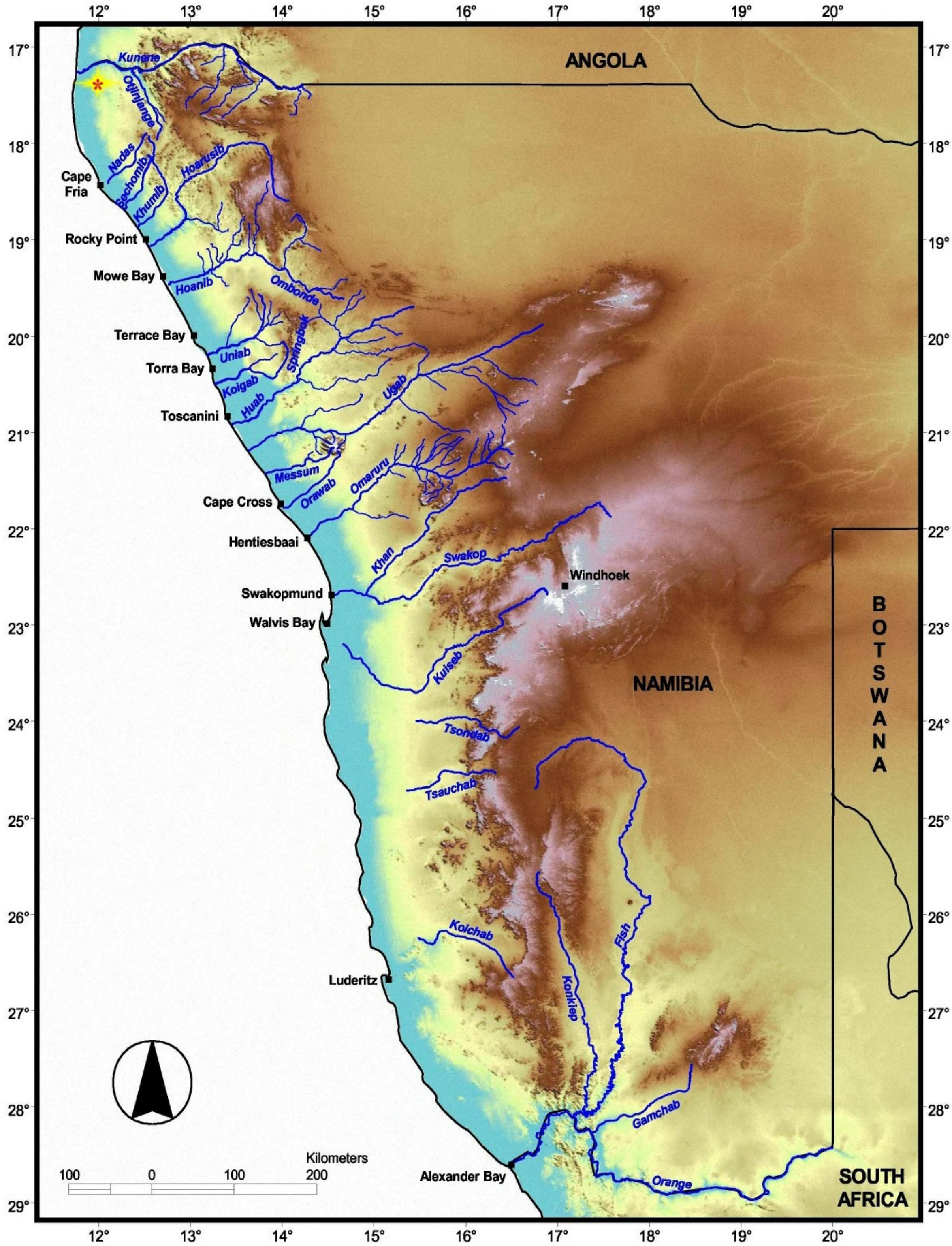


Figure 1.6. Detailed map - North-western portion of the study area, showing major westward drainages, the Skeleton Coast diamond sample locality (*) and important geographic localities.

Legend and data source as for Figure 1.2.

1.5 Methodology

To achieve the listed objectives, some areas in this study required reconnaissance or detailed geological mapping such as the Orange River valley between Prieska and Augrabies, the area between Randfontein and Bloemhof and parts of the Skeleton Coast, Namibia, to assist in the interpretation of the alluvial diamond occurrences.

A series of 62 bulk samples of gravel were collected from 15 localities along the Orange River, to allow for a comprehensive study of the sedimentary clasts found in the palaeo-fluvial deposits. Sample selection was supported by an overview of the geology and geomorphology of the study area. Statistical analyses of size frequencies, clast roundness estimates and litho-types of screened clasts, assisted in provenance identification and the characterization of the palaeo-fluvial system. All procedures are discussed in the Appendix, section 8.1. Sample localities are listed in Tables 1.1, 1.2 and 1.3.

Garnet and zircon grains were separated from the finer fraction of the Lower Orange River gravel samples. Quantitative mineral chemistry of garnet to allow for the distinction between on- and off-craton sources was done by means of the (EDAX) scanning electron microscope in the Central Analytical Facility, University of Stellenbosch.

Zircon geochronology was crucial to the reconstruction of the fluvial history of the Vaal-Orange system and the SHRIMP (sensitive high resolution ion microprobe) was chosen for this work, due to its ability to analyse different zones within the same zircon crystal. These were performed at the Australian National University, Canberra and included 106 zircon grains from drill core samples of the Ecca Group, Laingsburg district (Nguema-Mve, 2005). Localities are listed in Table 1.2.

Technical details of instrumentation used and operating conditions for the SHRIMP and SEM are presented in the Appendix, sections 8.3 and 8.4.

The purpose of the diamond study was to obtain information with respect to microscopic surface features and compositional qualities that could link these diamonds to known kimberlites. The FTIR method facilitates the comparison of the nitrogen content and aggregation state of different diamond populations with each other. In addition, it reveals the amount of platelet preservation, a feature that has diagnostic value in terms of (kimberlite) provenance identification in South Africa. This study was supported by FTIR data from 13 kimberlites available from the literature (Table 1.1). This data was processed to allow direct comparison with results from the present study.

Technical details of the instrumentation and analytical procedures of the FTIR method are presented in the Appendix, section 8.2.

The selection of a representative suite of diamonds for FTIR analyses has its limitations. The low concentration of diamonds in alluvial deposits (average 1.82ct/100 tons of gravel), the fact that recovery is seldom 100 per cent and that not all grains are suitable for FTIR analyses, precludes the assurance of total deposit representivity. All diamonds for this research have been collected from production parcels. Most diamonds used in this study were recovered by means of X-ray technology as opposed to grease table recovery and therefore present comparable populations. Investigations by the author (Van der Westhuizen, 2003a & b) showed that low-nitrogen diamonds may be recovered by the X-ray method. All the diamonds made available for this study had to be returned in pristine condition to their owners after completion of the analyses. Consequently, cut and polished sections could not be created to facilitate FTIR work on different layers or zones inside the diamonds, nor could inclusions be analyzed to facilitate the distinction between peridotitic and eclogitic diamonds.

Of the 1878 diamonds available 1221 – in the size range 0.08 to 0.2ct - were studied for their microscopic surface features. Only 1420 – in the size range 0.08 to 0.15ct - were found to be suitable for FTIR analyses partly due to the size constraint imposed by the limited penetrative capability of infrared (IR) light waves, and the generation of over saturated spectral peaks caused by the combination of a thick diamond sample and high nitrogen content. A total of 1198 (*i.e.* 84.37%) useful analyses were finally obtained. In addition to these studies the results of a surface feature study on 300 diamonds from the Buffelsbank Mine (Robinson, 1979) were also incorporated in order to broaden the data base.

TABLE 1.1: SAMPLE LOCALITIES SHOWN IN FIGURES 1.3 - 1.6

ID	NAME
1	LETSENG-LA-TERAI
2	LIQHOBONG
3	WESSELTON
4	FINSCH DIAMOND MINE
5	PREMIER DIAMOND MINE
6	DOKOLWAYO
7	JAGERSFONTEIN MINE
8	KAALVALLEI DIAMOND MINE (SAMADA)
9	BULTFONTEIN
10	DE BEERS MINE
11	KIMBERLEY MINE (BIG HOLE)
12	DE BEERS KOFFIEFONTEIN
13	MONASTERY DIAMOND MINE
14	MARSFONTEIN
15	NEW ELANDS DIAMOND MINE
16	HELAM MINING
17	LACE (CROWN) DIAMOND MINE
18	KLIPSPRINGER MINE
19	MARNITZ DIAMOND MINE
20	VENETIA DIAMOND MINE
21	ALEXKOR MINE
22	BITTERPUTS
23	BONTE KOE DIAMOND MINE
24	GALPUTS
25	HONDEKLIPBAAI MINE
26	KLEINZEE DIAMOND MINE
27	KOINGNAAS
28	KOMAGGAS MINE (Buffelsbank)
29	KWAGGASKOP DIAMOND MINE
30	REUNING
31	ROBERTS VICTOR (ROVIC) MINE
32	STRANDFONTEIN DE PUNT MINE
33	LANG HOOGTE MINE
34	BOSLUIS PAN
35	BRAKFONTEIN (plus gravel samples)
36	CHRISTIANA TOWN AND TOWNLANDS
37	DABERAS
38	DE KALK
39	GAL-PUTS
40	GEELWAL KAROO
41	GRAAUW DUINEN

42	GRACE'S PUT
43	JOUMAT
44	KOINGNAAS
45	LICHTENBURG TOWN AND TOWNLANDS
46	MAHURA MUTHLA
47	NIEWEJAARSKRAAL
48	NOOITGEDACHT
49	NOOITGEDACHT ALIAS VETPAN
50	OBEEP
51	QUAGGAS KOP
52	READS DRIFT
53	RIEDEL
54	UITGEVONDEN/RUIGTELAAGTE/COWPERS
55	SAXENDRIFT (plus gravel samples)
56	SCHUTSEKAMMA
57	SCHWEIZER RENEKE TOWN AND TOWNLANDS
58	THE POINT
59	JAKHALSBERG (plus gravel sample)
60	NXODAP (plus gravel samples)
61	XARRIES-BLOEDDRIF (plus gravel samples)
62	BAKEN (plus gravel samples)
63	VAALDRAAI
64	VANDERBIJLPARK TOWNLANDS
65	VIOOLSDRIF SETTLEMENT
66	ZWART LINTJES RIVIER
67	ZWARTPLAAT
68	ZWEMKUIL
70	MARTINSDRIFT
71	LANG HOOGTE MINE
72	SENDELINGSDRIFT *alias* Reuning (plus gravel samples)
73	WOLFBERG MYN
74	NUTTABOOI
75	ZWARTRAND
76	HOLFONTEIN
S in Fig. 1.4	Sydney-on-Vaal
★ in Fig 1.6	Skeleton coast

Turquoise: published data on diamond populations used
Pink: diamond populations studied
Yellow: gravel samples collected for sedimentary clasts, garnet and zircon studies

TABLE 1.2: SAMPLE LOCALITIES: GARNET AND ZIRCON GRAINS

No.	LOCALITY	m.a.m.s.l	DETAILS	NATURE of Sample
1	Baken	46	Koeskop upper gravel	Gravel
2	Baken	37	KS 15 S2 downstream of aplite dyke	Gravel
3	Baken	37	KS9-1A3 basal horizon, above aplite	Gravel
4	Baken	53	Upper Proto gravel, PK46	Gravel
5	Baken	51	Basal Proto gravel, PK46	Gravel
6	Baken, Skilpadsand Terrace	75	Basal Pre-Proto, pre-scour	Gravel
7	Baken, Skilpadsand Terrace	77	Upper Pre-Proto, pre-scour	Gravel
8	Baken	46	Upper Proto gravel in SWR 10	Gravel
9	Baken	44	Basal Proto gravel in SWR 10 W1	Gravel
10	Baken, PK13 W2		Basal Proto gravel	Gravel
11	Baken	68	Terrace 2, Pre-Proto	Gravel
12	Baken	71	Basal Pre-Proto in Trench 8, Terrace 1	Gravel
13	Baken	75	Upper-Proto Trench 6, Terrace 1	Gravel
14	Xheis	54	Basal Proto gravel	Gravel
15	Sanddrif Terrace		Meso	Gravel
18	Bloeddrif	44	Meso in eastern face of XAR1	Gravel
19	Bloeddrif		B2 N2, toe of ramp, Proto	Gravel
20	Bloeddrif		Basal Meso gravel Airport Terrace	Gravel
21-28	Saxendrif/Brakfontein		Proto gravel	Gravel
29	Grasdrif	116		Gravel
30	Grasdrif		Basal gravel in "B" Terrace	Gravel
31	Grasdrif Weaving's Hole 2	112		Gravel
32	Grasdrif Up.Terrace, north			Gravel
33	Baken	84	± 100 m. from top of ramp	Fine grd.sediment
34	Bloeddrif	31	Pre-Proto in ramp of XAR 1	Gravel
35	Bloeddrif	29	Pre-Proto gravel in ramp of XAR 1	Gravel
36	Bloeddrif		Meso 2 in XAR 5	Gravel
37	Bloeddrif	20	Meso 3 in XAR 6	Gravel
38	Nxodap	34	Basal gravel in depression in NXO 2	Gravel
39	Nxodap	44	Upper gravel in NXO 2	Gravel
40	Nxodap	38	Toe of ramp, northern face, NXO 3	Gravel
41	Nxodap	37	Basal gravel in northern face,	Gravel
42	Nxodap	43	Upper gravel, NXO 7	Gravel
43	Jakkalsberg SW	62	Basal Proto	Gravel
44	Jakkalsberg SW #1	58	Proto	Gravel
48	Jak'sberg SW (Reservoir)	68	Proto	Gravel
49	Jakkalsberg E	28	Meso	Gravel
50	Reuning	48	Western entrance, FH 2	Gravel
51	Reuning	60	SE side of Glory Hole	Gravel
52	Reuning	52	Airport Terrace Trench 2, Up. Meso	Gravel
53	Reuning	51	Airport Terrace Trench 2, Mid. Meso,	Gravel
54	Reuning	48	Airport Terrace Trench 2, Low. Meso	Gravel
55	AACE	72	Proto	Gravel
56	AACE	47	Meso	Gravel
58	Bloeddrif		Airport Terrace Basal gravel, scour,	Gravel
59	Daberas		Left bank upstream from Bloeddrif	<32mm sample
60	Renosterkop	685	Proto in neck	Gravel
61a b c	Daberas 8,		Downstream from Augrabies	Gravel
62	Renosterkop	677	Old excavations on plain	Gravel
63	Augrabies	618	Clasts from dry "middle terrace" river bed immediately above falls	
63a	Tanqua Karoo		Zircons from Drill core: Ecca Group turbidite fans	
64	Laingsburg			
65	Laingsburg			
66	Laingsburg			

TABLE 1.3 SAMPLE LOCALITIES: RESEARCH DIAMONDS

REF.	LOCALITY	n	DETAILS
A	Baken	77	Basal Proto gravel of palaeo-channel
B		52	Upper Proto gravel of palaeo-channel
C		4	Trench PK34, basal Proto/Pre-Proto gravel of palaeo-channel
D		1	Trench PK46, basal Proto gravel of palaeo-channel
E		33	Stockpile (Upper gravel, palaeo-channel)
G	Bloeddrif	1	Trench B2N2, Basal proto gravel
H		15	Proto gravel, contractors
I		23	Meso-Proto interplay, Xarries
J	Reuning	5	Meso , FH Terrace
K		14	Jakkalsberg; Proto
L		3	Reuning Central, Proto gravel
M	Brakfontein	14	Proto gravel
N	Saxendrif	41	Proto gravel
O	Hondeklipbaai	40	Land operations
P	Marine: 3B	54	Shallow water
Q	Marine: 5A	89	Shallow water
R	Hondeklipbaai	80	Surf zone
S	Marine: 7A	41	Shallow water
T	Marine: 11A	40	Shallow water
U	Marine: 12A	55	Shallow water
V	12A: Deep	30	Deeper water
W	12A: Geelwal	40	Surf zone
X	12A: De Punt	60	Beach mining
Y	Marine: 13A	46	Shallow water
ZvZ	Graauw Duinen	208	Selected from production, X-ray Tech and grease belt
ZA	Bosluispan	58	Selected from ball mill residue
ZB	Ventersdorp	24	Selected from ROM production from Klipgat 18 IQ
ZC	Ventersdorp	100	Selected from ROM production from Nooitgedacht 131 IP
ZD	Sydney-on-Vaal	60	Selected from ROM production
ZE	Christiana	42	Selected from ROM production
ZF	Samada	107	Selected from ROM production, kimberlite tailings dump
ZG	Holfontein	70	Selected from ROM production
ZH	Uitgevonden	51	Selected from ROM production
ZI	Skeleton Coast	100	Selected from ROM production
ZK	Swartruggens	200	Selected from ROM production (Helam kimberlite)
35*	**27 Localities**	**1878**	

* The 35 sample groups comprise 25 alluvial (with Saxendrif and Brakfontein treated as one combined sample) and two kimberlitic populations.

CHAPTER 2. GEOLOGY AND GEOMORPHOLOGY

2.1 Crustal evolution and diamond occurrences in southern Africa

Continents grow through a process often referred to as terrane accretion, a combination of subduction-related additions of new materials from the mantle and amalgamation of pre-existing lithospheric fragments of various sizes. The Kaapvaal Craton in southern Africa and the Pilbara Craton in north-western Australia were said to be the only regions that have retained a substantial portion of relatively unchanged mid-Archaean (3, 0 – 4, 0 Ga) rocks (Ben-Avraham, 1989; de Wit *et al.*, 1992). It is suggested that the Zimbabwe, Slave and Siberian Cratons be added to this list. Janse (1992) proposed the term "archon" for cratons that are older than 2.5 Ga.

Following the stabilization of the Kaapvaal Craton (an archon) around 2.6 Ga, a series of accretionary events characterized the geological development of southern Africa. One of these took place between 2.0 and 1.0 Ga. It led to the addition of the Namaqua-Natal Mobile Belt and culminated in the stabilization of the Kalahari Craton around 1.0 Ga (Partridge and Maud, 2000). This was followed by the development of a series of orogenic belts ("ridges" or "swells") between which there formed cratonic "basins" during the Pan-African tectonic cycle, which ended about 600 Ma (Partridge and Maud, *op cit.*). Table 2.1 lists a comprehensive sequence of events.

It stands to reason that pre-Karoo fluvial systems would have been active in the dispersal of diamonds liberated from pre-Karoo kimberlites, and that this process would most probably have taken place under the influence of the regional gradient that subsequently dictated the gravity-controlled movement of Dwyka glacials. The migration of Gondwana over the South Pole was responsible for the Dwyka glaciation. This event heralded the beginning of the Karoo deposition and played an important part in the southwesterly dispersal of diamonds liberated from pre-Karoo kimberlites in the north-eastern part of the subcontinent. Basaltic lava flows of considerable thickness and extent concluded the deposition of the Karoo Supergroup. On this post-Karoo Jurassic wasteland the present drainage systems of the subcontinent developed, and it is their Miocene and younger sedimentary packages that harbour the alluvial and marine diamond deposits of this study.

TABLE 2.1 GEOCHRONOLOGY OF SOUTHERN AFRICA.

ERA/PERIOD/EPOCH AND YEARS B.P.	EVENT (♦ = diamonds present, where known)	REFERENCE
3709 ± 3 Ma 3702 ± 1 Ma 3644 ± 4 Ma	Detrital grains associated with Beit Bridge Complex Ancient Gneiss Complex, Swaziland	Kröner *et al.* (1998) ; Compston and Kröner, (1988); Kröner *et al (1996)*
~3550 to >3683 Ma ~3550 Ma	Ancient Gneiss Complex (Kaapvaal Craton) Theespruit Formation, Onverwacht Group	Eglington and Armstrong (2004); Kröner *et al.(1996)*
~3,47 to ~3.48 Ga	Komati Formation, Onverwacht Group	Armstrong *et al.* (1990)
~3.45 Ga	Top of Onverwacht succession as well as granodiorite plutons along southern edge of Barberton Greenstone Belt	Eglington and Armstrong (2004); De Ronde and De Wit (1994)
~3.4 Ga	Magmatic event of Nondweni Greenstone Belt	Eglington and Armstrong (2004)
~3.37 to ~3.14	Halfway House granitoids, Kaap Valley tonalite, Nelshoogte gneiss, Anhalt leucotonalites	Eglington and Armstrong (2004)
~3.29 Ga	Granodiorite intrusive into Nondweni Greenstone	Eglington and Armstrong (2004)
~3.24 Ga	> ~500°C metamorphism in southern Barberton succession	Eglington and Armstrong (2004)
~3.23 Ga	Amalgamation of NW & SE sectors of Barberton Mountain land	De Ronde and De Wit (1994); Lowe (1999)
~3.3-3.2 Ga	♦: Formation of peridotitic diamonds in mantle underlying Kaapvaal Craton (Finsch & Kimberley)	Richardson *et al.* (1984, 2001); Smith *et al.*(1991)
~3.1 Ga	~500°C metamorphism in Vredefort dome; Mpuluzi granite, Nelspruit and Makhutswi granitoids, end of Moodies Group deposition; further plutonic activity in central Kaapvaal Craton; deposition of Dominion Group commenced; formation of the Kraaipan and Murchison Greenstone belts	Eglington and Armstrong (2004)
~2.95 Ga	Volcanism in the Pietersburg and Murchison Greenstone Belts	Eglington and Armstrong (2004)
2.90 Ga	♦: Formation of eclogitic diamonds underlying Kaapvaal Craton (Orapa, Jwaneng, Finsch & Koffiefontein)	Smith *et al.* (1991), Richardson *et al.* (1990), Pearson *et al.* (1998), Shirey *et al.* (2001)
2.89 ± 0.06 Ga	♦: Formation of eclogitic diamonds underlying Kaapvaal Craton (Kimberley)	Richardson *et al.* (2001)
~3.04 to ~2.88 Ga	Granitoids intruded on either side of the Witwatersrand-Kimberley boundary; Swaziland and Witwatersrand terrains of the proto-craton sufficiently stabilized to support early development of extensive sedimentary basins, *e.g.* WWR Supergroup (in centre of craton) and Pongola Supergroup in the southeast ♦ : Detrital diamonds from unknown primary source(s) deposited with WWR conglomerates less than ~2.91 Ga BP	Eglington and Armstrong (2004); Coetzee (1976) Armstrong *et al.* (1991)
~2.87 Ga	Intrusion of Usushwana Complex terminated the deposition of the Pongola Supergroup	Eglington and Armstrong (2004)
~2.75 Ga	Igneous activity in Amalia Greenstone Belt; indicated end of the development of the preserved limits of the Kaapvaal Craton	Eglington and Armstrong (2004)

~2.71 – 2.69 Ga	Termination of the deposition of WWR Supergroup sediments and onset of deposition of Ventersdorp volcanics in major extensional grabens; granitic intrusions took place across the craton, *e.g.* Gabarone granite suite and post-Pongola plutons	Tinker *et al.* (2002); Eglington and Armstrong (2004); Walraven *et al.*, (1990)
~2.75 to ~2.65 Ga	Early period in development of Kaapvaal Craton with *extensive* preservation of geo-chronological evidence for high grade metamorphism; zircon crystals occur either as metamorphic rims on older grains or as discrete metamorphic crystals	Eglington and Armstrong (2004); Retief *et al.* (1990); Kröner *et al*. (1999); Kreissig *et al.* (2001); Reimold *et al*. (2002); Schmitz and Bowring (2003)
~2.65 to ~2.6 Ga	Development of proto-basins for Transvaal Supergroup; intrusion of syntectonic granitoids associated with Limpopo orogeny along northern boundary of the craton	Eglington and Armstrong (2004)
2.6 Ga	♦: Formation of eclogitic diamonds underlying Kaapvaal Craton (Klipspringer)	Westerlund *et al.* (2004)
~2.6 to ~2.4 Ga	Igneous activity from both central and western (Griqualand) depo-centres of Transvaal Supergroup recorded by zircons in air-fall tuffs intercalated with carbonate sediments (Malmani and Campbell Rand Sub-groups) and ironstone (Penge Formation and Asbestos Hills Sub-group)	Eglington and Armstrong (2004)
2.55 Ga	♦: Formation of eclogitic diamonds underlying Kaapvaal Craton (Klipspringer)	Westerlund *et al.* (2004)
~2.4 to ~2.1 Ga	Transvaal Supergroup (Pretoria and Postmasburg Groups) accumulated	Eglington and Armstrong (2004)
< ~2.1 Ga	Transvaal Supergroup deposition terminated by extensive extrusion of Dullstroom Formation and Rooiberg Group	Eglington and Armstrong (2004)
~2.06 Ga	Rooiberg Group volcanism and intrusion of the granites and the mafic suite of the Bushveld Complex; extensive metamorphism (> ~500°C) evident over most of the craton, except the south- east.	Eglington and Armstrong (2004)
2.0 Ga	♦: Formation of eclogitic diamonds underlying Kaapvaal Craton (Premier & Venetia)	Richardson (1986), Richardson *et al.* (1993, 2009)
~ 2.0 Ga	♦: Formation of peridotitic diamonds in mantle underlying Kaapvaal Craton (Premier & Venetia)	Richardson *et al.* (1993, 2009), Richardson & Shirey (2008)
~2.02 to ~2.0 Ga	High grade deformation, metamorphism and partial melting in the central zone of the Limpopo Belt; intrusion of Gotha granitic complex in Limpopo Belt	Eglington and Armstrong (2004); Barton Jr *et al*, (2003)
2.0 – 1.9 Ga	Richtersveld sub-province (supracrustal sedimentary and volcanic lithologies, Orange River Group)	Reid *et al*, (1987b); Cornell *et al.*, (2006)
2.0 – 1.75 Ga	Intrusion of Vioolsdrif granitoids	
~1.95 Ga	Emplacement of Pruissen kimberlites, Limpopo Province	Skinner and Truswell (2006)
~1.93 Ga	Extrusion of Hartley Formation (Olifantshoek Supergroup) basalts	Cornell *et al.* (1998); Eglington and Armstrong (2004)
~1.92 Ga	Trompsburg mafic to felsic intrusion	Maier *et al.* (2003)
>1.88 Ga	Deposition of predominantly siliciclastic sediments of the Waterberg and Soutpansberg Groups	Thomas *et al.*, (1994); Hanson *et al.* (2004)
~1.8 Ga	Earliest deposition of Kheisian arenitic succession	Moen & Armstrong (2008)
1.758 Ga ± 64 Ma	Vioolsdrif Suite	Reid (1982), Hartzer *et al*, (1998)
1.7 Ga	♦: Formation of eclogitic diamonds in mantle underlying the Kaapvaal Craton (Jagersfontein)	Aulbach *et al* (2009)
1.650 Ga	♦: Earliest emplacement of Maartensdrif kimberlites	Jelsma *et al*, (2004)
1.606 Ga	♦: Earliest emplacement of Kuruman Grp. kimberlites	Bristow *et al*. (1986)
~1.6 Ga	Deposition of tuff layer in Palapye Group, central-northern Botswana, indicating slightly younger age compared to "main" Waterberg Group in southern Botswana and South Africa with which it is correlated	Mapeo *et al.* (2000)

1.58 ± 0.05 Ga	♦: Formation of eclogitic diamonds in mantle underlying the Kaapvaal Craton (Finsch)		Richardson *et al.* (1990)
1.5 Ga	♦: Formation of eclogitic diamonds in mantle underlying the Kaapvaal Craton (Jwaneng)		Richardson *et al.* (1999)
~1.37 to ~1.2 Ga	(1): Early Namaqua Metamorphic Event; (2): deposition of volcano-sed. Wilgenhoutsdrif Group		(1) Hartzer *et al.* (1998); (2) Moen & Armstrong (2008)
~1.29 Ga	Kalkwerf gneiss, indicating maximum age of Kheisian metamorphism		Eglington and Armstrong, (2004)
1.2 Ga	♦: Formation of eclogitic diamonds in mantle underlying the Kaapvaal Craton (Premier)		Richardson, 1986
1180 ± 30 Ma	♦ : Emplacement of Premier-National group of kimberlites		Allsopp and Kramers (1977)
1135 ± 9 Ma	Natal Metamorphic Province		Hartzer *et al.* (1998)
< ~1170 Ma	Intrusion of Koras Group		Moen & Armstrong (2008)
1.15 Ga	Aroams Gneiss: (1) Bushmanland sub-province and (2) in the southern Richtersveld sub-province		1. Armstrong *et al. (1988);* Pettersson *et al.* (2004) and (2) Moore *et al.* (1990)
1.1 Ga	♦: Formation of eclogitic diamonds in mantle underlying the Kaapvaal Craton (Jagersfontein & Koffiefontein)		Pearson *et al.* (1998), Aulbach *et al.* (2009)
~1.06 Ga	Accretion of the Namaqua-Natal Belt (with its various domains) to the Kaapvaal Craton completed		Thomas *et al.* (1994); Eglington and Armstrong (2004)
0.99 ± 0.05 Ma	♦: Formation of eclogitic diamonds in mantle underlying the Kaapvaal Craton (Orapa)		Richardson *et al.* 1990
905 ± 22 Ma	Low temp. rejuvenation of Natal Metam. Province		Dalziel (1992); Powell *et* al. (1993); Hartzer *et al.* (1998); Frimmel (2000); Frimmel *et al.* (2001); Eglington (2006) Rozendaal *et al.* (1999)
833 ± 2 Ma	Early, coarse-grained phase	Richtersveld Suite	
801 ± 8 Ma	Later, fine-grained phase		
771 ± 6 Ma	Lekkersing Granite		
780 – 750 Ma	Break up of Rodinia and opening of proto-Atlantic		
717 ± 11 Ma	Ganakouriep Suite		
750 – 580 Ma	Malmesbury Group; Gariep Super group; Gamtoos & Kaaimans Grps; Goegamma Subgrp. of Kango Grp.		
600 Ma	Bridgetown Fm., Saldania Belt		
580 – 540 Ma	Van Rhynsdorp and Nama Groups		
540 ± 15 – 506 ± 10 Ma	Cape Granite Suite		
533 Ma	♦ : Emplacement of Mwenezi kimberlite cluster		Phillips *et al.* (1997)
519 Ma	♦ : Emplacement of Venetia kimberlite cluster		Allsopp *et al.* (1995)
505 Ma	♦ : Emplacement of The Oaks kimberlite cluster		Phillips *et al.* (1998)
530 – 500 Ma	Kansa Subgroup		Hartzer *et al.* (1998)
520 – 500 Ma	Klipheuwel Group		
488	Natal Group, Durban Formation		
488 – 330 Ma	Cape Supergroup		
430 Ma	♦ : Emplacement of Beit Bridge kimberlite cluster		Kramers and Smith (1983)
312 – 280 Ma	Dwyka Group	Karoo Supergroup	Hartzer *et al.*(1998)
280 – 260 Ma	Ecca Group		
260 – 238 Ma	Beaufort Group		
243 Ma	♦ Empl. of Jwaneng kimberlite.		Kinny *et al.* (1989)
238 – 218 Ma	Molteno Formation		Hartzer *et al.* (1998)
218 – 210 Ma	Elliot Formation*		
200 ± 5 Ma	♦ : Emplacement of Dokolwayo kimberlite cluster *See footnote)		Allsopp and Roddick (1984)
210 – 182 Ma	Clarens Formation		Hartzer *et al.* (1998)
190-194 ± 12 Ma	Acid volcanics, Lebombo mountains		Vail, 1970
191 ± 8.8 Ma	Nuanetsi rhyolites		Allsopp *et al.* (1983)
Early Jurassic; 187±7; 183 ±1 Ma	Outflow of basaltic lavas particularly the Drakensberg Basalts associated with opening of Eastern Gondwana		Fitch and Miller (1971, 1983b) ; Duncan *et al.* (1997) ; Hargraves *et al.* (1997)
182 Ma	Karoo Dolerite Suite		
165 Ma	♦ Emplacement of Dulls room and Lamar diamondiferous kimberlites		Skinner (1989) and Jelsma *et al.* (2004)
145 Ma	Bambini Complex		Hartzer *et al.*(1998)

144 Ma	♦ Emplacement of Swartruggens and Klipspringer diamondiferous kimberlites; Adoonsvlei Suite	Allsopp and Barrett (1975); Westerlund *et al.* (2004); Hartzer *et al.* (1998)
140 – 120 Ma	Uitenhage Group	Hartzer *et al.* (1998)
135Ma – 120 Ma	♦ Emplacement of first Cretaceous diamondiferous kimberlites: Star, Lace, Voorspoed, Roberts Victor, Sanddrif (Prieska), Finsch	McIntyre & Dawson (1976); Phillips *et al.* (1998); Smith *et al.* (1985); Skinner *et al.* (1992); Allsopp *et al.* (1989).
134 ± 4 Ma	Kotzesrust Suite	Hartzer *et al.* (1998)
130/129 – 121 Ma	Opening of Western Gondwana assoc. with outflow of Etendeka/Paranha basalt, crustal upheaval of continental margins	Siedner and Mitchell, (1976) Fouché *et al.* 1992; Thomas and Shaw, (1991); Duncan *et al.* (1997)
118 – 117 Ma	♦ Emplacement of Barkly-West, Koffiefontein and De Beers diamondiferous kimberlites	Smith *et al.* (1985); Phillips *et al.* (1998); Davis (1978)
120 – 60 Ma	Zululand Group	Hartzer *et al.* (1998)
112 to 83 Ma Culmination of warm, wet period; Frakes (1986) — 105 Ma	The Falkland Plateau finally separated from Cape Agulhas Southern Africa essentially an inland plateau at a high altitude and at latitudes 50° – 55° S	Barnard (1996)
100 Ma	♦ Emplacement of Goedgevonden (low grade) diamondiferous kimberlite; ***initiation of Orange River fluvial system***	Kramers and Smith (1983); Ward and Bluck (1997)
100 – 80 Ma	Accelerated uplift of the southern and eastern continental margins;	de Wit, (1999)
93 Ma	♦ Emplacement of Orapa and Lethlakane diamondiferous kimberlites	Davis (1977); Haggerty *et al.* (1983)
92-91 Ma	♦ Emplacement of Kimberley diamondiferous kimberlites	Davis (1977); Smith *et al.* (1989); Fitch and Miller (1983a)
90 Ma	♦ Emplacement of Monastery (low grade) diamondiferous kimberlite; south to north opening of the west coast of southern Africa	Davis (1977); McIntyre and Dawson (1976); Barnard (1996)
86 Ma	♦ Emplacement of Jagersfontein diamondiferous kimberlites	Smith *et al.* (1985)
83Ma	♦ Emplacement of Wesselton diamondiferous kimberlite	Allsopp and Barret (1975); Kramers and Smith (1983)
"End- Cretaceous" (± 65 Ma) to about 30 Ma	Cosmic impact responsible for mass extinctions and major change in atmospheric chemistry that played a role in cooling of the climate, with global precipitation rates reaching a Cenozoic and Mesozoic minimum during the Eocene	Frakes (1986); Partridge (1998)
	Circumpolar circulation system in southern oceans following Gondwana break-up, climate went into cooling stage that persisted throughout the Cenozoic with the accompanying formation of polar icecaps and glaciation at high latitudes; initial glaciation records at 42 Ma in valleys of Antarctica; major accumulation of Antarctic ice occurred rapidly in earliest Oligocene (34 Ma); sea level dropped considerably with large scale erosion along the coastal margin; beaches located 40–50 km further west than today	Vail and Hardenbol (1979); Hallam, (1985); Partridge, (1998); Lear *et al.* (2000); Siesser and Dingle (1981); Hendey (1982); Tyson (1987)
Bredasdorp, Sandveld and Maputaland Groups, as well as — Appr. 30 Ma to 20 Ma	General warming in Early Miocene; precipitation increased and sea-level started to rise towards end of Oligocene, reaching its present level by ± 20 Ma ago, which coincides with the time when the subcontinent reached its present latitude.	Keller and Barron (1983) Barnard (1996); Rogers and Roberts (1997)

	± 20 Ma - ± 13 Ma	Humid "Early to Middle Miocene transgression" S. Afr. west coast inundated by the sea, perhaps up to >120m above present; epeirogenic uplift increased sediment supply to off-shore basins ♦: Aggradation of diamondiferous 90m sedimentary package along west coast and (15 – 22 Ma) Miocene fluvial gravels deposited	Hendey (1982) Haq *et al.* (1987); Partridge and Maud (1987); Tyson (1987); Pickford and Senut (1997); De Wit (1999)
	± 14 Ma	Major Antarctic ice cap formed, reaching a maximum at about 6.5 Ma; climate of west coast changed from sub tropic with summer rainfall to temperate with winter rainfall. (Cooling episode may have started earlier in the light of the indicator fossil Trigonepherus found recently by M. Pickford & B Sunet in 20 Ma Grillenthal Beds); ♦ diamonds redistributed in younger sediments	Siesser and Dingle (1981); Pickford and Senut (1997); J D Ward, pers. comm. (Nov. 2004)
	13 – 5,2 Ma	Cooling episode with concomitant regressive sea-level cycles; precipitation declined and cold water of the Benguela up welling intensified the aridity along the west coast; ♦ diamonds redistributed in younger sediments	Siesser (1980); Pickford and Senut (1997); Ward and Corbett (1990)
	5,2 – 4.2 Ma	General differential uplift of subcontinent; a warming trend in climate saw a higher rate of precipitation in the early Pliocene and a transgressive cycle (50m elevation) during which the fossiliferous Varswater Fm. at Langebaanweg was deposited; along the Namaqualand coast the zone fossil *Donax haughtoni* marks the +50m sedimentary package;	Hendey (1982); De Wit (1999); Pether (1994b)
	4.2 – 2.8 Ma	(1): Cooling of atmosphere; development of the Northern Hemisphere ice sheets; regressive cycles with sea-level dropping to below present level; ♦ marine diamonds concentrated in palaeo-shorelines (2): ♦ diamondiferous fluvial gravels (Meso Orange River) deposited 3.6 ± 0.6 Ma BP;	(1): Hendey (1982); (2): pers com, R Gibbon 2008
	2.8 – 2.6 Ma	Advent of desert conditions in extreme SW Kalahari	Partridge and Maud (1987)
	± 2.3 Ma	Tectonic uplift caused westward steepening of river gradients and subsequent increased fluvial activity	Partridge (1998)
	2.8 – 1.7 Ma	Late Pliocene transgression; zone fossil *Donax rogersi* marks the +30m sedimentary package along the Namaqualand coast	Hendey (1982); Tyson (1987); Pether (1994b)
	± 1.7 Ma	Regressive cycle at end of Pliocene	
	17 000 – 20 000 years	Last glacial maximum with global sea level about 125 – 130 metres lower than today	Tyson (1987); Fairbanks (1989)
	800 000 years	Mid-Pleistocene High (6 – 8m)	Corvinus (1983)

**Footnote: Some uncertainty surrounds the exact timing of the transition between the Elliot and Clarence Formations. Diamond surface feature studies (D. N. Robinson, pers comm.) and geochemistry of other kimberlitic minerals (Hawthorne et al. 1979) found in Elliot sandstone and grit horizons at Ehlane in Swaziland, have linked these conclusively to the Dokolwayo kimberlite cluster 30 km to the WNW. If the emplacement age of Allsopp and Roddick (1984) for the Dokolwayo K1 kimberlite is accepted, then that part of the Elliot Formation hosting the Ehlane diamondiferous deposits must be younger than 200 ± 5 Ma.*

Brown *et al.* (1995) stated that the south-western margin of southern Africa was a divergent plate margin underlain by synrift graben basins and the postrift or passive margin Orange Basin. These authors also suggested that rifting began during the Late Jurassic in response to extensional stress generated by the impending break-up of the South American and African continental plates, while actual rifting of the African plate along the south-western margin occurred at ~117.5 Ma.

Table 2.1 shows that diamondiferous kimberlites were emplaced in southern Africa since more than 3 Ga BP until as recently as 83 Ma BP. Geographically the known occurrences are located from Jagersfontein and Prieska in the SSW, to central Zimbabwe in the NE. Secondary diamond deposits do not only occur in close proximity to a number of these so-called primary deposits, but are especially well developed along the west coast of South Africa and Namibia, at considerable distances from the nearest diamondiferous kimberlite.

2.2 Geology of the study areas

Alluvial diamonds in southern Africa occur in four distinctly different modes and include:

- fluvial palaeo-deposits especially along ancient, but also in modern valleys and in karstic trap sites,
- raised as well as drowned marine terraces,
- loose gravel deposits on the sea floor and
- aeolian surface deposits, thus far only found in southern Namibia.

In the following paragraphs the geology of the different study areas and the mode of the diamond occurrences are described.

2.2.1 Randfontein-Ventersdorp-Lichtenburg

This area is underlain by dolomitic limestone - in places with intercalated chert beds - ascribed to the Malmani Subgroup of the Transvaal Supergroup.

The diamondiferous gravel deposits of this region are erosion remnants of a palaeo- fluvial system that transported material from the north and north-east along an ancient surface gradient towards the south and south-west (Wilson *et al.*, 2006). A complicated origin involving the chemical liberation of diamonds from pre-Karoo, Jurassic and Cretaceous kimberlites and their dispersal by fluvial and glacial processes is indicated. The following sequence of events resulted in the formation of trap sites that were very efficient in the retention of vast quantities of diamonds.

The dolomitic limestone that forms the country rock of this area is in itself a dense, featureless rock in its fresh, unweathered state. However, preferential leaching along zones of weakness resulting from fracturing was responsible for the development of a karstic landscape, often manifested in chamber-like hollows that, where located along a valley floor, acted as potholes forming very efficient trap sites for the sediment load of a river. This aspect was enhanced by the fact that valleys tend to form where the country rock is weakened by fractures and faults related to tectonic processes, and where two or more cross-cutting fracture or fault zones meet, leaching is increased dramatically. The two most important types of diamondiferous gravel occurrences found in this region, namely the so-called "gravel runs" which seem to follow palaeo-drainage lines, and the huge, sediment-filled solution cavities (*e.g.* Fig. 2.1), are genetically linked to the process described above.

Marshall (1987) drew attention to dome-like features resulting from up-warping in the granitic basement underlying the sedimentary country rock of the region, and pointed out that the diamondiferous alluvial deposits tend to be located along the troughs and basins between these features.

Selective weathering of dolomitic layers between intercalated chert beds caused a riffled surface in places that also offered trap sites for passing sediments.

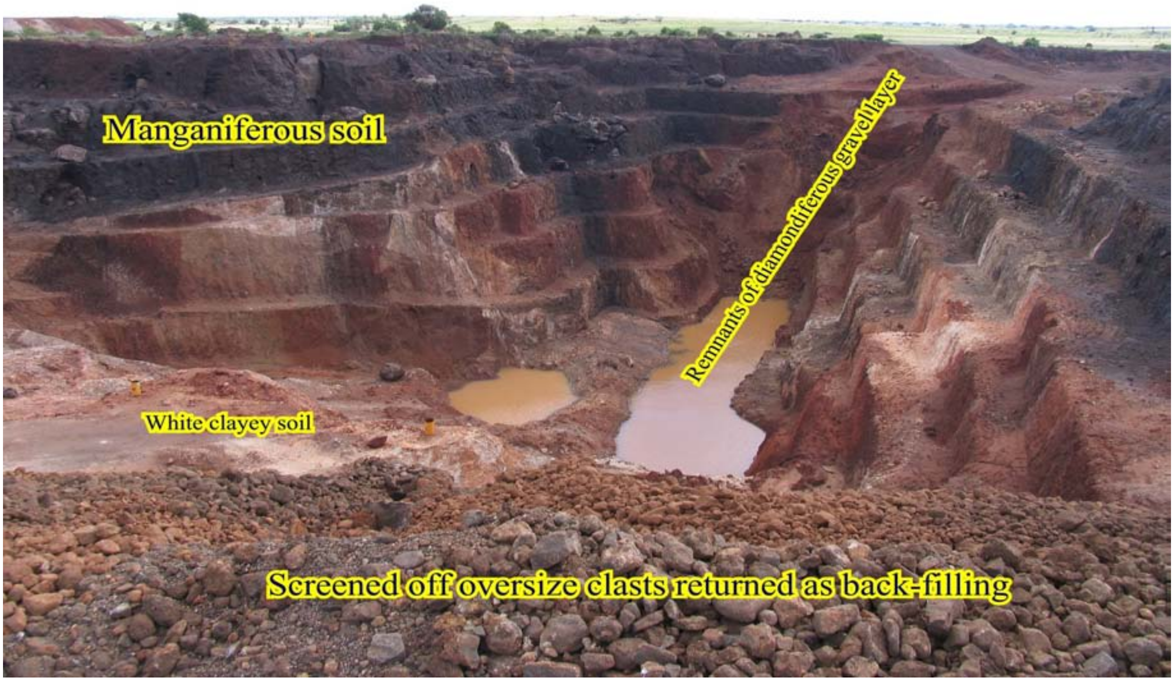


Figure 2.1 Mining pit developed in solution cavity at Honingklip Mine, district Lichtenburg.

The often chaotic stratigraphy of the material filling these solution cavities can be seen in this image. The diamondiferous gravel rests unconformably on cherty dolomite, and is covered upwards by white and red soil, manganiferous "wad" and Hutton soil at the surface. Post-depositional slumping was responsible for the irregular, steep apparent dip of the sedimentary units observed. Diamond sample locality ZH (Table 1.3) is adjacent to this excavation, while locality ZG comprises a similar feature at the Koufontein Mine between Randfontein and Ventersdorp.

2.2.2 Upper and Middle Orange River:

Near Aliwal-North, alluvial diamonds were mined on the farm Klipfontein 35 (Figure 1.5) during the early part of the 20th century. This is the only alluvial diamond mining operation ever to have existed on the Orange River upstream from Hopetown, apart from those in close proximity to some Lesotho kimberlites like Letseng. Here (on Klipfontein) preferential weathering of soft shale on either side of a dolerite dyke caused a local protuberance and associated scour in the otherwise flat-lying, smooth Karoo sediments. The scour became an effective fixed trap site for diamonds liberated from the

Lesotho kimberlites. Apart from this occurrence diamondiferous Cenozoic deposits along the Orange River only become significant downstream from Hopetown. This is attributed to:

- the transition from relatively smooth Karoo sediments to hard and variable Precambrian lithologies which instilled a micro-topography conducive to the retention of heavy minerals like diamond, to the bedrock;
- the addition of diamonds from diamondiferous kimberlites like Jagersfontein and Koffiefontein to the north of this sector of the Orange River, as well as a further diamond input *via* the Vaal River;
- the stream capture performed by the developing Orange River on the palaeo-Gamoep River between Hopetown and Douglas.

During the course of this study a new discovery was made on the farm Marksdrif 3 at the point where the Douglas-Prieska road crosses the Orange River. Outcrops of pyroclastic lava that had not been described before, are exposed over a distance of roughly 200 metres along the bed of the Orange River during times of low flood levels, as recorded by the author during May 2003 (Figure 2.2). These rocks are part of the Allanridge Formation, Ventersdorp Supergroup and can possibly explain some of the Archaean-aged zircons found in Miocene gravel deposits further downstream.

Figure 2.2 Outcrop of pyroclastic lava in the Orange River at Marksdrif 3 near Douglas (not recorded before)

The Mid-Orange area from where gravel and diamond samples for this study were available is situated halfway between the confluence with the Vaal River and the town of Prieska, at the Saxendrif/Brakfontein Mine.

TABLE 2.2 GENERALIZED STRATIGRAPHY OF TERRACES PRESERVED ALONG THE LEFT FLANK OF THE ORANGE RIVER VALLEY BETWEEN IRENE AND PRIESKA.

THICKNESS (m)	LITHOLOGY	NATURE
0.0 – 4.0	Layers/lenses of red sand	Aeolian
0.0 – 2.0	Rooikoppie gravel	Secondary deposits
0.0 –5.0	Calcrete	
0.0 – 4.0	Gravely calcrete	Primary palaeo-fluvial terrace/channel deposits
0.0 – 6.0	Calcretized gravel	
0.0 – 2.0	Gravel, sandy gravel and/or sand	
	Tillite/diamictite and/or shale	Dwyka Group (Karoo Supergroup)

Based upon relative elevation (all figures in relation to modern Orange River bed), clast composition and mineralogy, the upper (70 - 110 m) and intermediate (30 -60m) terraces are provisionally correlated with the Arrisdrif Gravel Formation (SACS, 1980) also termed proto-Orange River deposits by Fowler (1976, 1982) on the Lower Orange River, Richtersveld. The lower terraces (0 - 20m) correspond to Fowler's (*op. cit.*) meso-Orange River deposits which were dated by measuring *in situ* radioactive decay of cosmogenic nuclides giving an age of 3.8 ± 0.6 Ma (R. Gibbon, pers. comm.). Due to the Orange River's history of meandering and incision, the terraces which are erosional remnants of palaeo-channel deposits, young with decreasing elevation and vary from Pleistocene-Pliocene for the lower terraces to Pliocene-Miocene in the case of the upper terraces. The sediments forming these terraces and filling associated palaeo-channels unconformably overlie diamictite and shale of the Carboniferous-Permian Dwyka Group.

TABLE 2.3 LITHOLOGY AND POSSIBLE PROVENANCE OF SEDIMENTARY CLASTS FROM THE MID-ORANGE SECTION

<table>
<tr><th colspan="2">Litho-type</th><th>Most likely provenance</th></tr>
<tr><td colspan="2">Andesitic lava, often amygdaloidal</td><td>Ventersdorp Supergroup</td></tr>
<tr><td colspan="2">Basaltic lava, often with zeolites</td><td>Drakensberg Group, Karoo Supergroup</td></tr>
<tr><td colspan="2">Banded iron formation</td><td>Asbestos Hills Subgroup, Transvaal Supergroup</td></tr>
<tr><td colspan="2">Quartzite</td><td>Ventersdorp Supergroup</td></tr>
<tr><td colspan="2">Dolomite</td><td>Ghaap Plateau, or Malmani Subgroup</td></tr>
<tr><td colspan="2">Chert</td><td>Malmani Subgroup, Tvl Supergroup</td></tr>
<tr><td colspan="2">Agate (white, brown, black and bluish-grey)</td><td>Ventersdorp and (the bluish variety) Drakensberg Basalt</td></tr>
<tr><td rowspan="2">Chalcedony</td><td>yellow to yellow-brown</td><td>Ventersdorp Lava, mostly via the Vaal River</td></tr>
<tr><td>colourless to bluish-grey</td><td>Drakensberg Basalts</td></tr>
<tr><td colspan="2">Differently coloured, rounded quartz amygdales</td><td>Ventersdorp Lava, mostly via the Vaal River</td></tr>
<tr><td colspan="2">Zeolites</td><td>Drakensberg Basalt</td></tr>
<tr><td colspan="2">Siltstone and mudstone</td><td>Karoo Supergroup</td></tr>
<tr><td colspan="2">*Lydianite and hornfels</td><td>Karoo Supergroup</td></tr>
</table>

**In this study a distinction has been made between lydianite which refers to the aphanitic variety of hornfels, probably the result of contact metamorphism of mudstone, and hornfels if a grain texture not related to recrystallization can still be recognized macroscopically.*

The clast compositions as identified in outcrop and in the gravel samples of this study do not vary significantly between the different terraces, contrary to the Lower Orange River downstream from Grasdrif where banded iron formation clasts in the proto-sediments (higher terraces) mainly consist of lutite, with the heavier, iron-rich components only appearing in the younger, meso-sediments. It is suggested that this phenomenon reflects the difference in the specific gravity of the different components, with the lighter lutite being more amenable to fluvial transportation.

Diamond content decreases with lower elevations, with the exception of the upper sections of the highest terraces which seem to be virtually devoid of diamonds, as is the case with the modern Orange River bed. This phenomenon is also observed along the Lower Orange River valley, and could most probably be explained in terms of the evolution of the Vaal-Orange drainage network. It would appear that access to the diamondiferous debris shed from decomposing kimberlites had only been accomplished during the Late Oligocene-Early Miocene. Since then, mechanical erosion outstripped the chemical liberation of diamonds from the kimberlites, so that the supply of diamonds to the sediment load of the rivers kept on dwindling. In this regard the Vaal River differs from the Orange, in that lucrative concentrations of diamond had been extracted from its modern bed by dewatering of coffer dams. To a large extent this must be ascribed to the presence of numerous diamondiferous kimberlite dykes and pipes in or very close to the modern Vaal River valley.

Between the Boegoeberg hills and Gariep the softer quartz-schist of the Groblershoop Formation form the country rock into which the Orange cut its valley. Here the palaeo-Orange could once again meander more freely and remnants of its course occur up to 3 kilometres from the present river, sometimes only inferred by the presence of exotic clasts confined to curvilinear stretches at specific elevations sub-parallel to the present valley, but also confirmed by the presence of a buried palaeo-valley discovered during the course of this investigation. At the time of writing, this has already led to the identification of a diamond bearing buried palaeo-channel – now called the Grootdrink Palaeochannel - on the farms Sterkstroom 399, Grootdrink 400 and Onder Plaats 401 near the village of Gariep; it contains sedimentary clasts that link it beyond doubt to the Miocene Orange River system. Diamondiferous Cenozoic sediments had not been reported between Prieska and Renosterkop before.

Between Gariep and Renosterkop near the town of Augrabies, Cenozoic deposits along the Orange River are conspicuously insignificant. On the farm Renosterkop, approximately 12 kilometres upstream from the Augrabies Falls, Cenozoic (Miocene-aged) deposits were preserved in a number of bedrock depressions, including some potholes. In the 1930's this locality was known as the Hartebeestriviermond Diggings. Some 340 carats of diamond at an average size of about 2ct/stone was reported from here (Du Toit, 1936).

The clast assemblage studied in the Renosterkop deposits includes banded iron formation from the Asbestos Hills Subgroup, Transvaal Supergroup, agates, including those typical of both the Vaal and upper-Middle Orange catchments, epidosite, red jasper, quartz porphyries and amygdaloidal volcanics. Zeolites, accepted to have been derived from the Drakensberg volcanics, are more abundant in the low-level deposits, as is the case with the meso-deposits in the Richtersveld and Sperrgebiet.

In the past (Ward *et al.,* 2002) the Renosterkop deposits were thought to represent the so-called "proto" and "meso" deposits respectively, identified by Fowler (1976, 1982) along the Lower Orange in the Richtersveld and Sperrgebiet. However, a topographic survey during this study showed that the era represented by the deposits on the plain is distinct from the low-level, typical meso-event and rather suggests a later proto-period. Such a paragenesis for the Cenozoic deposits would be in line with observations made in the Douglas-Prieska sector, namely that the (Cenozoic) deposits found at different elevations along the river are genetically linked (Gresse, 2003). This is also in agreement with the author's own field observations both along the Middle and Lower Orange River valley, and the work of Van Wyk and Pienaar (1986) in the Richtersveld.

2.2.3 Lower Orange River

The sector of the Orange River from Vioolsdrif to the Atlantic Coast is important both from a sedimentological and economic perspective. A résumé of its geological history serves as background to the discussions of the various deposits of Cenozoic age found along this sector of the river. This stretch of the Orange River has been subdivided into five morphological sectors by Hill and Van der Westhuizen (1995).

The total elevation drop of the present river bed over the 250 km from Vioolsdrif to the Atlantic is only 150 metres, or 1 metre in 1.667 km. The presence of important deposits of clastic sediments shows that substantial aggradation took place since the Miocene along this part of the Orange River. The combination of hardness contrasts between different litho-types and structure was responsible for the development of bedrock trap sites that were instrumental in the retention of transported heavy minerals like diamond. The morphological evolution of the river ensured that significant quantities of these often diamondiferous sediments evaded post-depositional erosion. The majority of the gravel samples of this study were collected from such deposits.

The gneisses of the Namaqua Metamorphic Complex dominate the modern river bed from near Upington to more or less the end of the Kamchab gorge about 3 kilometres upstream from Vioolsdrif, at Bushmanskop, where a fault separates it from the Dwyka tillite. The left bank here reveals some vertical cliffs comprised of lower Nama metasediments, capped by Dwyka tillite. Immediately downstream from Vioolsdrif the Orange River cuts through black limestone of the Neint-Nababeep Plateau (Nama Group) as illustrated in Figure 2.3.

Figure 2.3: Folded and thrusted black limestone and other sediments of the Nama Group, Lower Orange River (photography: Don Pinnock).

In the diamond mining industry along the Lower Orange River valley, the presence of limestone clasts derived from the various carbonate units in the Nama Group are used to distinguish between gravel bodies derived purely from distant sources closer to the diamondiferous kimberlites of the Kaapvaal Craton, and those that have been diluted by local tributaries.

Downstream from Swartbas the Nama Group rocks give way to the Orange River Group of the Richtersveld Suite. The rocks that build the mountains, valleys and plains of the Richtersveld cover a time span of more than 2 billion years. Volcanic, igneous and sedimentary rocks as well as their metamorphic derivatives, here constitute the hard country rock of Precambrian age. The Orange River Group locally is subdivided into the basal De Hoop Subgroup and the younger Rosyntjieberg Formation (Beukes, 1997; De Villiers and Söhnge, 1959).

Between 870 and 720 Ma BP, a dolerite dyke swarm (the Gannakouriep Suite) intruded along fractures in the older rocks (Reid *et al.*, 1987b; Table 2.1).

The western part of the Orange River Group and Vioolsdrif Suite are overlain by a belt of mainly sedimentary rocks of the Gariep Belt (Von Veh, 1993) that extends all the way to the Atlantic Coast.

About 530 Ma BP the Kuboos Complex intruded the deformed rocks of the Gariep Supergroup, as witnessed by the impressive granite batholith of Kuboos, rising to more than 1000 m.a.m.s.l. in the vicinity of the village by that name (Frimmel, 2000). Other similar granite plutons belonging to the Kuboos Complex are found at Swartbank to the southwest and Tatasberg to the northeast of Kuboos village. Younger dykes of leucogranite transect the Tatasberg pluton, while younger transgressive dykes of bostonite, diabase and aplite intruded the Kuboos pluton.

TABLE 2.4 GEOLOGICAL FEATURES OF THE 5 MORPHOLOGICAL SECTORS OF THE LOWER ORANGE RIVER BETWEEN VIOOLSDRIF AND THE ATLANTIC COAST (MODIFIED FROM HILL AND VAN DER WESTHUIZEN, 1995).

Section	Dist. from coast (km)	av. gradient (m/km)	General River Morphology	Cenozoic Deposits	Bedrock
1	270-250	0.5	River flows in narrow valley with less steep flanks	• Narrow bands of Holocene alluvium • Small isolated terrace deposits (Pleistocene)	Essentially near-horizontal quartzite, shale & limestone (late-Precambrian, Nama)
2	250-150	0.75	River flows in narrow valley with steep flanks, except at Grasdrif and Aussenkehr where local widening occurs	• Narrow bands of (Holocene) alluvium, broadening at Grasdrif and Aussenkehr • Smaller, isolated river terraces (Pleistocene) • Larger river terraces at Grasdrif & Aussenkehr (Miocene – late-Pleistocene)	Granodiorite (Proterozoic Vioolsdrif Suite), mafic lava & metasediments (Orange River Group); granite (Richtersveld Suite), diamictite (Karoo) in Nabas Basin.
3	150-115	0.85	Low-amplitude meanders inside narrow valley with steep flanks	• Narrow bands of (Holocene) alluvium • Smaller river terraces (Late Pleistocene to Pliocene)	Granodiorite (Proterozoic Vioolsdrif Suite), mafic lava and metasediments (Orange River Group); steep flanks.
4	115-30	0.4	High-amplitude meanders inside relatively wide, open valley	• Wide stretches of floodplain alluvium (Holocene); • Relatively large river terraces (Pleistocene – Pliocene) • Palaeo-channel deposits (Miocene)	Essentially arenite, schist, diamictite and carbonates (Gariep Group)
5	30 – 0	0.25	Braided streams in relatively wide (0.5 – 2km) straight stretches on Neogene coastal plain	• Numerous point bar and inter-channel Holocene sand deposits; • Isolated palaeo-floodplain gravel deposits (late Pleistocene)	Deeply incised (≤50m below sea level) chlorite schist of late-Proterozoic Gariep Group

Aplite dykes a few cm to ± 10m wide exploiting fracture planes in the meta-sediments up to 3km away from and sub-parallel to the granite/meta-sediment contact, were observed during this study in the valley of the Annis River immediately downstream from Cornell's Kop and intermittently further west as far as the Swartwater section of the Baken Mine, where their associated bedrock scours played an important role in diamond concentration (Figure 2.4).

Figure 2.4. Aplite veins in tightly folded schist near contact with major aplite dyke (Skilpadsand Terrace, Baken Mine).

Tillite, reddish-brown sandy mudstone and rippled flagstone of the glacial Dwyka Group occurring in the eastern part of the Richtersveld near Grasdrif testify to the presence of a glacial lake, locally known as the Nabas Basin. This, together with the occurrences in the Good House-Vioolsdrif sector comprise the only Dwyka outcrops in the Orange River valley downstream from Prieska and is accepted to be an extension of the Karoo-aged Karasburg Basin (portion of western edge illustrated in Figure 2.5) described by Haughton and Frommurze (1936) and Schreuder and Genis (1975). It is suggested here that the contrast in competence between these Karoo sediments and the more resistant Richtersveld Suite was responsible for the pronounced change in direction - from generally east-west to south-north - of the Orange River south-east of Aussenkjer and Grasdrif.

Figure 2.5 Southwestern edge of the Karasburg/Nabas Karoo Basin opposite Grasdrif (facing east). A dolerite sill caps the greyish-green Ecca shale; a white talus slope derived from the well-known "White Band" (boundary between Dwyka and Ecca) is conspicuously portrayed. A portion of the Orange River, line of dense green vegetation, is barely visible beyond the edge of the terrace.

Observed geomorphological and sedimentological parameters such as the proven linear relationship between the width of a valley and the wavelength and amplitude of freely developed meanders on the one side, and full bank load during peak floods on the other side, indicate a theoretical maximum flow rate of nearly 30 000 m^3 per second for the palaeo-Orange, which is nearly three times higher than the maximum measured in human history (Ward and Bluck, 1997). The work of Zawada *et al.* (1996) showed that such catastrophic floods also occurred as recently as 900 years BP. The results of the study of the sedimentary clasts discussed in Section 8.1.3 and 8.1.4, show that high energy fluvial conditions intermittently characterized the Orange River during the Cenozoic. During this period it also experienced numerous changes of its erosion base. Apart from epeirogenetic rises during the Late Miocene, relatively fast eustatic sea level changes characterized the Quaternary (Rogers *et al.,* 1990).

The result of all the above was a meandering river valley up to 1,2 km wide, repeatedly cutting across geological boundaries, then drowning in its own sediments, cutting through these sediments and partly changing course before drowning in its own sediments again. This is where Fowler (1976, 1982 as referred to under Previous Work) introduced the term proto-Orange River for the palaeo-river whose deposits fill the abandoned sinuous course that is discordant with the present day river, and the younger meso (incision and aggradation during the Plio-Pleistocene) suite of terraces with bedrock elevations closer, and which follows a course very similar, to that of the modern river. In the Richtersveld the meso deposits are characterized by a high incidence of iron-rich banded ironstone clasts, which are rare in the proto-deposits downstream from Grasdrif.

Because of the meandering nature of the palaeo-Orange River described above, sediments of the proto-Orange are found in:

- Abandoned portions (palaeo-channels, terraces and ox-bows) of the older river away from and at higher elevations than the meso-Orange,
- "higher" terraces adjacent to the meso-Orange and
- as sediments filling local bedrock depressions below meso deposits.

A schematic illustration of the relationship between the deposits of various ages and their relative bedrock elevation appears in Figure 2.6.

The proto- and meso-deposits in the sector downstream from Vioolsdrif are downstream thickening-and-fining, coarse clastic wedges representing relatively short-lived periods of aggradation due to a rise in sea level (Ward *et al.*, 2002). The proto aggradational wedge thickens from five metres at Noordoewer to 90 metres at its currently preserved downstream end, 10 kilometres from the present coast (Figure 2.7). The loss in energy is reflected in the clast sizes which fine upwards from a large cobble/small boulder framework through pebble-sized gravel and coarse sand to silt and clay.

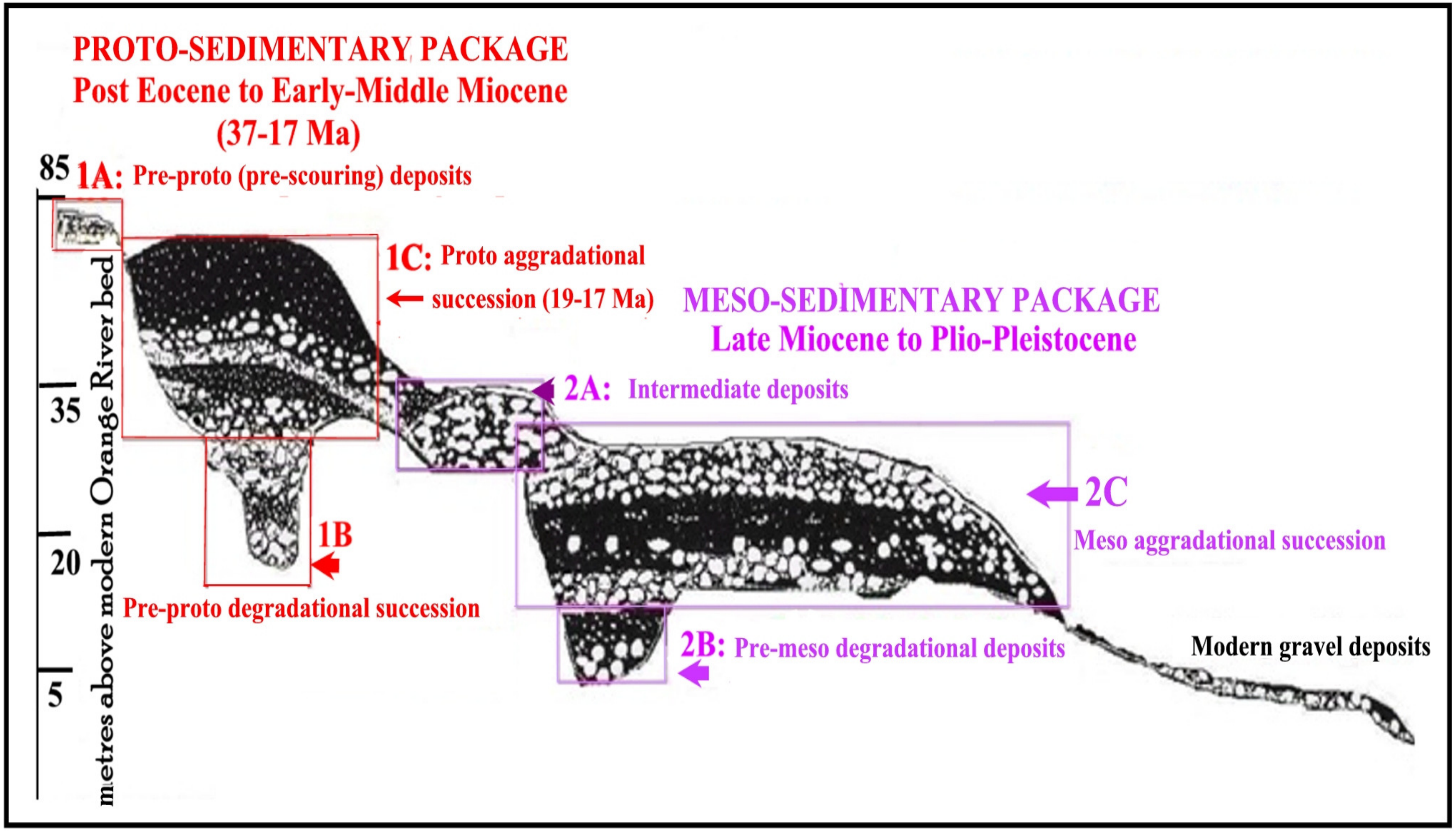


Figure 2.6 Schematic cross section through terrace deposits, Lower Orange River between Vioolsdrif and the Atlantic coast (Modified and updated after Ward *et al.*, 2002)

TABLE 2.5 CENOZOIC DEPOSITS AT DIFFERENT ELEVATIONS IN THE 5 MORPHOLOGICAL SECTIONS OF THE VIOOLSDRIF-ATLANTIC SECTOR OF THE ORANGE RIVER VALLEY (MODIFIED AND UPDATED FROM HILL AND VAN DER WESTHUIZEN, 1995).

Section	Locality and dist. from coast (km)	Appr. Surface Area (ha)					RSA/Namibian side and Special Grant No.
		PC	HT	MT	LT	FA	
1	Noordoewer; 270 – 278		???			500	NAM. SG 15
	Rooiwal; 264 – 272				120	350	RSA
	Nuwe Modderdrif; 263 – 268				<50	100	NAM. SG 14
	Modderdrif; 255 – 257				10	100	RSA
2	Olifantshoop; 219 – 221				10	50	NAM SG 11
	Navignab; 208 – 210					785	NAM SG 10
	Grasdrif; 194 – 205		200		200	500	RSA
	Aussenkjer; 193 – 203	440				>1000	NAM SG 9
	Gamkabmond; 183 – 186				10	80	NAM SG 8
	Stormberg 2; 166 – 170			10		100	NAM SG 6
	Stormberg 1; 160 – 163		10	-	5	50	NAM SG 6
	De Hoop; 154 – 158				2	10	RSA
3	Kabies (Fish River confluen.); 149-151				5	50	RSA
	Blokwerf; 143 – 149				80	100	NAM SG 4
	Blokwerf; 138 – 144				40	500	RSA
	Sandberg; 134 – 135					100	RSA
	Boomrivier; 130 – 135		30		50	200	BAM SG 3
	Oena; 126 – 131		15		50	150	RSA
	Swartpoort; 122 -126		25		30	200	SC 2
	Swartpoort; 119 – 123		10			1000	RSA
	Lorelei; 115 – 120		2-	50	10	150	NAM SG 2
4	Reuning: AACE;		25	50	15	500	RSA
	Reuning: Reuning; 101 – 116		70		100		
	Reuning: Mehl;		50	120			
	Sendelingsdrif; 96 – 110	?	>400	200	?	500	NAM.
	Jakkalsberg; 91 – 99		50	120			RSA
	Obib; 87 – 94	?		500		600	NAM
	Nxodap; 82 – 87;	3			90	200	RSA
	Daberas; 73 – 82	?	?		500	400	NAM
	Bloeddrif/Xarries; 59 – 73	470	20		600	800	RSA
	Auchas; 54 – 61	500	?	?	350	400	NAM
	Xheis;		100		500	300	RSA
	Auchas Lower; 44 – 49	?	100		400	150	NAM
	Koeskop/Swartwater;	840		400	400	200	RSA
	Arris; 35 – 37		15	25		50	RSA
	Arrisdrif; 32 – 40	?	400	20		400	NAM
5	Witvoorkop; 28 – 31		30	50?	50?	100?	RSA
	Grootderm; 22 – 27				200	300	RSA
	Kortdoorn; 9 – 14				500		

PC: Palaeo-channel; HT: Higher terrace; MT: Middle terrace; LT: Lower terrace; FA: Floodplain alluvium

Along the Lower Orange River a number of features reminiscent of waterfalls were discovered during exploration drilling, both by previous workers and under the author's supervision. These features seem to have some morphologic properties in common. They all have a steep, almost vertical drop at the upstream side, then a deep, essentially sand-filled scour at the toe of the drop, followed by an "exit ramp" on which a so-called "push bar" accumulated. Invariably the diamond content is poor in the sand-filled deepest scour, followed by well-mineralized gravel deposited along the "push bar" where the energy of the basal portions of the stream would have been negatively influenced by the micro topography and gradient of the bedrock. This aspect is illustrated in Figure 2.13.

The sandy nature of the deepest portions of the scour features, where high energy conditions were thought to prevail can be explained as follows: the vertical or near-vertical drop in bedrock elevation at the upstream (deepest) part of the scour was responsible for energy levels well above those prevailing in the river up- or downstream from the scour. This local increased energy level did not favour the deposition or retention of heavy minerals or sedimentary clasts in the scour pool – everything was flushed out of the pool, with the larger clasts and heavy minerals packed against the exit ramp or "push slope", while the lighter sand particles were swept away. As the flow of the river subsided, the point was reached where only sand-sized particles could be transported and washed into the scour, and eventually the available energy was too low for even these fine-grained particles to be moved to higher bedrock elevations downstream from the scour feature. Thus, during the dying phases of the stream, sand could only be washed into the scour pool, with the energy level insufficient to move the sand up the push slope.

Moving downstream, the first major occurrence of Cenozoic deposits of economic importance found along the left bank of the Lower Orange River, are those at Oënas (not part of this study) and Reuning.

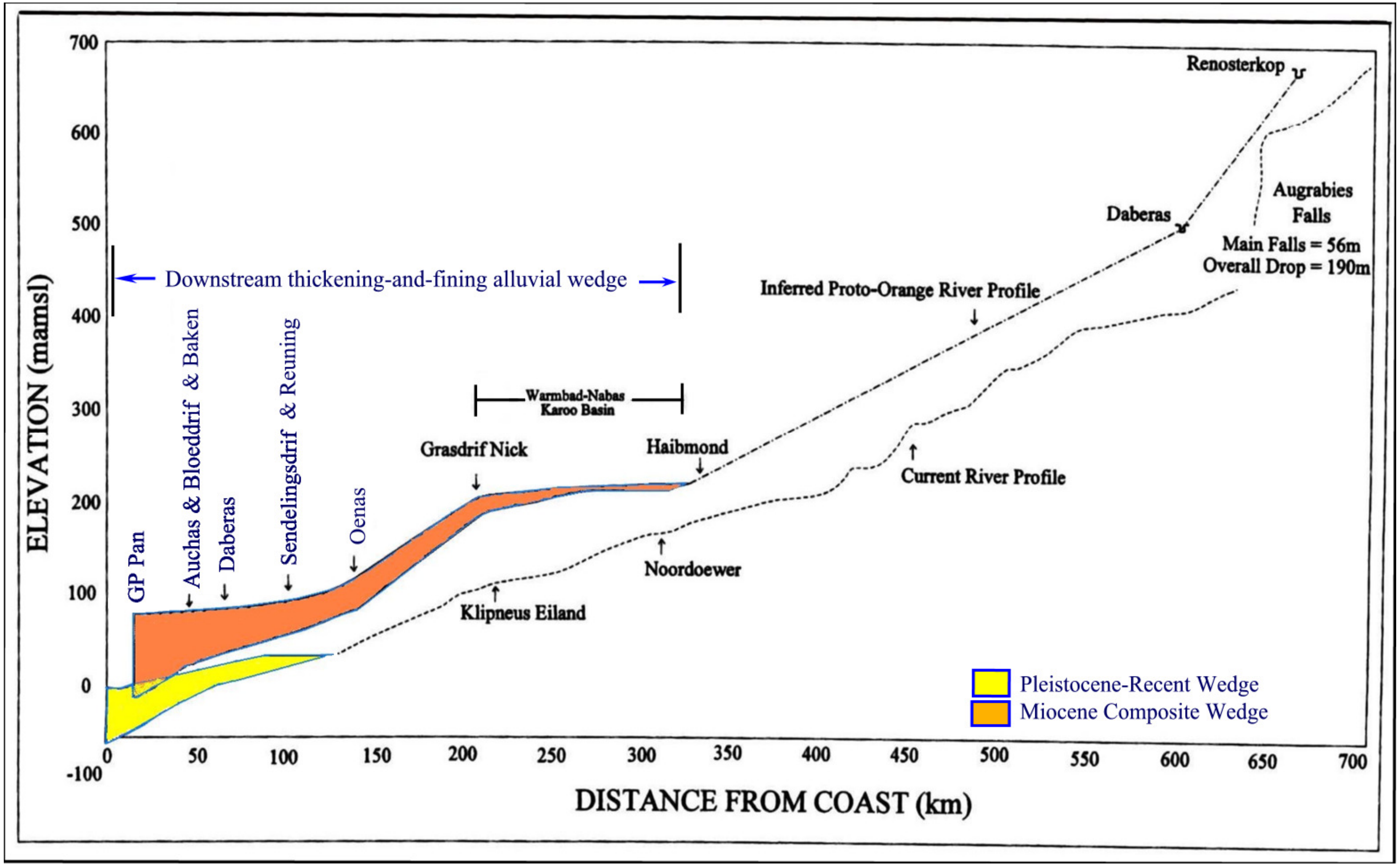


Figure 2.7 Profile of the Orange River valley downstream from Renosterkop (Modified from Ward *et al.,* 2002)

The Reuning Mine comprises three main localities along a stretch where the Orange River flows north-south. These are (from north to south): AACE, Reuning-Central and Mehl. The most lucrative deposits mined at these localities were confined to:

- AACE: a high-level proto-terrace located immediately downstream from a macro-point bar position. This is in line with earlier observations (Hill and Van der Westhuizen, 1995) for the entire sector between Vioolsdrif/Noordoewer and the coast.
- Reuning Central: a huge plunge-pool scoured out by the predecessor of the proto-Orange at the contact between harder and softer lithologies, and subsequently filled with diamondiferous sediments, especially along the "push slope" exiting from the deepest part of the scour. This feature is regarded as equivalent to the deep scours at Daberas (Namibia) and Bloeddrif discussed further on.
- Mehl: high-level proto-terrace on extremely irregular bedrock.

The terrace gravels consist of cobble to boulder-sized clasts (well-rounded to subangular) set in a pebbly-sand matrix. Locally-derived, sub-angular boulder-sized clasts are found nearer to the base of the gravel deposits. The graphs depicting lithology, roundness estimates and size frequency distribution of the gravels – results of this study - appear in Section 8.1 with the complete tables.

On the shallow bedrock affected by the Mehlberg dolerite dyke crossing the Orange River a bedrock-attached bar developed that offers the observer a glimpse of a modern analogue to the Cenozoic deposits found on the terraces. The following sedimentological features can be recognized here:

- A gravel bar head dipping upstream, comprising coarse, imbricate discoidal clasts.
- Moving downstream towards the inner accretionary bank, sand bars appear while the clasts become smaller and more spherical in shape.
- This trend continues downstream until the entire bar tail is composed of sand.

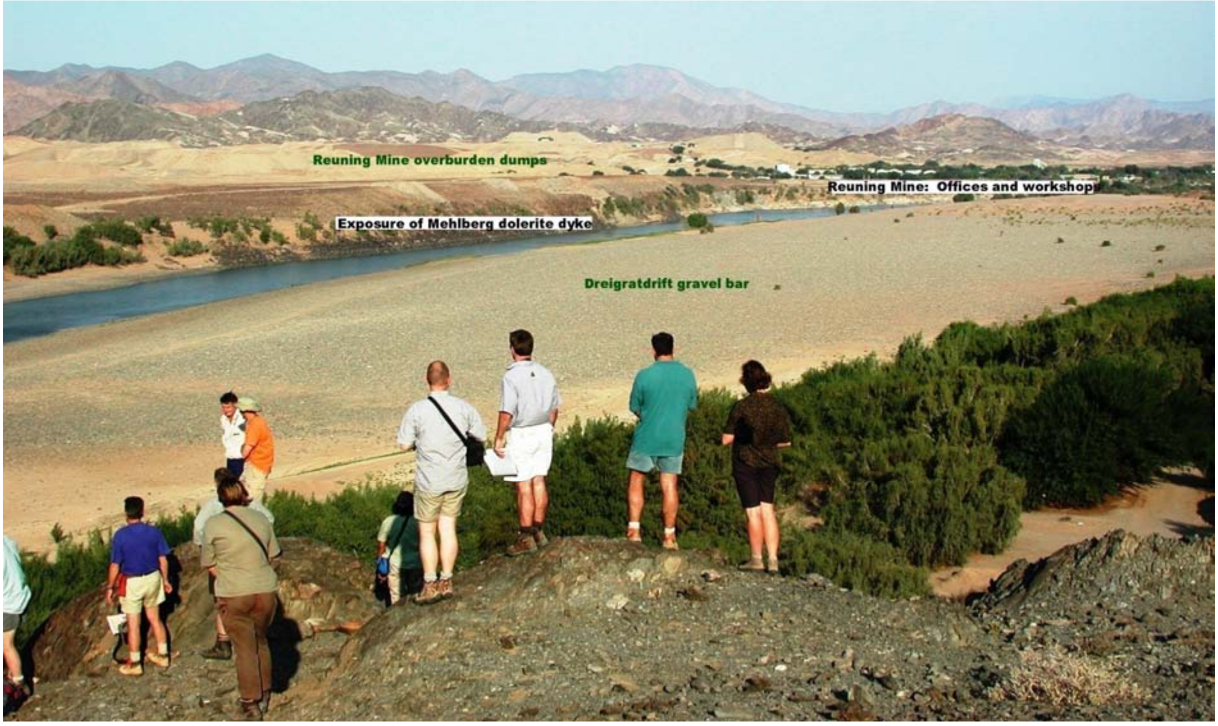


Figure 2.8 Dreigratdrif gravel bar, modern bed of Orange River.

Delegates to the IAS 2002 field excursion standing on outcrops of Numees diamictite are overlooking the Dreigratdrif bar in a south-easterly direction. On the opposite bank a portion of the Mehlberg dolerite dyke is exposed, while the central portion of the Reuning Mine can be seen in the middle background.

Opposite Reuning Central on the Namibian side, the peculiarly sculptured Dreigratberg overlooks the Orange River valley. This is the site of a deep plunge-pool (identified by side-scan sonar and sampled under the author's supervision, 1997) that was scoured out of the Numees diamictite bedrock behind (downstream from) the Mehlberg dolerite dyke shown in Fig. 2.8.

Immediately downstream from Reuning at Sendelingsdrif sediments of five different events in the history of the palaeo-Orange are present in one locality. This area is located on the Namibian side of the Orange River and was visited through the kind hospitality of NAMDEB geological staff. Due to strict security arrangements applicable to visitors, no samples could be collected here.

The oldest and highest is the terrace on which the Snake trigonometric beacon is located, and the youngest, the gravel in the modern river. The size of the Snake Hill deposit bears no relation to its importance in terms of the Cenozoic history of the region. With a bedrock elevation of 104 m.a.m.s.l. (79.4 metres above present river level) the Snake Hill deposit must be regarded as the farthest upstream preserved deposit of the Orange River in Eocene times. A selection of zircon grains from this locality formed part of this study and the sedimentary clast composition is discussed as part of the drainage evolution of the region.

All the occurrences discussed downstream from Sendelingsdrif – with the exception of Daberas – are located on the South African side (left bank) of the Orange River, and formed part of this study.

Along the Jakkalsberg to Daberas stretch of the Orange River valley a number of smaller Cenozoic deposits were preserved. The more important of these are found at Nxodap (left bank), where proto-deposits occurred in the form of a small high-level terrace, as well as some lucrative pre-proto deposits in bedrock depressions covered by low-grade younger sediments.

The economic geology of Bloeddrif is closely linked to the presence of a prominent ridge of bluish-black dolomitic limestone belonging to the Neoproterozoic Hilda Group. It would appear that major joint systems initiated the separation of this ridge into 6 discrete hills numbered - in magenta - from 1 to 6, from north to south on Figure 2.9. The mining fraternity numbered the two oxbows B1 (the southern one) and B2. Thus the mining blocks (in red on Figure 2.9) are denoted B1S, B1N, B2S and B2N, implying the southern and northern mining blocks respectively in each oxbow.

Three major morphological features characterize the course of the palaeo-Orange River at Bloeddrif: The northern portion, termed Xarries on the published 1:50 000 topo sheet of the area, comprises a huge, flat meso terrace with some proto-remnants visible along its northeastern perimeter. This is followed downstream by two loops that developed around the dolomitic limestone hills mentioned above and deposited diamondiferous proto-Orange sediments during the Miocene.

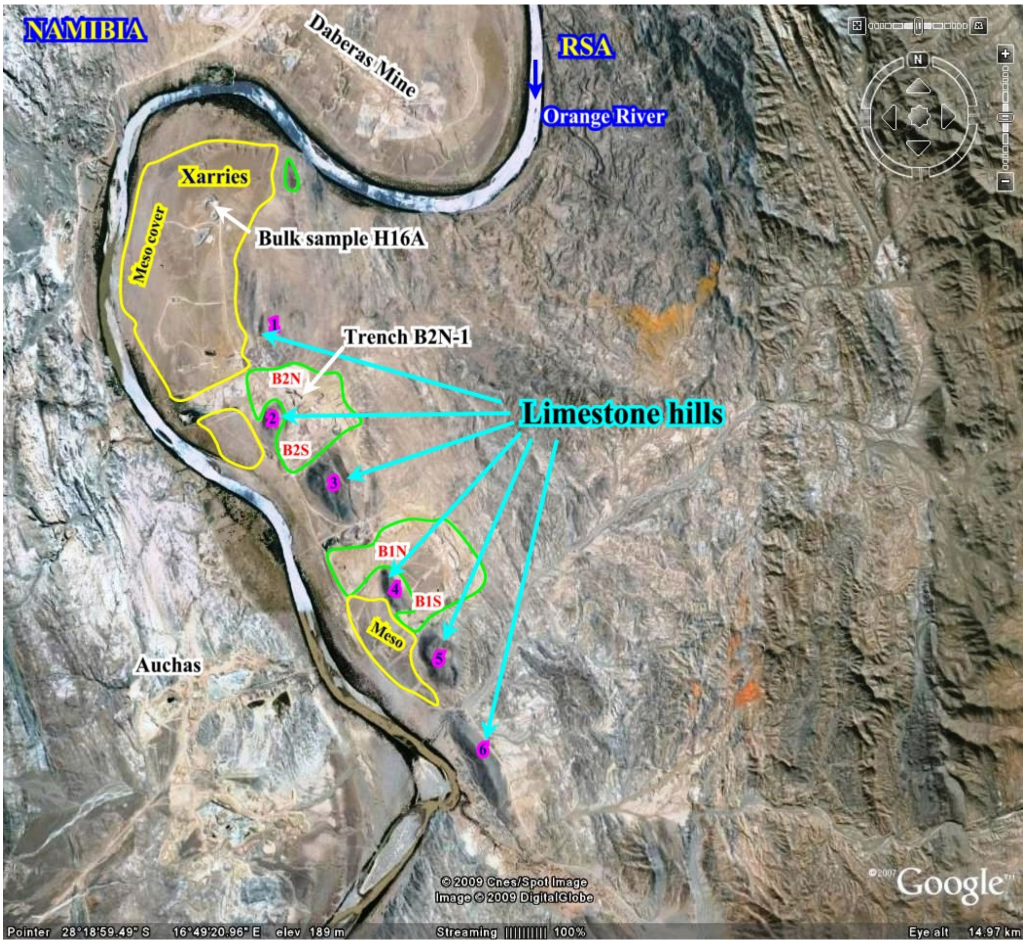


Figure 2.9 Schematic site plan of Bloeddrif showing the modern Orange River, the Miocene route of the Proto-Orange (in green), the Daberas and Auchas mining areas in Namibia, the Xarries terrace where deep scours below meso sediments (outlined in yellow) were found (Figures 2.11 and 2.12) and the Bloeddrif oxbows and mining areas described above.

Figure 2.10 Meso 2 incision into meso 1 sediments (Xarries 5, Bloeddrif).

Exposures like these allowed sample collection from different meso deposits in an effort to identify any possible changes in provenance and/or energy level during the Plio-Pleistocene as discussed on pages 48 and 49.

Pronounced bedrock scouring preceded the deposition of the Early Miocene sediments. Exploration drilling under the author's supervision on Xarries revealed the presence of five such features covered by younger Meso deposits. The first one to be discovered and tested (Trench H16A) yielded just over 10 000 carats of diamond sold for more than R30 million, over a period of 10 weeks.

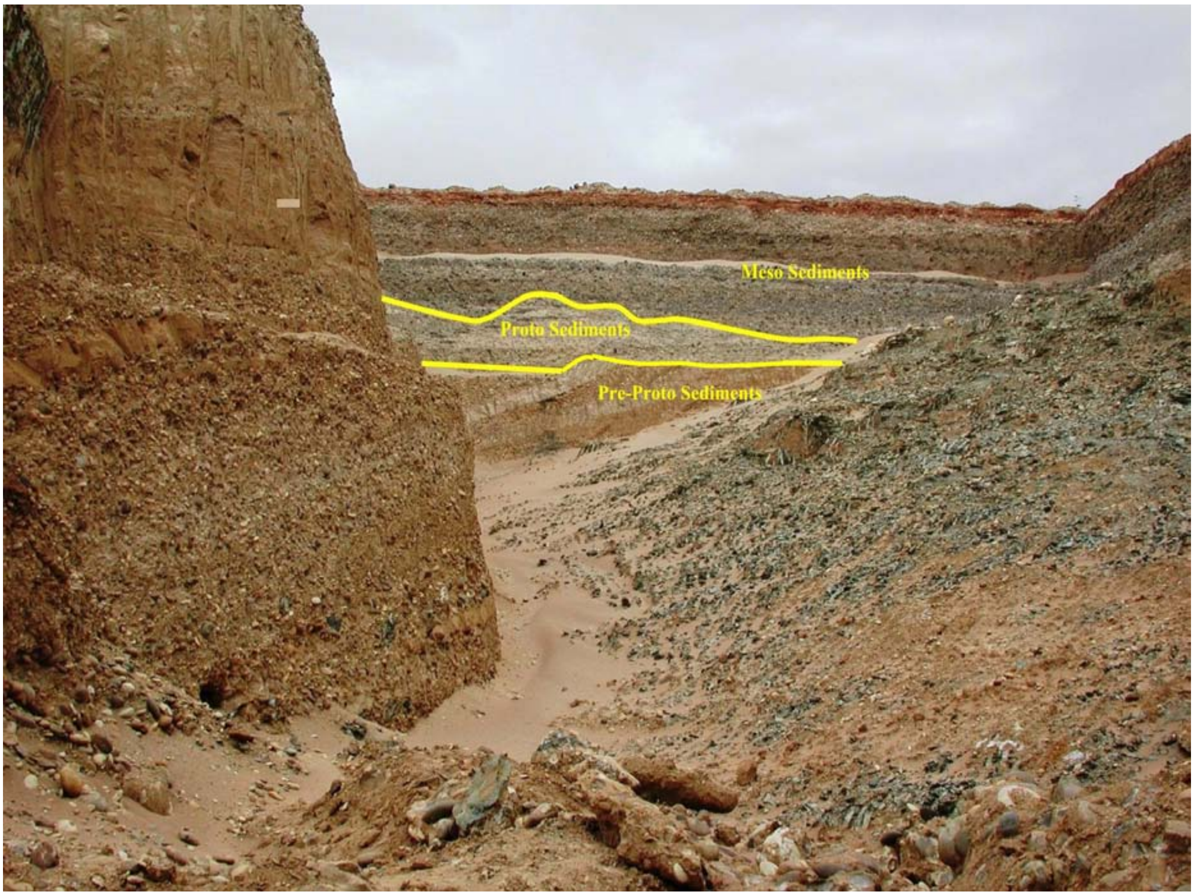


Figure 2.11 Bulk sampling trench H16A, Xarries, Bloeddrif

Note the unconformity between cross-stratified pre-proto and proto, and the undulating unconformity separating the light coloured proto sediments and overlying darker meso deposits. Gravel samples for clast studies and the extraction of garnet and zircon, were collected from the three major different units illustrated above, in an effort to detect differences in provenance regime and fluvial energy from the Miocene through to the Plio-Pleistocene.

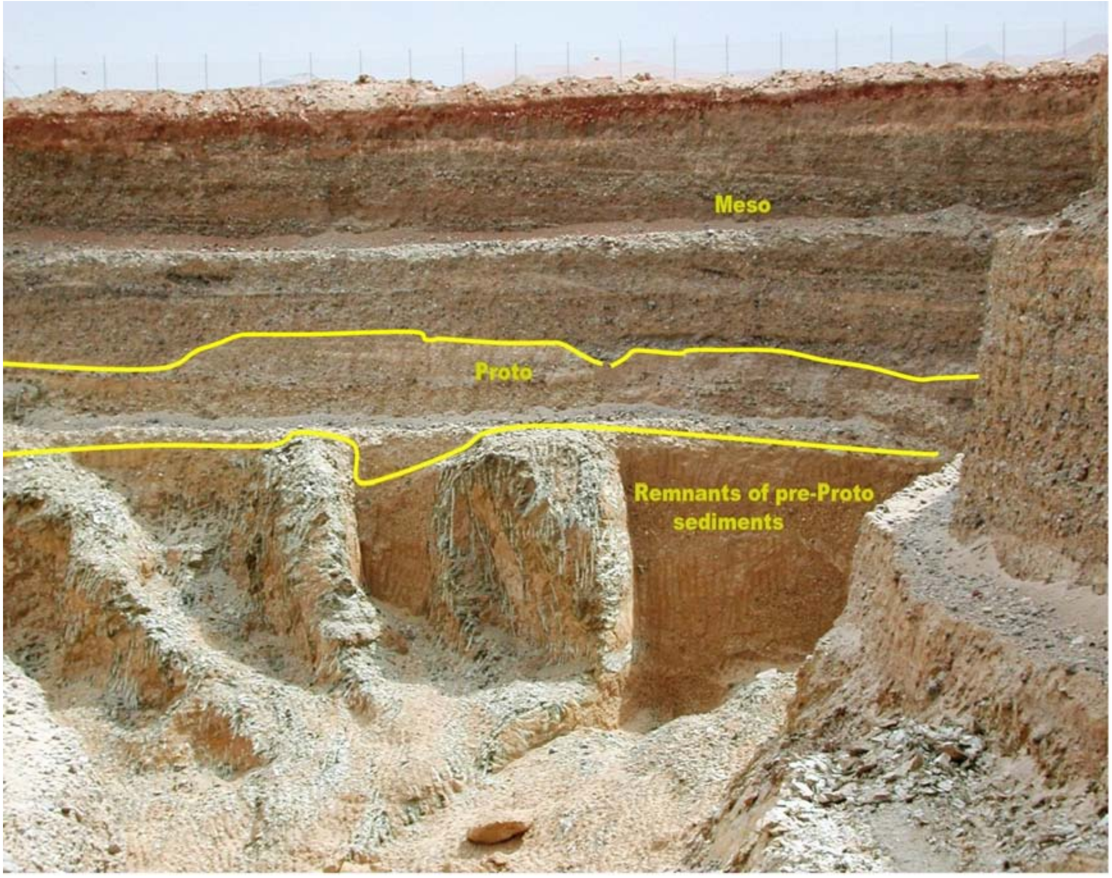


Figure 2.12. Foliation-parallel scours in schistose bedrock, trench H16A after bulk sampling. The fence poles on the surface are 1.8 metres in height.

The lucrative diamondiferous sediments found in the basal parts of the deep scours shown in Figure 2.12, were termed "pre-proto" because of marked unconformities both in sediment composition and in terms of bedding between these and the overlying proto-sediments. These are in turn unconformably overlain by meso-Orange River deposits. (Refer to schematic illustration in Figure 2.6). The important implication of these features is that the deposition of the pre-proto must have been preceded by a scouring event that could only have been brought about by a high energy fluvial system as discussed below.

The earliest onshore preserved Orange River-related deposits known are those of the Buntfeldschuh Formation, Sperrgebiet coast, dated as Middle Eocene, ~42 Ma (Kaiser, 1926; Stocken, 1978; SACS 1980; Corbett 1989; Ward *et al*., 2002). Significantly, not far from Buntfeldschuh is a small outcrop of fossiliferous limestone termed the Wanderfeld IV Beds. These have been dated as Santonian (~85 Ma, SACS 1980) and represent the only known locality of Cretaceous marine deposits along the Namibian coast. No typical, coarse Vaal-Orange River clastics which occur in abundance at Buntfeldschuh are associated with this outcrop. Very few clasts that could possibly be correlated with the Richtersveld occur at Buntfeldschuh, indicating that the Orange River was still transporting the siliceous clasts from the hinterland on a Karoo cover in its lower reaches at that time.

The earliest preserved Cenozoic deposit along the Orange River valley is that of Snake Hill at Sendelingsdrif (Ward *et al.*, 2002). This deposit, as well as those in the deep scours contains abundant clasts of Nama and Namaqua Metamorphic Complex litho-types, indicating that by that time Lower Orange River incision had gone through the Karoo rocks. It would therefore appear that somewhere between ~42 Ma and the deposition of the proto deposits in the Early Miocene (Corvinus and Hendey, 1978; Pickford *et al.,* 1995) the scours in which the pre-proto sediments accumulated must have been formed. This probably happened because of the enhancement of the energy level of the Lower Orange River during the Oligocene, brought about by a drastic lowering in base level due to a pronounced global sea level low stand (Haq *et al.,* 1987). The pre-proto sediments were laid down subsequent to this during an aggradational phase of the palaeo-Orange River.

Comparing the modified sea level curve of Haq *et al.,* 1987; Wigley, 2005, for the Early Miocene - when the Arrisdrif Gravel Formation was deposited - with the period between the Oligocene and deposition of the Arrisdrif Gravel Formation, an age of about 23 Ma for the pre-proto sediments is indicated. Sample 34 from which zircon and garnet were extracted for age determinations and geochemical analyses was collected in one of these scours, at the transition between pre-proto and proto sediments.

The northern subdivision of loop B2 at Bloeddrif, *viz.* B2N, is situated where the palaeo-Orange meandered from west to east and scoured a depression to approximately sea level, a total vertical depth of about 58 metres.

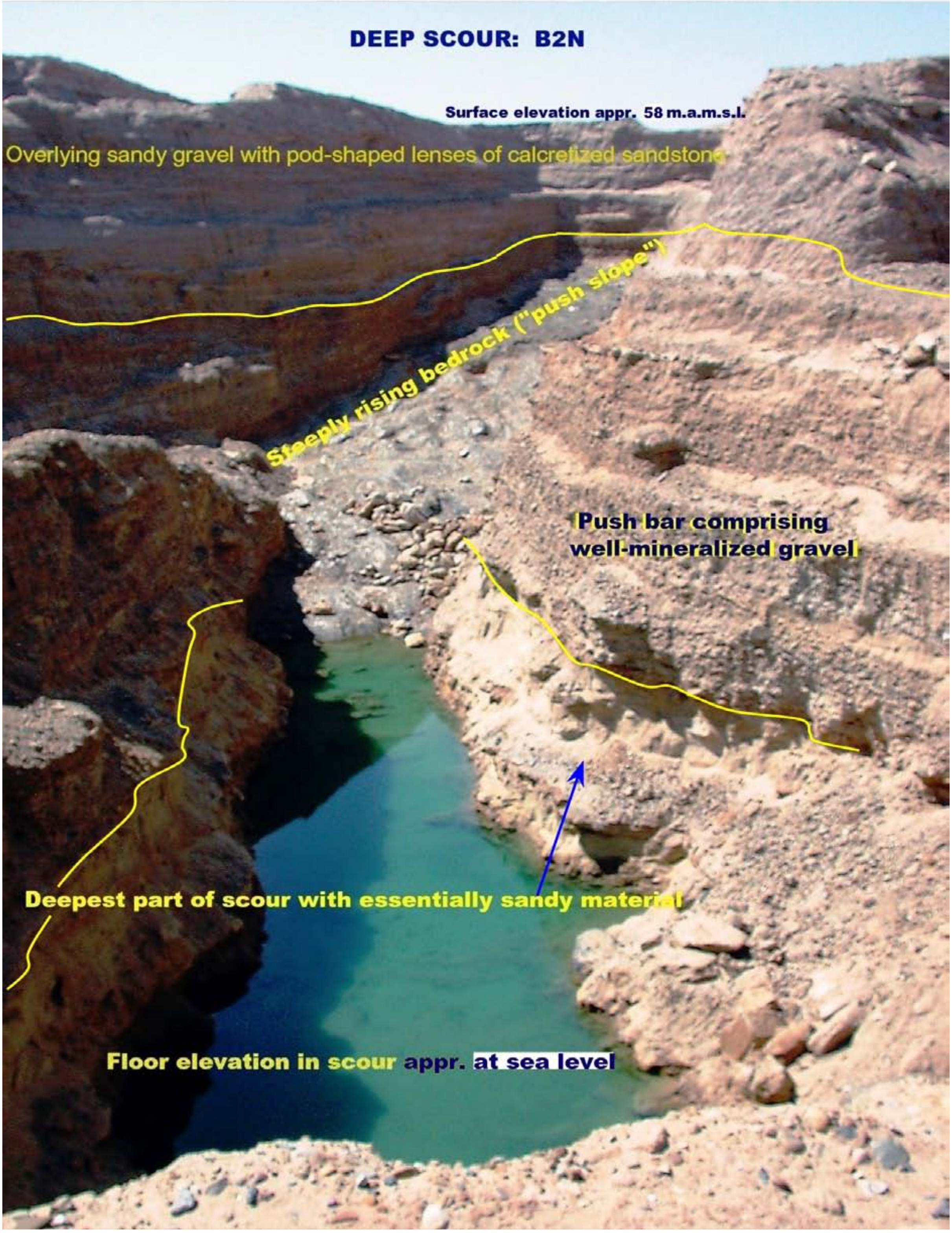


Fig 2.13 Deep scour at B2N, Bloeddrif. *This image offers a three dimensional view of the local stratigraphy with the exposed bedrock of Gariep Belt meta-sediments overlain by sandy gravel in the deep scour, followed upward by well-packed, well-mineralized gravel with orange matrix in places and topped by younger gravel.*

This feature developed at a point where the palaeo-river flowed over dolomitic limestone (Hilda Group) onto argillite, between hills 1 and 2 (Figure 2.9). Chemical weathering of the limestone probably contributed to the deepening of a scour that was initiated by the contrast in bedrock competency.

The regional geology of the Bloeddrif/Baken area is determined by the fact that it is located within the Gariep Belt, an arcuate north-south trending tectonic unit straddling the Orange River along the south Atlantic coast in the north western portion of the Northern Cape Province of the Republic of South Africa and in southern Namibia. It is considered to be a sub-province of the extensive Damara Orogenic province, which formed during the Neo-Proterozoic/early Palaeozoic Pan-African event (Clifford, 1967; Stowe *et al*., 1984; Von Veh, 1993; Frimmel, 2004).

The clastic sediments of the Arrisdrif Gravel Formation in the Koeskop-Swartwater palaeo-channel comprise the main ore body at Baken Mine. It is located in a classic ox-bow feature measuring 7 km along its course, with an average width of just less than 1,2km. Scouring of the channel must have occurred during late pre-proto times, since erosion remnants of pre-proto sediments occupy high level terraces along the inner, point bar position at Skilpadsand, while proto deposits were subsequently deposited in the thalweg portion. This sediment package has a total preserved thickness of up to 70 metres and represents a typical fining upward sequence starting with boulder gravel at the base and topped by silty clay (Figure 2.17). Recent surface debris and coarse feldspathic sand derived from the nearby Kuboos pluton blankets the proto-sediments. For the proto-deposits a Middle Miocene age is indicated from the occurrence of vertebrate fauna in the gravels at Arrisdrif, the type locality for the Arrisdrif Gravel Formation (Corvinus and Hendey, 1978; Hendey, 1978; Pickford *et al*., 1995) as well as at Baken (Mouton, 1999).

In the Koeskop-Swartwater palaeo-channel, the bedrock is comprised of either Gariep-age schist with occasional lenses of dolomitic limestone, or granite (essentially syenitic in composition) of the Kuboos pluton. Lenses of aplite occur sub-parallel to the schist-granite contact and, where exposed in the Koeskop mining area (Figure 2.14), were responsible for the development of deep scour pools which had a very positive impact on diamond concentration.

Fig. 2.14 Aplite dyke with downstream scour, Koeskop Mining Area, Baken Mine. (Camera facing upstream, viewer standing on back-filled portion of deep scour)

The westward extension of these dykes was responsible for similar but somewhat smaller wall-like features in the Swartwater mining area (Figure 2.15). In addition vast quantities of huge aplite boulders were liberated from these dykes into the palaeo-stream. Tails of heavy minerals accumulated on the lee side of these boulders.

Figure 2.15 Aplite dyke and boulders in Swartwater section of Baken Mine.

The basal member of the Arrisdrif Gravel Formation can best be described as well-packed boulder gravel with a sandy/clay-rich orange to brown matrix. Intercalated lenses of sand and clay also occur. The clasts consist essentially of quartzite.

In both the Koeskop and Swartwater mining areas, schistose metasediments building the floor of the palaeo-river was tectonically deformed causing a series of tight folds and cross-folds, with numerous gullies that developed along fractures. The result was a river bed with a rough, "riffled" surface texture, conducive to diamond concentration. This style of deformation is evident in Figure 2.16.

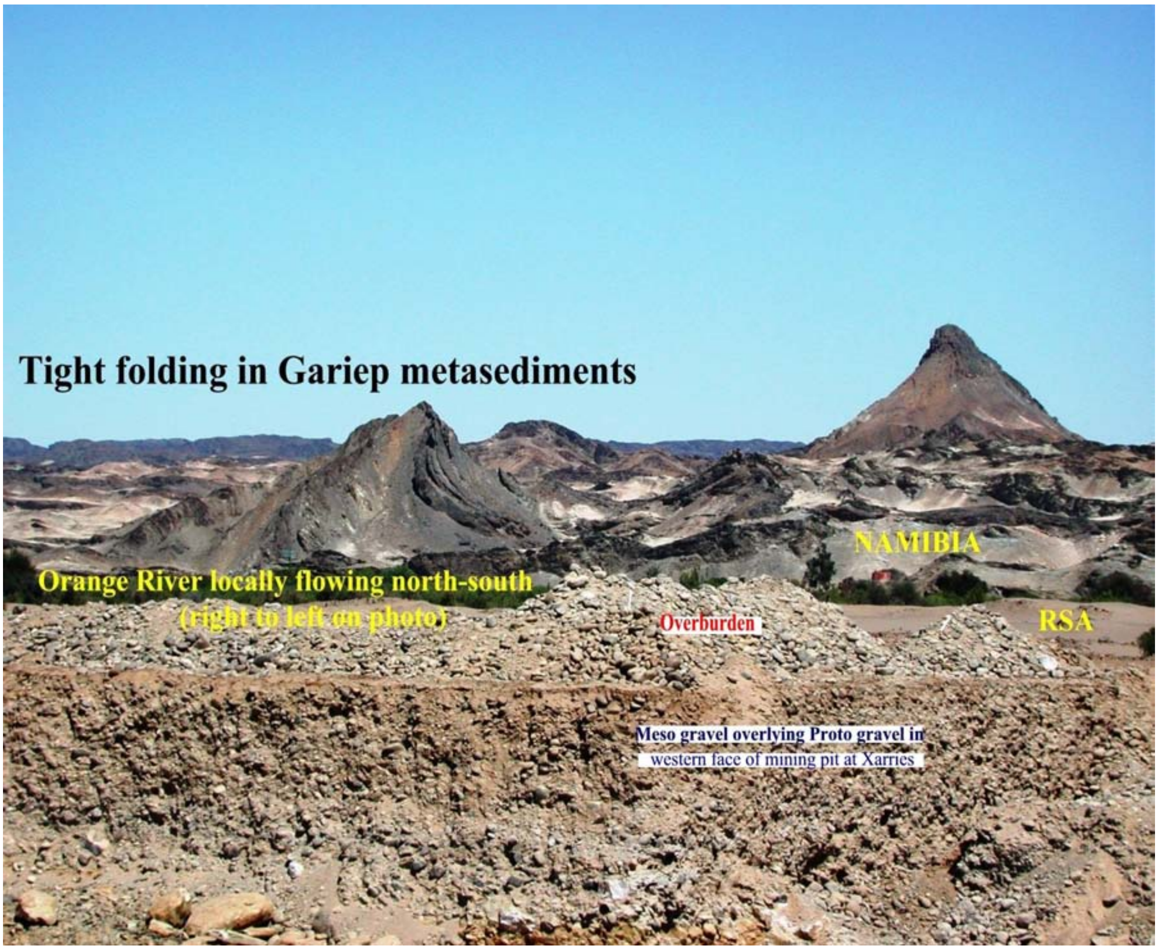
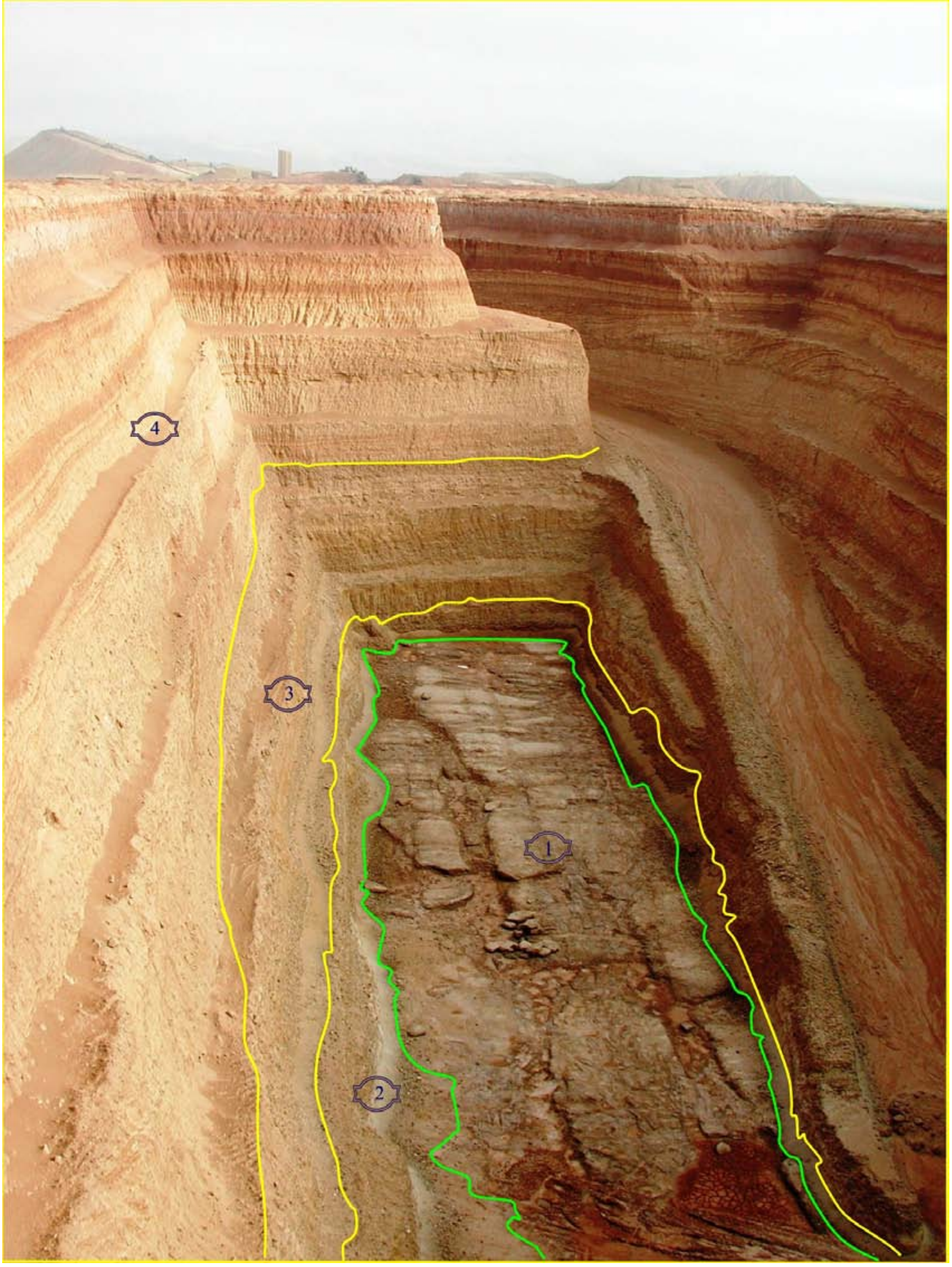


Figure 2.16 Isoclinal folding in schistose metasediments of the Hilda Sequence, Port Nolloth Assemblage, Gariep Belt. View across Orange River from meso mining pit on Xarries.



4: Silt representing final stage in deposition of Arrisdrif Gravel formation
3: Upper gravel, in places incised into top of basal gravel
2: Basal gravel with debris obscuring contact in places
1. Bedrock comprising syenitic granite (NW perimeter of Kuboos Pluton)

Figure 2.17 The 65 m deep bulk sampling trench PK4. Looking north, with palaeo-flow generally from right to left; Baken Central Plant in background. Irregular nature of contacts often the result of uneven breakage during and subsequent to mining operations.

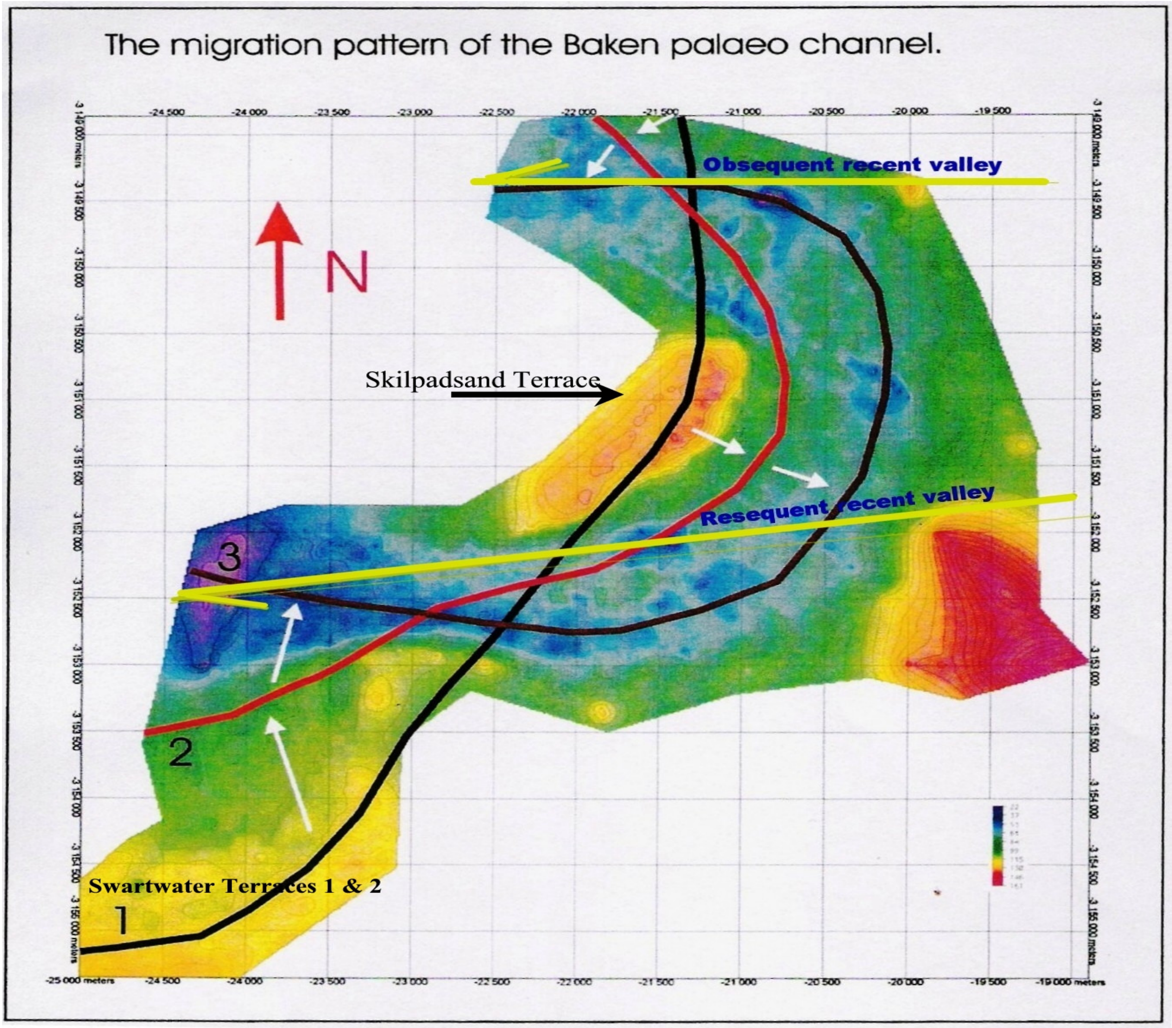


Figure 2.18 Migration routes of palaeo-Orange River – Koeskop-Swartwater

White arrows indicate postulated shifts in position of the palaeo-channel:

Black line (No. 1): Middle Oligocene.
Red line (No. 2): Late Oligocene.
Black line (No 3): Early Miocene

(Modified from Kruger & Davel, 2002).

The Skilpadsand terrace is the oldest portion of the Arrisdrif Gravel Formation preserved here, and is located on the eastern edge of the hub around which the original meander developed. The yellow arrows indicate the general route of two recent rivers, prior to mining activities

In the light of field observations during the course of this study as well as the study on the sedimentary clasts described in Chapters 3 and Section 8.1, the model proposed by Kruger & Davel (2002) for the migration pattern of this palaeo-valley as illustrated in Figure 2.18, is preferred to that of Mouton

(1999) who suggested that the Swartwater Terraces are younger than the oxbow deposits. (Kruger and Davel and this author had access to a significant amount of additional, detailed information which was not available to Mouton).

The discovery of vertebrate fossils at Arrisdrif (Figure 2.19) allowed Corvinus and Hendey (1978) to determine an Early to Middle Miocene age for the proto-Orange River deposits.

Figure 2.19 *In situ* vertebrate fossils at Arrisdrif, Lower Orange River valley

2.2.4 West Coast in general

The coastal plains of south-western Africa includes the Namib Desert and extends for over 2000 km, from the Olifants River in the south to north of the Kunene. Its eastern boundary is the Great Escarpment which lies 70 – 200 km from the coast, forming the western edge of the interior plateau (Figs. 1.2 and 1.3).

The regional geology of the west coast of southern Africa reflects the geological history of this part of the subcontinent back to pre-Gondwana times. Approximately 540 – 440 Ma ago the Adamastor Ocean that separated proto-South America from Africa, was closed up by continental collision when Gondwana was formed. The resulting mountain chain was subsequently extensively eroded and planed down. Between late Neo-Proterozoic and early Permian times a hiatus in sedimentation occurred.

Between 295 and 300 Ma BP sedimentation was resumed with the advent of the Karoo depositional era. The basal Karoo sediments comprising Dwyka tillite and terrigenous clastic sediments were deposited unconformably on the underlying basement. In the south, the basement rocks are comprised of intrusives and metasediments of the Namaqua Metamorphic Complex. Along the Skeleton Coast the basement is built of Proterozoic rocks consisting of Kuiseb Formation schist, quartzite, meta-greywacke and amphibolites as well as subordinate occurrences of phyllite and quartzite of the Mulden Molasse Formation. Where the lower and middle Karoo stratigraphic column is fully preserved, the older units are capped by Huab and Mt Etjo Formation aeolian sandstone. At the time when rift break-up heralded the demise of Gondwana, the Karoo depositional era culminated in the outflow of continental flood basalt and quartz latite, currently building the Etendeka plateau in north-western Namibia.

Isostatic uplift along the continental margin increased erosion of the rift escarpment and as a result, deposition of sediments in the shallow marine environment and along the coast took place. The combination of isostacy, sea level changes and the reworking of marine sediments under the influence of the north-flowing Benguela current and prevailing south-westerly winds, saw the formation of beach terraces (palaeo-shorelines) parallel to the coast and above and below present sea level. Many of the raised beach deposits reveal sedimentological characteristics similar to those of the adjacent modern beaches of the Atlantic.

Apart from earlier work by Krige (1927) the geology of the west coast has been described by several researchers.

- Haughton used molluscs (Haughton, 1926; 1928) and altitude measurements (Haughton, 1931) to establish biostratigraphic subdivisions.

- Sea level fluctuations were induced by Neogene glacial-interglacial cycles (Hallam, 1964; Siesser & Dingle, 1981; Dingle *et al.*, 1983; Gresse, 1988).
- The beaches were part of the legacy of transgressive complexes (Carrington & Kensley, 1969).
- Namaqualand littoral deposits were essentially regressive in origin and correlate with published Plio-Pleistocene sea level curves (Vail and Hardebol, 1979; Haq *et al.*, 1987).
- Discussions by Stocken (1962); Hallam (1964); Pether (1986); Corbett (1996); Pickford & Senut (1999) reveal that the main obstacle in the way of arriving at an acceptable model for the formation of the raised beach complexes of the west coast of southern Africa, was the absence of reliable absolute dating which would have afforded a chronological classification of the deposits.
- Besler (1984) described the development of the Namib dune field according to sedimentological and geomorphological evidence.
- Pickford (1998) and Pickford & Senut (1999) compared global sea level changes with offshore deep sea drilling data of South Africa, and compiled age-altitude relationships of the following raised beach deposits of the Namib Coastal Plain:

m.a.m.s.l.

2 ↑
5
8 Neogene
30
50 ↓
90
140 – 160 (Palaeogene)

- Partridge and Maud (2000) concluded that the entire subcontinent of southern Africa experienced significant post-Gondwana uplift, which occurred asymmetrically, tilting the entire subcontinent in a westerly direction.
- The fact that sea temperatures along the west coast were once significantly warmer than at present, was recognized.

After the separation of Africa and South America small grabens formed parallel to the structural grain and defined the early coastline. Erosion during the Early Cretaceous exposed the coastal gneisses from beneath a cover of Nama and Dwyka rocks. These gneisses later became deeply weathered and kaolinized under the influence of the humid tropical climate of the time. In Namaqualand, remnants of the Late Cretaceous African Surface can be seen in the coastal hinterland as silcrete-capped mesas underlain by deeply kaolinized bedrock. Along the coast these profiles have been truncated beneath Neogene marine sediments (Pether *et al.,* 2000).

2.2.5 Namaqualand

Incised into this ancient land surface are remnants of several fluvial palaeo-channels, whose infill have also been kaolinized, disguising their presence at the surface. These channel sediments consist of oligomictic, subangular para-conglomerates, usually rich in diamonds, overlain by beds of clayey sand, clay and carbonaceous material containing plant fossils. Van der Westhuizen (1982) and Pether (1994b) concluded that the channel sediments were originally derived from the surrounding gneisses and decomposed to a mixture of clay, quartz and diamonds, with the source(s) of the diamonds still to be determined. Support for this view came from Rozendaal *et al.* (2002) who showed that:

- The zircon population from within these channels consists of a "homogeneous selection of relatively large, rounded colourless grains" showing a unimodal age range between 1000 and 1100 Ma. This age matches that of the proximal gneisses of the Namaqualand Metamorphic Complex perfectly.
- The zircons from the nearby shallow marine environment comprise a heterogeneous population, with ages that vary from ~130 Ma to 1150 Ma. These ages were interpreted by Rozendaal *et al. (op. cit.)* as indicative of derivation from magmatic rocks associated with the break-up of Gondwana, the Neoproterozoic Gariep Belt and related late tectonic intrusives, as well as the Namaqualand Metamorphic Complex.

Diamonds for FTIR analyses and surface feature studies were selected from ROM production parcels from marine as well as coastal on-shore deposits available to the author, from south of the Olifants River to Concession 3B. The aim was to identify any significant trend in the parameters studied, and to compare the results from the different sample locations (Figure 1.3) with each other and with similar data from known kimberlitic diamond populations in the hinterland.

Diamonds are won from the shallow marine environment by extracting unconsolidated gravel from the sea floor by means of diver-operated suction or air-lift pumps. Two of the diamond sample populations for this study were selected from ROM production of the Hondeklipbaai land operations and Graauw Duinen, both land based, conventional opencast mines.

Hondeklipbaai Mine

The onshore activities at Hondeklipbaai is generally referred to as the "Hondeklipbaai land operations" to distinguish it from the shallow water and beach mining operations also conducted there from time to time.

The now defunct mine is situated on the eastern portion of the farm Hondeklip and the adjoining western portion of the farm Avontuur A. The diamondiferous marine gravel (generally about 0,5 metre thick) does not occur in classic raised beach terraces like those at Alexander Bay, but rather in a series of depressions reminiscent of erosion remnants of a palaeo-channel, and embayments in the gneissic bedrock.

Diamond concentration as a function of marine reworking is indicated by the presence of typical marine components and an almost linear relationship between gravel thickness and diamond grade. The most lucrative ore bodies comprised mature gravel layers not thicker than 60 cm. Gravel layers thicker than about 60 cm up to about 1 metre seldom reached an economic ore grade and those thicker than 1 metre, only where it occurred as gravel filling in deep bedrock depressions.

Graauw Duinen

The bedrock in the mining pits on Graauw Duinen is comprised of gneiss (Namaqua Metamorphic Complex) and occasionally inliers of dolomite of the Widouw Formation, Gifberg Group (correlated with the Gariep Supergroup of northern Namaqualand) are found.

The oldest preserved Quaternary sediments, termed the "Older Unit" (OU), locally lies unconformably on bedrock. The OU is usually 1-2 m thick and can be divided into an upper sandy unit and a gravely basal unit. The sandy unit typically is about 1m thick and consists of medium- and fine-grained, pale to mustard-yellow and in some cases olive-greenish sand. Sorting is usually good and the absence of shell fragments is characteristic and useful in separating this unit from the 30 metre package (30mP). The upward fining unit consists of gritty sand with a basal band of pebbles and cobbles. The gravel band at the base is usually about 0.3 m thick, but can reach a thickness of 1-1.5 m. The clasts are mostly of an allochtonous origin – laminated light grey chert, jasper, quartzite as well as quartz and other chemical resistates. The elevation of this unit along the western extremity of the coastal plateau is situated at 7-8 m.a.m.s.l. and rises to a maximum elevation of 12 m.a.m.s.l. toward the east.

The OU is unconformably overlain by the 30mP (Pether, 1994b) which can be identified by pale orange to orange-brown coarse-grained sand (pers. comm., J. Thom).

2.2.6 Namibian Skeleton Coast

The Skeleton Coast deposits are not so well-known as their counterparts in southern Namibia and Namaqualand but have been discussed and described in a number of reports and publications (Rabie, 1955, 1969; Hallam, 1959; Hoffman, 1962; Van der Westhuizen, 1962; Van der Westhuizen, 1979; Le Riche, 1963; Baxter-Brown, 1963a; 1975; Jenner-Clarke and Baxter-Brown, 2/1963; Stocken, 1962, 1965, 1978; Martin, 1973b; Lyle, 1982, 1983a, 1983b; Van Zyl and Scheepers, 1992; Palfi and Hutton, 2002, Hagedorn, 2006; Van der Westhuizen and Hutton 2008). Many of these were internal company reports with restricted circulation.

The Skeleton Coast diamond deposits were enigmatic with respect to their probable provenance. Some researchers (H.L. Van der Westhuizen, 1979) maintained that they merely represent the fine-grained tail of the Oranjemund population, transported northwards under the influence of the prevailing south-westerly wind and the Benguela current. The following aspects argue against this theory:

- Rouffaer (1988) pointed out that the Benguela current only came into being since the Late Pleistocene, and is too weak to have been able to transport heavy particles like diamond over such distances during such a short time.
- Chameis Bay is described by Namdeb geologists (Spaggiari *et al.,* 2006) as the distal end of the Oranjemund deposits. Here, the average diamond size diminished from 1.5ct/stone at Oranjemund (Sutherland, 1982), to <0.1ct/stone.

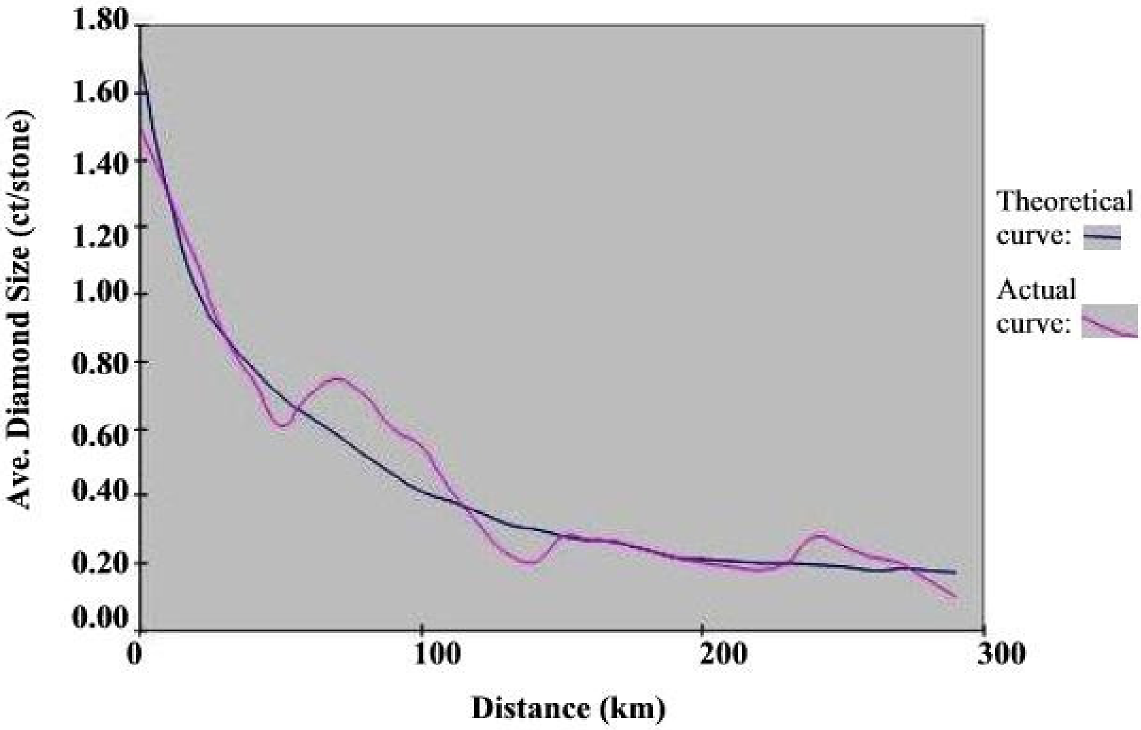


Figure 2.20 Theoretical and actual size distribution of alluvial diamonds with distance from source. Actual curve is for data from the Namibian west coast, with the Orange River at point zero. Kinks coincide with entry points of rivers. The size distribution fits a modified exponential model:
y = a.Ln(-bx.0.5), where
y = average diamond size expressed as carat/stone,
x = distance from source in kilometres
a = average diamond size in source area and
b = decay constant
(After Sutherland, 1982).

- Figure 2.20 indicates that without additional input from the hinterland, the diamond size would become insignificant not too far north of Chameis Bay. Indeed, north of Chameis Bay no significant diamond deposits are known for a distance of about 300 kilometres to the mouth of the Huab River near Toscanini. Here, at Toscanini, the average diamond size varies between 0.25 and 0.4 ct/stone, orders of magnitude larger than at Chameis Bay. An Orange River origin for the Skeleton Coast diamonds cannot account for this stone size, or for the 300 kilometre gap devoid of significant diamond deposits between Chameis Bay and the Huab mouth. The absence of Dwyka Group outcrops on or near the Western Escarpment opposite this 300km gap, has been noted, and so is the reappearance of these glacials east of the Huab mouth.

- Hallam (1959) after conducting an extensive exploration programme along the Skeleton Coast, emphatically declared that the source for these diamonds should be sought inland from there.

Along the Skeleton Coast sand dunes developed from the landward wind transport of beach sands, while salt pans (Figure 2.21) evolved in fault-related depressions close enough to the sea to receive sea water either through wave action during sea level high stands, or through underground seepage. These salt pans are generally situated between the marine sediments associated with the coastal belt, and the elevated bedrock occurrences to the east thereof. In the light of their location and surface elevation, it is conceivable that these depressions accumulated terrestrial sediments transported by seaward-flowing drainages, subsequently reworked by a transgressive sea. Evidence for this latter event is found in the presence of marine shells caught up in indurated gravel found in the salt pan near Waikiki Beach, Toscanini, during this study (Figure 2.22).

Raised marine beaches are present at Toscanini over a distance of 25 kilometres, ranging from 2 to 30 metres above present sea level. They can be grouped into three main packages, separated by pan systems. The lower (beaches A-C) are well represented between 0-9 m.a.m.s.l. The middle (beaches D-F) are present discontinuously from 9-20 m.a.m.s.l and the upper (beaches F and older) are present at 20-30 m.a.m.s.l.

Figure 2.21 Salt pan between eastern edge of +28 metre raised beach opposite Grootbaai, Toscanini, and western edge of the Etendeka Plateau

Figure 2.22 Fossilized Bullia digitalis (Dillwyn, 1817) shell from conglomerate beds in salt pan east of Waikiki beach, Toscanini, Namibia. Maximum dimensions of fossil: 20mm x 7mm.

Higher elevation marine gravels may be present, but would be obscured by alluvial fans at the foot of the Etendeka Plateau and have yet to be proven.

Gravel clasts consist mainly of quartz latite of Karoo age and Damaran meta-sediments. The < 2 mm fraction was studied under a binocular microscope and found to consist essentially of quartz and feldspathic sand, with the following heavy mineral suite:

garnet, deep purple to red, rounded
epidosites, well rounded
jasper, well rounded
banded iron-stones, well rounded
cream/brown calc-silicates, well rounded
agate
topaz, zircon, rutile, monazite, magnetite, ilmenite, tantalite, cassiterite and other unidentified dark heavy minerals
diamond.

Fine gold nuggets were also recorded by previous operators but were not recovered during this study.

2.2.7 Laingsburg

The Ecca Group in the southwestern Karoo basin comprises an approximately 1300 metre thick succession of siliciclastic sediments. It rests on the glaciogenic Dwyka Group, and is in turn overlain by the fluvial Beaufort Group. The southwestern part of the Ecca Basin is subdivided into two sub-basins, each with a separate sedimentary succession. These are referred to as the Tanqua and Laingsburg Sub-basins respectively. The Tanqua subbasin comprises:

- A lower unit consisting of five predominantly arenaceous fan systems, separated by shale units, and numbered 1 to 5 from the base upwards;
- Deltaic deposits representing the last major phase of Ecca deposition.

The Laingsburg sub-basin consists of:

- A lower, basin-fill succession comprising the Vischkuil and Laingsburg Formations (the Laingsburg Fan Complex, with fans numbered A-F from the base).
- The overlying Waterford Formation representing a fluvio-deltaic succession (Wickens, 1994).

Zircons extracted from available drill core from the Ecca Group turbidite fans (Tanqua Karoo and Laingsburg) by Nguema-Mve (2005) for his MSc dissertation, were analyzed by this author together with the zircons obtained from the gravel samples of this study. These results allowed the broadening of the data base with which the zircon ages from the gravel samples could be compared. The Ecca zircons in general are more euhedral and show less abrasion of crystal edges than those recovered from the Lower Orange River gravel samples. This is not surprising, when the depositional environment of the Laingsburg turbidites is compared to the high-energy, highly abrasive nature of the Orange River gravel deposits as implied by the size, composition and physical appearance (abundant percussion marks on siliceous cobbles and boulders) of the Orange River sedimentary clasts.

The zircons that formed part of this study were derived from the following stratigraphic units:

Number 63:	*Tanqua Fans 3, 4 and 5*
Number 64:	*Laingsburg Fan F*
Number 65:	*Slope Sandstone, Waterford Formation, Tanqua Fan complex*
Number 66:	*Laingsburg Fan A*

2.3 Drainage evolution

2.3.1 Geomorphology

The two processes that had a pronounced effect on the landscape evolution and distribution of diamonds in southern Africa are:

- The mechanical planation and smoothing of pre-Karoo landforms imparted by the Dwyka glaciation.
- The post-Karoo removal of vast amounts of sediments to produce the Bushmanland and Karoo plains that currently characterize a large portion of the interior of the subcontinent. The contribution of the near-horizontal attitude of the Karoo sediments in the development of these extensive flat surfaces cannot be overemphasized.

Initially, glaciation associated with the Dwyka Group was responsible for a considerable amount of landscape sculpturing (Wellington, 1958). Du Toit (1910) recognized the dry Harts River valley as an exhumed feature that originally formed in this way. Glaciers exploited major zones of structural weakness or the contrast between harder and softer formations to carve glacial valleys. Elsewhere the plains were planed down and mountains and hillocks smoothed. Secondly the ice sheets and glaciers that moved over the subcontinent entrained surface debris (including diamonds liberated from older kimberlites) and transported these for long distances towards the south and southwest, where they became part of the coarse-grained glacial deposits. During subsequent weathering processes the chemically resistant components (notably diamonds) of these glacial deposits were once again liberated and encapsulated in the bed load of the subsequent drainage systems. This aspect is discussed in more detail in Chapters 4, 5 and 6.

Wellington (1958) argued that the top of the Drakensberg Range in Lesotho could have been substantially higher at the time of formation than today. Considering the humid climate and the time span since the indicated end of the Karoo volcanism, it must be conceded that it is indeed very likely that the Orange River drainage system as we observe it today, was inherited from a predecessor that developed about 100 Ma ago (Ward and Bluck, 1997) on a part of the Jurassic lava surface substantially higher – at least 300 metres according to Hawthorne (1975) - than currently exposed. This is also in agreement with the views expressed by Mabbutt (1955) and Partridge and Maud (1988) and found support in the work of Lock (1980). This erosion was also enhanced by numerous cycles of uplift, doming and warping interspersed with times of crustal stability during which river systems were responsible for extensive erosion and even planation (Du Toit, 1939; Taljaard, 1948; Maske, 1957). It no doubt played an important role in the liberation of diamonds and resistant crustal xenoliths from older volcanics such as the diamondiferous kimberlites of the Lesotho Highlands, the western Free State and Northern Cape to be incorporated in fluvial systems like the Vaal-Orange.

The geomorphological processes responsible for the shaping of the present surface of the southern African subcontinent have been a subject of debate for many years. One aspect central to this debate involves the mechanism(s) responsible for an interior plateau at an elevation of 1500 to 2000 metres above sea level, the gently undulating "coastal" plain which attains only a few hundred metres above sea level and the plateau edge which has been termed "The Great Escarpment" that divides the plateau and coastal plain.

King (1951) proposed a model comprising six erosion cycles. Subsequent to this work the availability of good quality aerial photographs, satellite imagery and detailed topographic maps enabled Partridge and Maud (1987) and Maud and Partridge (1987) to follow a more empirical approach with the following conclusions; both palaeo-landforms and exposed marine sediments at the west coast attest to periodic uplift since the Late Cretaceous and this periodic uplift repeatedly renewed degradational processes, giving rise to the multi-cyclic character of the landscape.

This model was relatively close to King's ideas, but their South African landscape was differentiated rather than purely multi-cyclic. Aggradational surfaces like the Kalahari and the Namib Dune Sea required a different interpretation, while mountainous areas like the Cape Fold Belt, the plateau blocks of Lesotho, the Drakensberg in the Eastern Transvaal and the Auasberge in Namibia, retained so much local relief throughout 180 Ma of geomorphologic evolution that they can best be explained in terms of structure (Barnard, 1996).

2.3.2 Drainage evolution of southern Africa

The new river systems that developed on the Jurassic lava surface of southern Africa started in the areas of highest surface elevation. In the southeast it was the Lesotho highlands, predominantly a south-west to westward drainage (Figure 2.29), and in the northwest essentially an eastward drainage into the Etosha region of southern Africa.

Stankiewicz and De Wit (2005) suggested that the highlands where the Orange River originated was caused by a deep mantle plume (Figure 2.24) which was instrumental in the incipient break-up of Gondwana ~ 180 Ma BP.

Drainages like the Vaal and Orange Rivers superimposed themselves onto and into the underlying Precambrian bedrock, while older drainage systems were obliterated as time went by.

Figure 2.30 illustrates that the Orange and Vaal Rivers currently comprise the largest drainage system in southern Africa, with the birthplace of the Orange being the top of the Drakensberg volcanics as suggested by Maske (1957) and Wellington (1958). This system covers a drainage basin measuring 1 040 000 km^2 (Stankiewicz and de Wit, 2005) and has an annual water discharge of approximately 9×10^9 cubic metres (De Villiers *et al*., 2000).

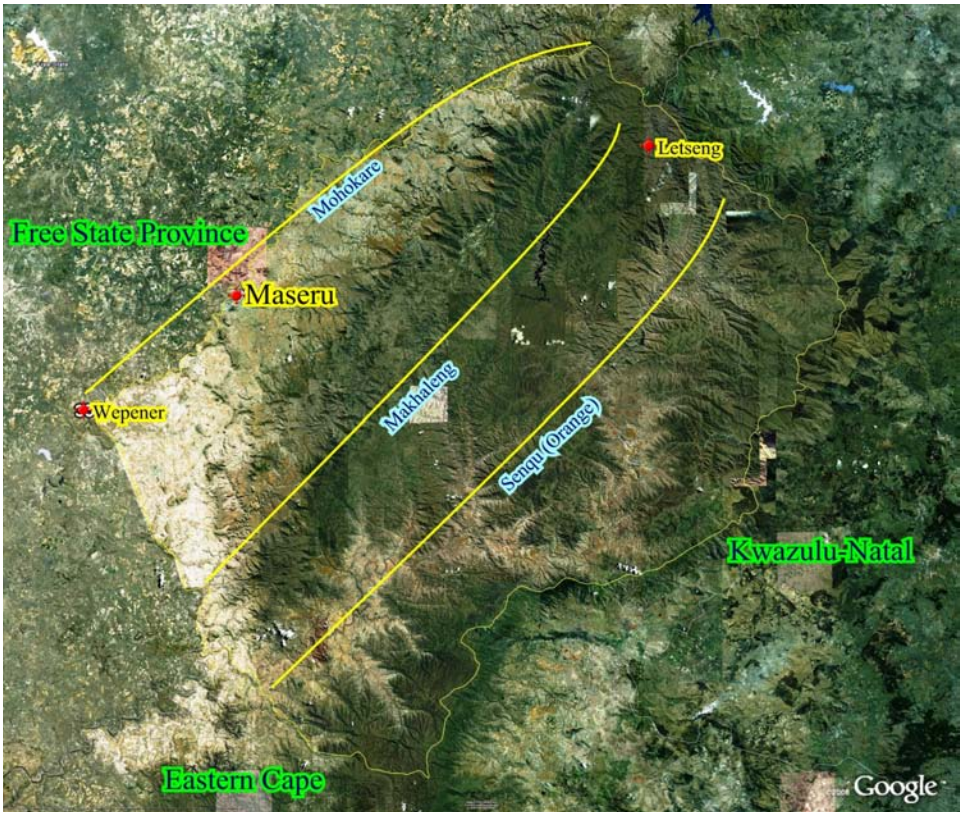


Figure 2.23 Google Earth Map of Lesotho, with postulated primitive drainage lines (Reed, 1982) that represent the primitive major drainages that developed on top of the Lesotho Highlands, namely the Mohokare (Caledon), the Makhaleng and the Senqu (Orange).

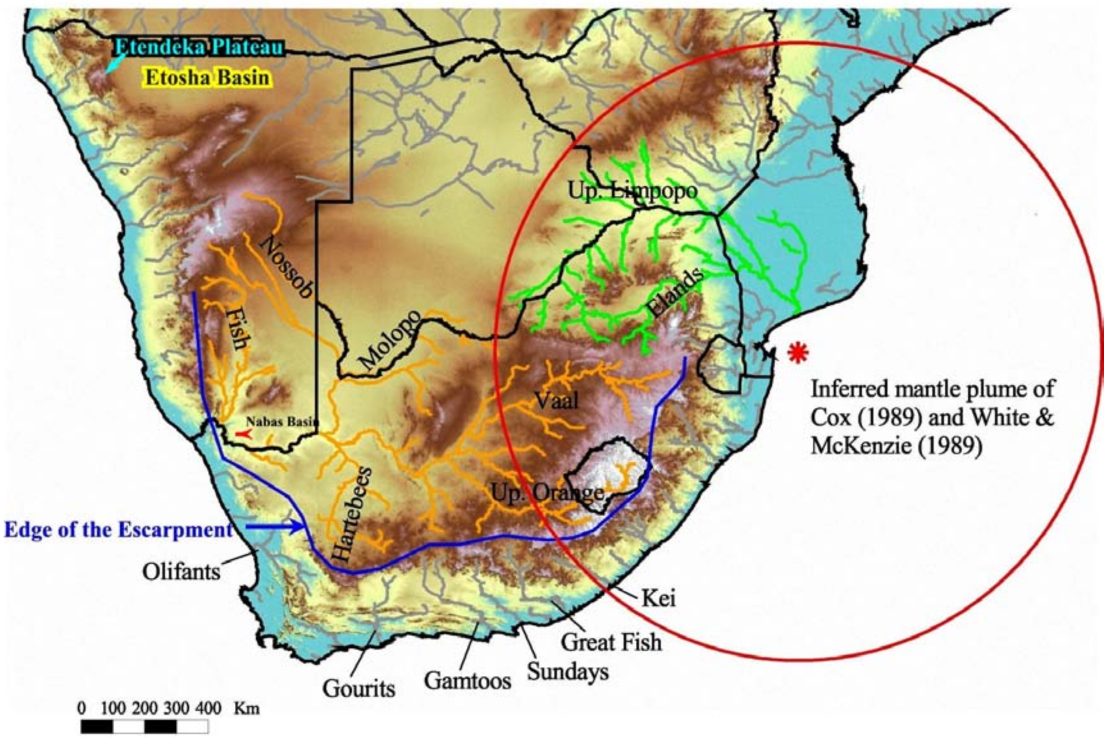


Figure 2.24 Drainage map of southern Africa (modified using SRMT90 data, after Stankiewicz and de Wit, 2005)

A brief review of the sedimentary evidence supplied by the Orange River with regard to this drainage evolution follows.

- The earliest sedimentary record linked to the Orange River, is the southern portion of the off-shore Orange River Basin near the present Olifants River delta, with a maximum age of 117 Ma (Brown *et al.,* 1995). Wigley (2005) however demonstrates that it is unlikely that this portion of the so-called Orange River Basin received its sediments *via* a palaeo-Karoo/Orange River. The northern portion of the Orange River Basin coincides with the position of the current Orange River, with the oldest post-Karoo offshore sediments here dated at 103 Ma. (Brown *et al.,* 1995).

- The oldest preserved <u>onshore</u> sedimentary record of the Orange-Vaal system, the Buntfeldschuh Formation (Figure 2.25) in the Sperrgebiet between Oranjemund and Lüderitz, is of Eocene age (Stocken, 1978). It has been interpreted as a regressive package linked to a sea level high stand in the Eocene (Stocken, 1978; Corbett, 1989). It comprises a lower marine sequence, including agate-chalcedony-quartz gravels and a sandy intertidal unit capped by an aeolianite that hosts, in places, a well-developed ferricrete, as illustrated in Figure 2.25. (The aeolianite and ferricrete do not form part of the Buntfeldschuh Formation). The clast composition (Figure 2.26) reflects initial stages in the incision of the Orange-Vaal River system following uplift of the subcontinent during the Late Cretaceous to Palaeocene (Ward and Bluck, 1997; Ward and Jacob, 1999). The importance of the Buntfeldschuh Formation with respect to its location, age, clast composition and geochronology of some zircons found here, is discussed in Chapters 4, 5 and 6.

Figure 2.25 Outcrops of Buntfeldschuh Formation with ferricrete capping

Figure 2.26 Orange River clasts (agate, chalcedony and quartz, foreign to this region), weathered out from the lower unit of the Buntfeldschuh Formation.

This early drainage development of the sub-continent occurred in harmony with the consequential slope of the surface. At this time, southern Africa formed the interior region of Gondwanaland, with the Lebombo monocline forming the watershed between east- and westbound drainages. These rivers had also uncovered pre-Karoo formations, superimposing their courses on these older rocks and in some instances exploited glacial valleys recognized by Du Toit (1910) and Visser (1987). Thus, the middle and lower Orange River, most of the Vaal River, the Limpopo, the Olifants, the Sabi and a small stretch of the Zambezi Rivers all possess courses superimposed from the rocks of the Karoo Supergroup (Maske, 1957). During the cause of this study, a number of instances were noted where local changes in the course of the Orange River resulted from the hardness contrast between dolerite and soft Karoo sediments upstream from Hopetown, and between sediments of the Karasburg Karoo Basin and the hard igneous rocks of the Richtersveld downstream from Vioolsdrif.

A summary remark with respect to the evolution of the Orange River is appropriate. From its current headwaters close to Mont-aux-Sources at latitude 28° 46' in the Maluthi's of Lesotho – only about 150km west of the Indian Ocean - the Orange River flows in a generally southwesterly direction. At Aliwal North it reaches its southernmost point from where it starts migrating north-westwards. The direct north-south distance from Aliwal North to latitude 28° 46' is about 230 kilometres. Immediately upstream from Upington, it crosses this latitude and from there it meanders back and forth over it before making the big Richtersveld bend that takes it to 50 kilometres north of its original latitude. From AACE (near Reuning) the Orange meanders in a generally southwesterly direction and, finally, after 2150 kilometres, it reaches the Atlantic at latitude 28° 39' - only about 13 kilometres north of its original latitude.

Along its course the Orange River cut through the entire preserved Karoo stratigraphy from the Drakensberg basalts in its source regions down into the Dwyka Group near Hopetown, and further downstream into underlying Proterozoic and Archaean basement rocks. While its initial drainage direction reflected a response to tectonism along the eastern margin of the subcontinent after Gondwana break-up, its course below the Drakensberg highlands was dictated by a combination of regional and local geology. While gradual crustal warping was probably responsible for its change in direction from southwest to northwest in the vicinity of Aliwal North, its detailed pattern was dictated by local geological features. The most important of these are probably the structural lineament of the Vaal River which deflected the Orange near Douglas from its pronounced northwesterly direction to the southwest, and the almost 90° course adjustment to the north-west at Prieska, where it started to follow the

Doornberg lineament. East of Upington, on the farm Leeuwdraai 403, it is the resistant Koras quartzites and conglomerates that are responsible for the sharp deflection from north-west to west, and downstream from Vioolsdrif the contact between the soft Karoo sediments of the Karasburg Basin and the exhumed competent Richtersveld intrusives was instrumental in the sharp northwards deflection towards the great bend of the Richtersveld. While it responded to various geological features and events, it also played a part in writing the Cenozoic chapter in the geological history of southern Africa, transporting and depositing sediments from afar along its valley flanks and into the Atlantic Ocean.

Since its inception about 100 million years ago the Orange River underwent numerous changes. The full bank load capacity of the Lower Orange reached nearly 30 000 cubic metres per second about 900 years ago (Zawada *et al*., 1996), comparable to that of the palaeo-Orange in Late Cretaceous times (Ward and Bluck, 1997). This is about 2.7 times more than the highest recorded in human history. In response to factors such as climatic changes and crustal movement it went through phases of youth, old age and rejuvenation, while hardness contrasts in the underlying strata invariably resulted in the river changing its course.

2.3.3 Palaeo-climate and sea level fluctuations

Zachos *et al.* (2001) combined the most recent deep-sea isotopic records and sediment cores with available literature and came to the conclusion that the earth's climate underwent a significant and complex evolution during the past 65 Ma. This included:

- Gradual warming and cooling (time scales 10^5 to 10^7 years) in response to tectonic processes.
- Rhythmic or periodic cycles (time scales 10^4 to 10^6 year cyclicity) driven by orbital processes.
- Rare, rapid aberrant shifts and extreme climate transients with durations of 10^3 to 10^5 years which apparently arose through a number of mechanisms.

These fluctuations were responsible for base level changes which influenced the development of the Lower Orange River since the Mid-Cretaceous. Wigley (2005) updated the record on Oligocene to Holocene sea level changes along the South African west coast (Figure 2.33).

Apart from fluvial diamondiferous deposits found along the course of the Orange and other rivers, the sea-level fluctuations were also instrumental in the formation of wave-cut platforms at different elevations above and below current sea level. Diamonds washed into the Atlantic Ocean by numerous westward draining rivers were concentrated in these palaeo-beach deposits.

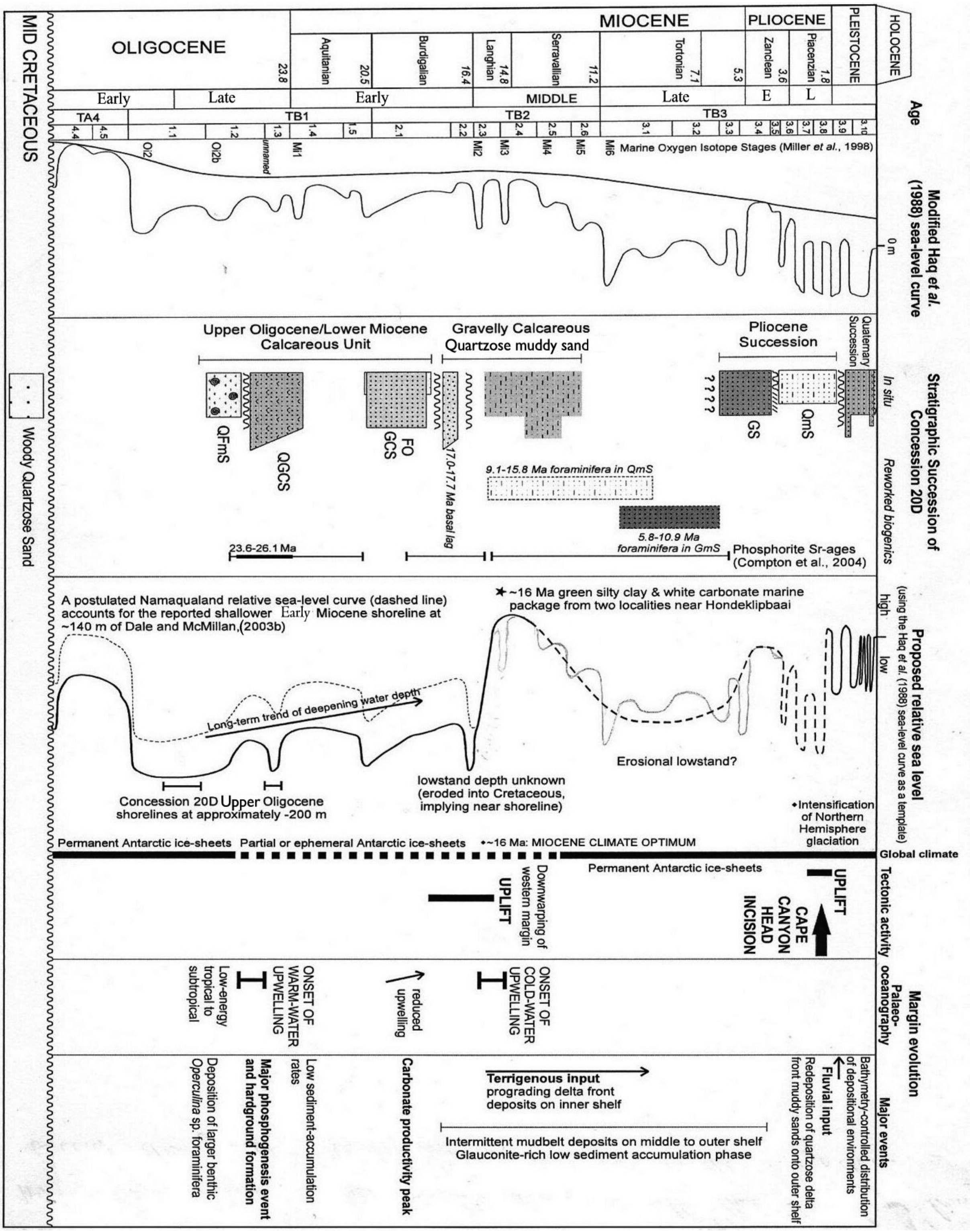


Figure 2.27 Oligocene to Holocene sea level changes recorded along the South African west coast. After Wigley (2005).

CHAPTER 3 SEDIMENTOLOGICAL ASPECTS OF FLUVIAL DEPOSITS

3.1 General

The sedimentary clasts screened out from the different sediment samples listed in Table 1.2, were studied in terms of particle size distribution, roundness, lithology and shape. It was soon recognized that the shape analyses would contribute very little to the thesis, because different litho types reacted differently to fluvial transport, and certain lithologies like quartzite and meta-quartzite hailed from sources ranging from quartzitic outcrops, to older conglomerates and diamictites in the Orange River valley. Banded iron formation clasts with a known provenance region in Griqualand-West, would occasionally reach the Atlantic Ocean as blades reminiscent of debris of these litho-types in the source region, rather than as spheres, due to the combination of stratification and durability. Likewise, sphericity was not attended to either, because of the propensity of certain litho-types to acquire a degree of sphericity prior to any transportation because of their mode of weathering as illustrated in Figure 3.1, or because of the isotropic character of the parent rock, for instance unfoliated quartzite.

Figure 3.1 Spherical exfoliation in outcrop of dolerite sill along highway N10, about 30 km from Britstown *en route* to Prieska. Note high degree of apparent sphericity and roundness of some boulders prior to any form of transportation.

When processing and interpreting the results of the study of the sedimentary clasts, it was realized that this information contributes very little to the provenance study, other than the recognition of certain litho types referred to above. For this reason the discussion on theoretical sedimentology as well as the record of the work done on the sedimentary clasts, were moved to Section 8, the Appendix.

It is a well-known fact that only gem quality diamonds survive the torrid conditions encountered in an energetic fluvial system (Figure 3.2). The results of the study on the sedimentary clasts confirmed that conditions in the palaeo-Orange were indeed very destructive. This observation finds support in the low percentage of flawed and poor quality stones in the palaeo-Orange and west coast diamond populations.

Figure 3.2 Metaquartzite cobble, Jakkalsberg. Abundant percussion marks on this tough, resilient clast attest to torrid conditions that prevailed in the fluvial system.

CHAPTER 4. HEAVY MINERALS

The characteristics that make diamond, garnet and zircon suitable for a study aimed at provenance identification were discussed in Section 1.3. This chapter studies diamonds in detail with the aim to locate their provenance and trace their fluvial transport evolution. In addition zircon and garnet are used as an indirect indicator of provenance that could support the diamond study.

4.1 DIAMOND CHARACTERISTICS AND SOURCE

Diamond, graphite and charcoal are the allotropic forms of the element carbon (Parker, 1989). In this discussion "diamonds" refer to natural diamonds found in secondary placer deposits or as part of the primary mineral suite in mantle-derived rocks. The rare, small (sometimes hexagonal) diamonds formed in impact meteoritic events (Yerofeyev and Lachinov, 1888; Russel *et al.,* 1993) do not form part of this study. Likewise, the presence of micro-diamonds (*i.e.* diamonds <0.5 mm) found in most diamondiferous kimberlites, as well as those that apparently formed in metamorphic rocks (Sobolev and Shatsky, 1990; Shatsky and Sobolev, 1993; De Corte *et al.,* 1998; Massonne, 1998; Cartigny *et al.,* 2004) is noted here for the sake of academic interest only. McCandless *et al.* (1997) showed that the micro-diamonds found in metamorphic rocks at Dachine, French Guiana, have originally been derived from mantle source rocks. Thus, although they are currently hosted in a metamorphic rock their ultimate origin is still the mantle.

Although diamonds initially crystallized in the upper mantle, it is customary to use the term "primary" when referring to diamond occurrences at or near the surface in kimberlite or lamproite that transported them from their birth place to the surface of the earth, while "secondary" refers to all colluvial/eluvial/alluvial deposits comprising their current secondary resting place regardless of the number of cycles of erosion and sedimentation involved. Collectively, therefore, all diamonds in colluvial, eluvial and alluvial deposits are termed "alluvial diamonds".

Diamonds containing a high proportion of impurities and flaws are orders of magnitude less resistant against mechanical abrasion than their more perfect counterparts (Linholm, 1973).

TABLE 4.1 CLASSIFICATION OF DIAMONDS (SUNAGAWA, 1984)

MORPHOLOGY	*CRYSTALLOGRAPHIC DESCRIPTION*
Single crystalline diamonds	*Octahedral and rounded dodecahedral crystals, twinned crystals and aggregates of small numbers of coalesced single crystals.*
Coated diamonds	*Consisting of a crystalline core and thin rims with fibrous textures*
Cuboid diamonds	*Having a radiating structure with or without a single crystalline core*
Polycrystalline aggregates	*Subdivided into framesite, bort, stewartite, carbonado, shot bort, balas and hailstone bort*

Conditions of low super saturation give rise to the growth of single crystal diamonds while fibrous coats, fibrous radiating cuboid diamonds and all the polycrystalline aggregates are the result of much faster growth from numerous nucleation sites under much higher super saturation conditions (Gurney, 1989).

In the diamond structure each carbon atom is covalently bonded to four other carbon atoms; lines joining the centres of these four atoms define a tetrahedron (Raman, 1944; Bloss, 1971; Collins, 1982). The fact that every carbon atom is joined to four other carbon atoms and that covalent bonds permeate the entire structure, means that in order to fracture a diamond many covalent bonds must be broken. Hence the diamond structure is a very difficult one to break making it the hardest natural substance known (Hutchinson, 1959). Robinson (1978) concluded that experimental results in diamond synthesis pointed to two primary growth forms, namely cubic and octahedral, concordant with its isometric crystallography. (Supported by Boyd and Pillinger, 1994).

Harris (1992) expressed the opinion that, since studies by, *e.g.* Robinson (1978), Robinson *et al.* (1984) and Hall and Smith (1984), on diamonds from southern Africa indicated that the primary growth form of diamonds in the upper mantle is most commonly the octahedron, the presence of substantial numbers of cubic diamonds in the productions from Zaire (now the Democratic Republic of Congo) and Botswana may reflect a diamond formation event which is distinct in time and thermal characteristics from that which formed the octahedra. To this list can be added the anomalously high percentage of cubic forms found at the Helam Mine, Swartruggens (Harris *et al.,* 1979; Robinson, 1979; McKenna, 2001, and the results of this study).

4.1.1 Luminescence/fluorescence

Bloss (1971) described a number of phenomena observed in certain natural and synthetic materials under different conditions, including luminescence.

Luminescence occurs in diamond when, *e.g.* electrons in nitrogen atoms that occupy defect positions in the crystal lattice of the diamond, are being excited to higher states under the influence of broad band short wave energy like X-rays, and drop back to their original state, giving off the extra energy in the form of long-wave light. In other words, the induced energy is not absorbed by the crystal. It follows *ipso facto* that measurable luminescence will be affected by the size of the crystal, the amount of nitrogen and the aggregation state of the nitrogen. This property of Type I diamonds is used in the X-ray recovery of diamonds.

4.1.2 Colour in diamond

In other gemstones and minerals colour is caused by the presence of minor impurities in the form of atoms of the transition-element metals of the periodic table. While blue diamonds also derive their colour from the presence of minute quantities of the element boron, most of the colours observed in diamond are not related to metal impurities, but to the presence of nitrogen and mostly to defects in the crystal structure of the diamond (Harris, 1987; Fritsch, 1998). The term "colour centres" is applied to structural defects within the crystal lattice where they act as "pseudo-atoms", imparting colour to diamond (Fritsch, 1998).

Harris (1992) pointed out that brown diamonds have been associated with plastic deformation, exhibiting lamination lines on resorbed surfaces caused by plastic slip during the deformation of the crystal. Urusovskaya and Orlov (1964), attributed the brown colouration in diamond to incipient graphitization of the diamond along {111} diamond lattice planes outside of the diamond stability field. Gurney (pers. comm., 2004) pointed out that this is not necessarily the case, as pressure relaxation during plastic deformation would have the same effect. The relationship between brown, pink and mauve diamond colour and plastic deformation is discussed in Section 5.2 where platelet destruction resulting from plastic deformation is used as a diagnostic feature in terms of provenance identification.

4.1.3 Primary sources of diamond and their origin

The first discovery of a diamondiferous kimberlite (Jagersfontein in South Africa in 1870), as well as the introduction of the term "kimberlite" by Lewis (1887), is described in the Appendix, Section 8.5.

In the >140 years that followed the discovery of Jagersfontein more than 3000 kimberlite pipes and dykes were discovered in South and Central Africa alone, as well as a considerable number in South America, Australia, Canada, China, Greenland, India, Siberia and the USA (Kirkley *et al*., 1991). It is now generally accepted that over 5000 kimberlite occurrences are known worldwide (Nixon and Davies, 1987), of which more than 500 are diamondiferous. About 50 have been or are being mined while 15 sustain large active mines (Janse and Sheahan, 1995).

Kimberlites are texturally and mineralogically diverse. Wagner (1914) classified kimberlites into a basaltic variety with relatively few micaceous minerals and more frequently typical of pipe-like occurrences, and a mica-rich, lamprophyric type, commonly associated with dyke-like intrusions, sills and dyke enlargements. Other efforts towards the recognition and classification of kimberlite include the work of Du Toit (1906), Williams (1932), Dawson (1960, 1967, 1971), Kovalsky (1963), Kennedy and Nordlie (1968) and Mitchell (1970, 1979, 1986) but these were hampered by a lack of consensus with regard to its exact nature.

The discovery of the Siberian kimberlites stimulated a vast amount of research by Soviet scientists, resulting in the publication of a number of classification systems especially during the period 1954 to 1965 (Bobrievich *et al.,* 1959; Milashev, 1963; Artsybasheva *et al*., 1964).

Smith (1983) showed that Wagner's (1914) classification of "basaltic" and "micaceous" groups is indeed supported by their differences in age, distribution, characteristic mineralogy, major and trace element contents and megacryst assemblages, and proposed the terms **Group I** (≈ basaltic) and **Group II** (≈ micaceous). These terms are preferred and commonly used today (Skinner, 1989), although Group I kimberlites with a micaceous character are known to exist (Gurney *et al*., 1991).

Smith (1983) arrived at a model indicating separate origins for Group I and Group II kimberlites. Group I kimberlites have Sr, Nd and Pb isotopic signatures reminiscent of those of ocean island basalts, indicating derivation from the asthenosphere. Group II kimberlites have higher $^{87}Sr/^{86}Sr$ ratios and somewhat lower $^{143}Nd/^{144}Nd$ ratios than their Group I counterparts, giving rise to the conclusion that they have been derived from a source within the sub-continental lithosphere. This is the fundamental difference between Group I and Group II kimberlites.

Of importance for this study is the fact that the emplacement ages of Group I and Group II kimberlites broadly define two epochs, *viz.* 1950 Ma, 1650 Ma, 1350 Ma, 1200 Ma, 500 Ma, 240 Ma and 102 – 63 Ma in the case of Group I kimberlites, and mainly 200 Ma – 110 Ma for Group II kimberlites (Bristow *et al.,* 1986; Jelsma *et al.,* 2004; Skinner and Truswell, 2006). This observation currently applies to southern Africa only since Group II kimberlites have to date only been reported in southern Africa. The apparent paucity of Group II kimberlites in west and central Africa can be ascribed to two possibilities or combinations thereof:

i. Mantle processes, where Type II kimberlitic magma was never available for emplacement in these regions.

ii. The deep tropical weathering and low pH soil conditions negate the survival of garnets and primary source rocks near the surface.

Furthermore, Type II kimberlites are known to be barren or virtually so in respect of ilmenite. Thus the three foremost prospecting tools for the discovery of new kimberlite bodies (surface expression, garnet and/or ilmenite haloes and magnetic anomalies) would have been non-starters in the search for Type II kimberlites in west and central Africa.

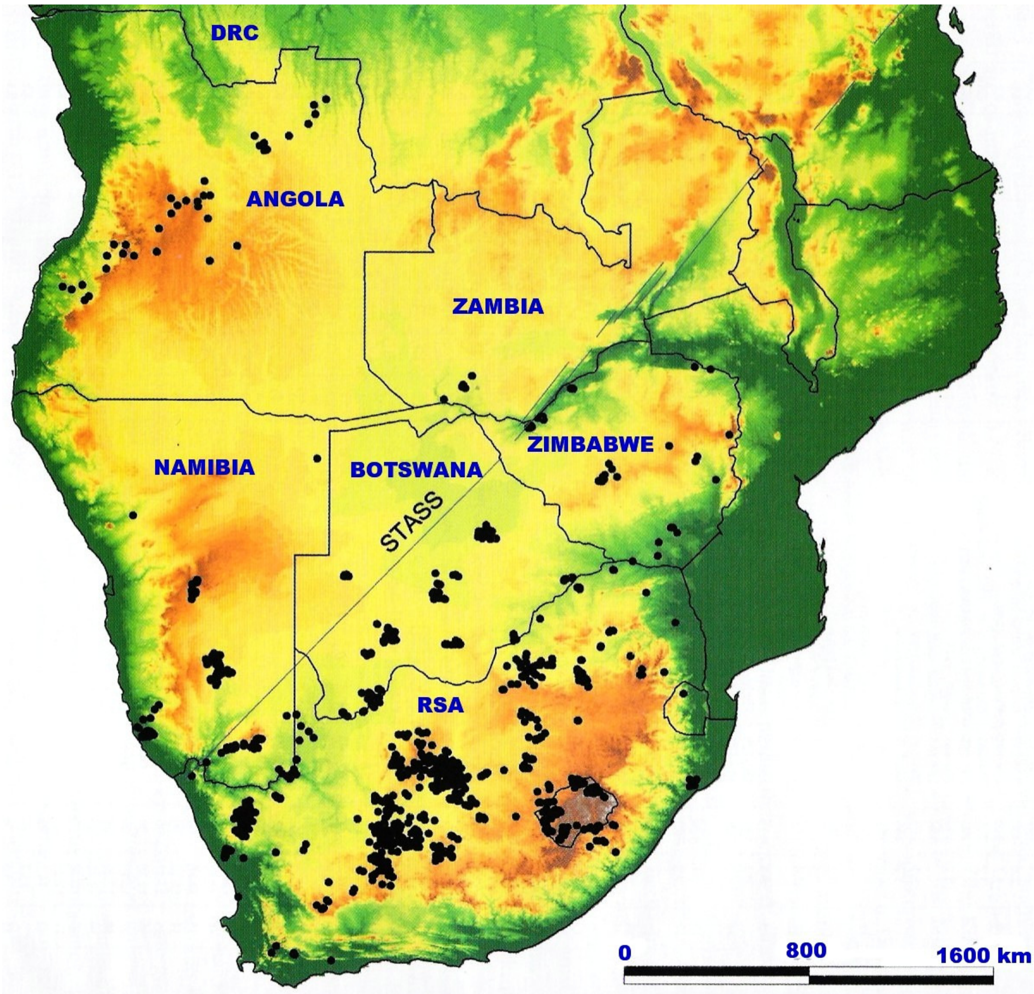


Figure 4.1: Distribution of known kimberlites and related rocks in southern Africa. (Modified from Jelsma *et al.,* 2004).

TABLE 4.2 ISOTOPIC EMPLACEMENT AGES AND DIAMOND CONTENT OF SOME KIMBERLITES OF SOUTHERN AFRICA Modified from Gurney *et al.*, (1991), Jelsma *et al., (2004)*, Gurney *et al. (2010)* and for Diamond content: E.M.W. Skinner (pers. comm., January 2009).

Locality	Grp	Ma	Diamond content*	Reference
Alkmaar	II	165	Low	Jelsma *et al.* (2004)
Ariamsvlei	I	72	Zero	Jelsma *et al.* (2004)
Beitbridge	I	430	>10cpht	Kramers and Smith (1983)
Bellsbank	II	118.8 ± 2.8	High 70 cpht	Smith et al, (1985
Blaauwbosch	II	133 ± 27[a]	>10 cpht	Smith *et al.* (1985)
Bobbejaan	II	118.8 ± 2.8	High 70 cpht	By association
Boschkop	I	86	?	Jelsma *et al.* (2004)
Britstown	II	114; 74	Zero	Skinner *et al. (1992)*
Bultfontein	I	86 ± 3	High	Allsopp and Barrett (1975)
Bultfontein		91.2		Davis *et al.* (1976)
Colossus	I	502 ± 47	?	Allsopp *et al.* (1985); Phillips *et al.* (1997)
De Aar	II	120 (124-115)	Zero	Jelsma *et al.*, (2004)
DeBeers	I	86 ± 2	High	Fitsch and Miller (1983a)
DeBeers		117		Davis (1978)
Dokolwayo	II	200 ± 5	High	Allsopp and Roddick (1984)
Doornkloof	II		Moderate	Skinner, pers. comm..
Dullstroom	II	165	Moderate to low	Skinner (1989)
Eendekuil	II	109	Zero	Allsopp in: Jelsma *et al.* (2004)
Elandskloof	I	165 – 176	Moderate to low	Smith *et al.* (1985)
Finsch	II	118 ± 3	High : 100cpht	Smith *et al.* (1991); Richardson *et al.* (1984)
Frank Smith	I	113.6 ± 1.8	5 to 10cpht	Smith *et al.* (1985)
Gamoep	?	67	Zero	Moore and Verwoerd (1985)
Gibeon	I	70	Zero	Reid *et al.* (1990)
Goedgevonden	I	100 (95-104)	Moderate to	Kramers and Smith (1983)
Gross Brukaros		84[a]	Zero	Allsopp and Barrett (1975)
Gwape-Xadi	I	90		Skinner (1989)
Jagersfontein	I	86 ± 8	High	Smith *et al.* (1985); Aulbach *et al.* (2009)
Jwaneng	I	235 ± 2	Very High >150cpht	Richardson *et al.* (2004)
Kampfersdam	I	86.9	Moderate to high	Davis (1977)
Kang	I	90	Zero	Jelsma *et al.* (2004)
Kao	I	89 ± 14	Moderate 6-20cpht	Kramers and Smith (1983)
Kgalagadi	I	90	Low	Jelsma *et al.* (2004)
Kimberley	I	85	High	Richardson *et al.* (1986) ; (2001)
Klipfontein	II	159 ± 40[a]	?	Smith *et al.* (1985)
Klippoort	I	67	Zero	Jelsma *et al.* (2004)
Klipspringer	II	155	High 70 cpht	Westerlund *et al.* (2004)
Koffiefontein	I	90.4	Moderate	Pearson & Harris (2004); Pearson et al. (1998)
Krugerskraal	I	92	?	Jelsma *et al.* (2004)
Kuruman group	I	1606 – 1200	Zero	Bristow *et al* (1986)
Lace	II	134	High	Phillips *et al.* (1998)
Leeuwkuil	II	120 (124-115)	?	Jelsma *et al.* (2004)
Leicester	I	93.6	Moderate	Davis (1977)
Lethlakane	I	92.4 ± 6.1	High	Haggerty *et al.* (1983)
Lesotho	I	85 – 90	Various	Smith *et al.*, (1993)
Loxtondal	II		10 to 40 cpht	Skinner, pers. comm..
Lushof	I	78	Zero	Davis (1978)
Maartensdrif	I	1650 – 1200	Low	Skinner (In: Jelsma *et al.*, 2004)
Makganyene	II	121	Moderate	Allsopp *et al.* (1989)
Melkfontein	I	63	Zero	Davis (1977)

Meltonwold	II	138	Zero	Skinner *et al.* (1992)
Middelputs	I	78	Zero	Jelsma *et al.* (2004)
Molopo	I	78	Zero	Davis (1977)
Monastery	I	90.4	Moderate	McIntyre and Dawson (1976); Davis, (1977)
Mothae	I	87.1	Low	Davis *et al.* (1976)
Mwenezi cluster	I	533 (530-255)	Low	Phillips *et al.* (1997)
Mzongwana	I	152.0 ± 3.4	Zero	Smith *et al.* (1985)
National	I	1180 ± 30	Moderate	Allsopp and Kramers (1977)
New Elands	II	125.7 ± 2.2	>10cpht	Smith *et al.* (1985)
Newlands	II	114.1 ± 1.6	High	Smith *et al.* (1985)
Nouzees	I	72	Zero	Jelsma *et al.* (2004)
Okwa	I	90	Zero	Jelsma *et al.* (2004)
Orapa	I	93.1;	High	Shirey *et al.* (2001); Richardson (1986)
Palmietfontein	I	92	Low	Jelsma *et al.* (2004)
Palmietgat	I	92	High	Jelsma *et al.* (2004)
Pampoenpoort	I	102 (95 – 104)	Zero	Smith *et al.* (1985); Skinner *et al.* (1992)
Pine Grove	I	86	?	Jelsma *et al.* (2004)
Premier	I	1180 ± 30	High 70cpht	Richardson *et al.* (1993, 1990); Phillips *et al.* (1989)
Prieska	I and II	120 (124– 15)	Low to zero	Skinner *et al.* (1992); Davis (1978)
Ramatseliso	I	194	Zero	Davis (1978)
Rietfontein	I	95 ± 4[a]	Zero	Smith *et al.* (1985)
Roberts victor	II	127 ± 3		Allsopp and Barrett (1975)
Roberts Victor		92.2		Davis (1977)
Roberts Victor		128 ± 15[a]	>10cpht	Smith *et al.* (1985); Allsopp *et al.* (1989)
Saaiplaas/Samada	I	89	Moderate	Jelsma *et al.* (2004)
Sikwane	I	90	?	Jelsma *et al.* (2004)
Skeyfontein	I	91	?	Jelsma *et al.* (2004)
Sover	II		Moderate	Skinner, pers. comm..
Star	II	124; 135	High	McIntyre and Dawson (1976); Phillips et al (1998)
Swartruggens	II	147 ± 4	High >100	Allsopp and Barrett (1975)
Swartruggens		150 ± 3		Allsopp and Kramers (1977)
The Oaks cluster	I	505 (530-255)	High	Phillips *et al.* (1998)
Tsabong	I	78	Zero	Jelsma *et al.* (2004)
Uintjiesberg	I	100.7 ± 1.4	Zero	Smith *et al.* (1985)
Venetia cluster	I	519	High	Allsopp *et al.* (1995); Richardson *et al.* (2009)
Voorspoed cluster.	I and II	132 (134 -125)	High	Phillips *et al.* (1998)
Wesselton	I	90.3 ± 6.5		Davis *et al.* (1976)
Wesselton		83 ± 4	High	Allsopp and Barrett (1975)
Witberg	I	91	Low	Jelsma *et al.* (2004)

**Diamond content: low ~1 cpht; moderate ~10 cpht; high >10 cpht. Without knowledge of diamond size and quality, these values have no economic significance.*

In 1871, only about one year after the discovery of the Jagersfontein kimberlite (Table 4.2), E. J. Dunn stated that the ultimate source of the diamonds existed before they were brought to surface, and that the host rocks in which they are now found only served as "transport channels" to the surface (Schwartz, 1917). In the absence of scientific evidence, Dunn's views were subsequently challenged by other observers and for many decades the xenocrystic and phenocrystic hypotheses for diamond formation opposed each other. The advent of the electron microprobe during the second half of the 20th century brought about a quantum leap in our knowledge and understanding of kimberlite petrology and diamond genesis.

The ability to accurately determine the chemical composition of minute mineral inclusions in diamond as well as those of co-existing mineral phases of ultramafic xenoliths found in kimberlite, led to the following important conclusions:

- The kimberlite magma originated in the mantle at depths of 100 – 200 km (Boyd and Nixon, 1973; Wilding *et al.*, 1991).
- Diamond requires a pressure of 38 to 60kb (equating to depths of about 125 to 200 km) to reach stability at 900°C to 1300°C (Harris and Middlemost, 1969; Meyer, 1987; Kirkley *et a*l., 1991; Harris, 1992).
- The age of diamond crystallization has been determined as being up to 3 Ga prior to the emplacement of the kimberlites (Kramers, 1977; Richardson *et al*., 1984, 1990; Wilding, 1990; Richardson 1986; Tables 4.2 and 4.3).
- Peridotite and eclogite in the upper mantle are the two primary host rocks in which diamond crystallizes. Ascending kimberlitic/lamproitic magma acted as transport media to bring the diamonds and mantle xenoliths to the earth's surface (Meyer, 1985; Gurney, 1989; Gurney *et al*., 1993).
- Many diamonds that arrive at the surface of the earth are not pristine primary crystals any longer. Most diamonds reveal a deviation from the perfect octahedral or cubic forms, towards forms exhibiting multiple crystal faces. Seal (1965) and Moore and Lang (1974) demonstrated that this is the result of dissolution of the primary crystal forms. This event has been termed resorption which, if able to proceed, will eventually result in the transformation of a smooth-faced octahedral crystal to a tetrahexahedroid crystal (Robinson, 1979; Otter, 1990). A minimum of 45% of the original mass and volume of the diamond is lost during the complete conversion of a regular octahedral diamond to dodecahedral morphology (Robinson, 1979). Frank and Puttick (1958) suggested that any process that causes the development of trigonal etch pits on

octahedral faces would also result in the conversion to dodecahedral morphology. Kanda *et al.* (1977) indeed produced trigonal etch pits and curved resorption surfaces by reacting octahedral diamond with water vapour at temperatures between 1100 and 1500°C and 50 kb pressure.

• With dissolution not always being completed various stages of resorption may be seen in different diamonds; these have been graphically illustrated (Figure 4.2) by Robinson *et al.*, (1989), Otter (1990) and McCallum *et al.* (1994). Haggerty (1986) suggested that diamond resorption can take place within the earth's mantle and therefore pre-dates the entrainment of the diamonds in the kimberlite. However, Robinson *et al.* (1989) proposed that the majority of resorption occurred within the kimberlite with different degrees of resorption observed today, reflecting different depths at which the diamonds were liberated from their protecting primary host xenoliths. The greater the depth at which the diamond is liberated from its protecting host, the longer the time it spends exposed to the kimberlite magma on its way to the surface and therefore the longer the time that it is subjected to resorption processes. It would thus appear that diamond resorption can take place in the mantle prior to entrainment in the kimberlitic magma, as well as in the magma itself.

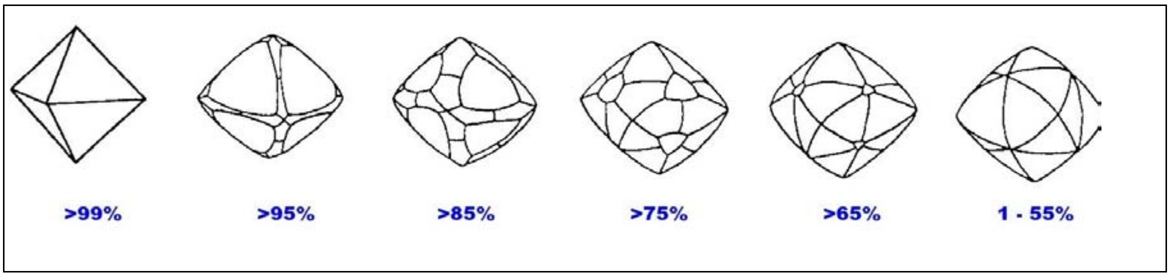


Figure 4.2 Estimated preservation values of differently resorbed diamond crystals. Composed from Robinson *et al.* (1989).

TABLE 4.3 SOUTHERN AFRICA: AGES OF DIAMONDS AND EMPLACEMENT AGES AS DETERMINED FROM THEIR SYNGENETIC MINERAL INCLUSIONS (composed from Harris, 1992; Gurney *et al.* 2010)

SOURCE	PARAGENESIS	DIAMOND AGE (Ma)	METHOD	EMPLACEMENT AGE (Ma)	REF.
Finsch	Peridotitic (garn. hartzb.)	3200 ± 100	Sm-Nd	118	1
Finsch	Eclog. grnt.	1580 ± 50	Sm-Nd	118	2
Finsch	Eclog. grnt.	P: 3200; E: 1670 ± 40	Sm-Nd	118	1, 3
Kimberley Pool	peridotite (garn. hartxb.)	3200 ± 100	Sm-Nd	90	1, 14
Premier	ecl. (gnt + cpx)	1150 ± 60	Sm-Nd	1180 ± 30	4
	ecl. Cpx	1198 ± 14	$^{40}Ar/^{39}Ar$	1180 ± 30	5
	ecl. cpx.	1185 ± 94	$^{40}Ar/^{39}Ar$	1180 ± 30	6
	per. Grn. (lherzolitic)	1930 ± 40	Sm-Nd	1180 ± 30	7
Orapa	ecl. (grn + cpx)	2992; 1969; 990 ± 50	Sm-Nd	93	2, 13
Jagersfontein	Hartzburgitic	1100; 1700		86	9
	ecl. (cpx)	102 (min. age)	$^{40}Ar/^{39}Ar$	93	8
Jwaneng	ecl. (cpx)	244 (min. age)	$^{40}Ar/^{39}Ar$	235 ± 2	8
Klipspringer	Hartzburgitic	2550		155	10
Koffiefontein	Hartzburgitic	2600; 1400; 1100		90.4	15, 16
Venetia	Lherzolitic	E: 2050 P: 2030-2000		519	11, 12

1	Richardson *et al.* (1984)	10	Westerlund *et al.* (2004)
2	Richardson *et al.* (1990)	11	Richardson *et al.* (2009)
3	Smith *et al.* (1991)	12	Richardson *et al.* (2008)
4	Richardson (1986)	13	Shirey *et al.* (2001)
5	Phillips *et al.* (1989)	14	Richardson *et al.* (2001)
6	Burgess *et al.* (1989)	15	Pearson & Harris (2004)
7	Richardson *et al.* (1993)	16	Pearson *et al.* (1998)
8	Burgess *et al.* (1992)		
9	Aulbach *et al.* (2009)		

An association between ancient cratons and diamondiferous kimberlites has been hinted at by Wagner (1914) and reiterated by modern researchers (Clifford, 1966, 1967; Gurney and Switzer, 1973; Dawson, 1980; Boyd and Gurney, 1986; Gurney, 1990; Janse, 1984, 1992). It would appear that kimberlite magma originating beneath the old thick cratons are best suited to sample deep-seated, diamondiferous layers in the upper mantle during ascent (Gurney *et al*., 1991). The suggestion that diamonds reside in Archaean lithospheric mantle keels beneath cratons originate from the intersection of graphite-diamond geotherms indicated by mantle xenoliths, and the Archaean ages of inclusions in diamonds. (Fig. 4.3; Richardson *et al., 1984;* Boyd *et al.,* 1985; Boyd and Gurney, 1986; Haggerty, 1986; Kirkley, 1998; Shirey *et al.,* 2004).

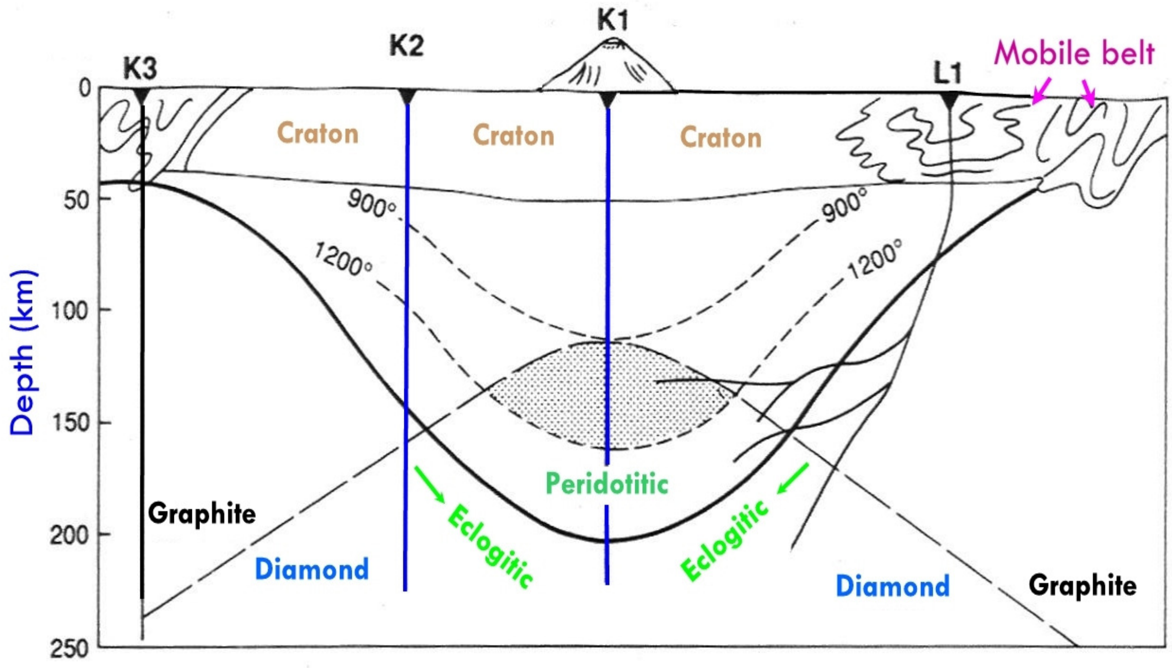


Figure 4.3 Barren and diamondiferous kimberlites and lamproites and their craton settings.

The stable craton and sub-cratonic areas are demarcated with the thick black line, and are bounded by mobile belts. While the diamond stability field, the area where prevailing temperature and pressure facilitate the crystallization and survival of diamond crystals, is convex upward, the isotherms are concave downward. Although the K1 kimberlite pipe is more likely to contain peridotitic diamonds because it sampled the "storage area" at the keel of the craton where this type of diamond is presumed to reside, the presence of eclogitic diamonds is not entirely ruled out. K2 will most probably contain only eclogitic diamonds, while K3 will most likely be barren of diamonds or nearly so due to its off-craton location. On-craton location is no guarantee that a kimberlite will be diamondiferous: if it failed to sample diamondiferous mantle rocks it will also be barren (Haggerty, 1986; Kirkley et al., 1991).

The above model has an important bearing on the present study and explains the barren para-kimberlites of Bushmanland, Namaqualand and the kimberlites at Noenieput-Rietfontein. These are off-craton rocks intrusive into the Namaqualand Metamorphic Complex and can be ruled out as a provenance for the alluvial and marine diamondiferous gravels along the west coast and the Orange River. Likewise, the wedge of the Rehoboth Terrane accreted to the western edge of the Kaapvaal Craton underlying the Gibeon kimberlite cluster in southern Namibia is too thin to be of any significance (Muller *et al.*, 2009), a fact borne out by the numerous unsuccessful diamond sampling programmes carried out there in the past (Von Bezing *et al.*, 2007).

4.1.4 Microscopic Surface Features of Diamonds

Diamond may be affected by a number of events subsequent to its formation, like post-crystallization deformation or the processes of oxidation and dissolution (Robinson, 1975; Otter, 1990). Primary growth features on diamonds include smooth faces and triangular plates. These features do not often survive the later events of resorption and etching (Robinson, 1979). Some of them occur fairly ubiquitously in South African kimberlitic diamond populations while others have, in a provenance study, diagnostic value.

i. Plastic deformation is evident by the presence of lamination lines on resorbed tetrahexahedroidal faces. They generally appear as a system of fine parallel lines that cross dodecahedron edges at 90°, combined with two, generally weaker, systems that cross these edges at a smaller angle. They are relatively common and well developed on brown, pink and mauve diamonds.

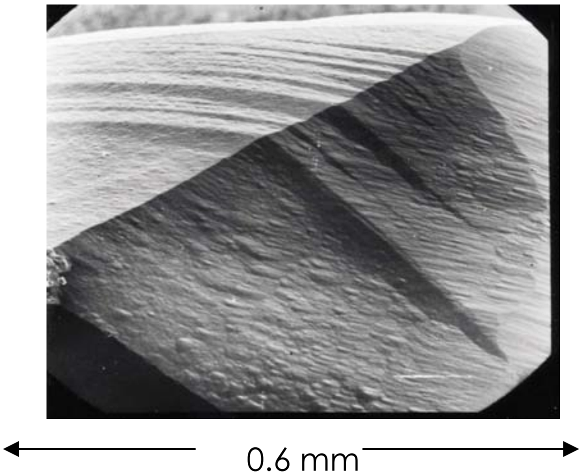


Figure 4.4 Lamination lines on diamond crystal faces due to plastic deformation (indicated by parallel lines crossing a dodecahedron crystal edge at 90°). Photo: courtesy Robinson, 1979.

ii. Tetragonal etch pits tend to develop on cubic faces and breakage surfaces parallel to cubic planes, while trigonal and hexagonal etch pits develop on octahedral faces or breakage surfaces parallel to octahedral faces (Sutton, 1928; Censier and Tourenq, 1995). Apart from the crystallographic orientation of the edged surface, the morphology of the etch features seems to vary according to the temperature and pressure prevailing during oxidation and the nature of the oxidizing agent (Orlov, 1973; Robinson, 1979).

iii. Polished surfaces.

Phaal (1965), using dry CO_2 in oxidation experiments on diamonds produced low-relief, lustrous "chemically polished" surfaces. Subsequently Robinson (1979, Figure 4.5 below) reported similar features on some diamonds from the west coast of southern Africa and accepted Phaal's (*op. cit.)* explanation for their presence. According to Hall and Smith (1984) such features are common among the diamond populations from the Ellendale lamproites in Australia and Chinn (1995) reported similar features on two diamonds in the population studied from George Creek, Colorado. Support for the explanation offered by Phaal (1965) seems to come from the presence of a small proportion of CO_2-bearing diamond in one of these two reported on by Chinn (1995).

However, further studies convinced Robinson that the polished surfaces described by the other authors are different from those found on the west coast and Zambian diamonds recovered from Kalahari deposits, where the very nature of the polished area(s) argue for a mechanical, rather than a chemical process. Robinson (*op. cit.*) suspects abrasion by wind-borne dust to be the polishing agent in these instances. It is concluded that polished surfaces are indicative of prolonged exposure to adverse climatic conditions and could therefore also be an indication of liberation from pre-Karoo kimberlites.

0.5 mm

Figure 4.5 Strongly polished surfaces on diamond. *Note the rounding of the crystal edge running more or less north-south and the fine network pattern evident at the left. Photo: courtesy Robinson, 1979.*

iv. Green and brown spots

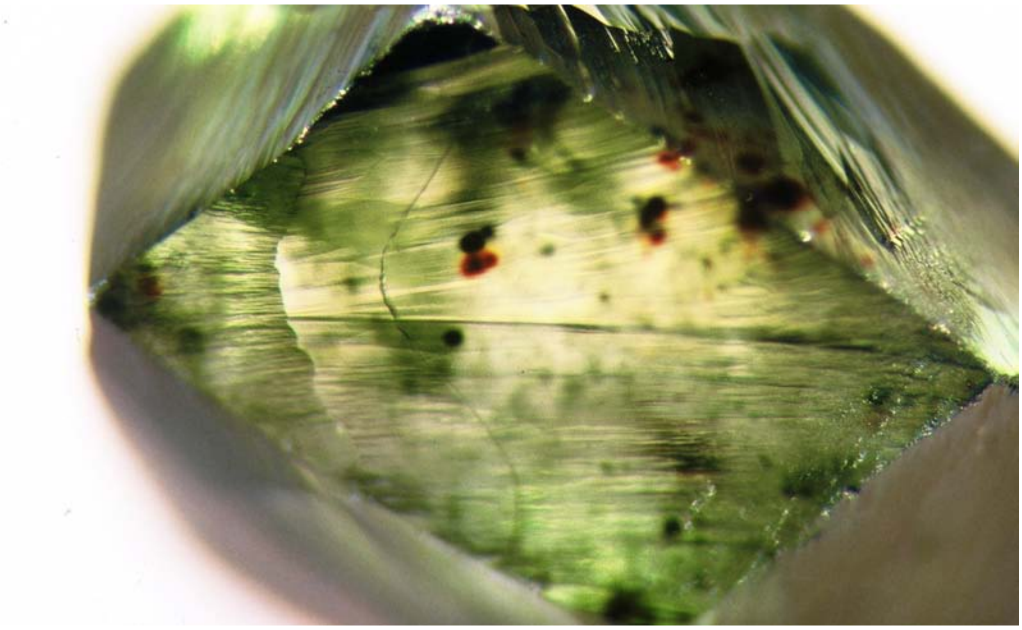
Lind and Bardwell (1923), Vance *et al.* (1973), Harris *et al.,* (1975) and Raal and Robinson (1980) reported on the presence of green spots in the outer 20µm of the surface of some diamonds resulting from α-particle irradiation. Theoretically, therefore, all the green spots on diamonds would be expected to appear in the sedimentary environment where diamonds stand a greater chance to come into contact with radio-active particles, as opposed to the very low level of radio-activity encountered in a kimberlite. This seems to be not exclusively the case. Robinson (pers. comm.) saw single green spots on occasional diamonds from many kimberlites while such spots are relatively common, and occasionally present in numbers, on diamonds recovered from the Lethlakane satellite pipe and Maartensdrif kimberlites. Vance *et al.* (1973) and Harris *et al*., (1975) reported a greater abundance of green-stained diamonds in the near-surface, weathered kimberlite at Finsch Mine, compared to the fresh kimberlite from underground. This phenomenon was ascribed to the more abundant availability of radio-active elements leached from their host minerals and fairly evenly distributed within the weathered material by percolating ground water.

In laboratory experiments (Vance *et al.*, 1973) it was demonstrated that the green spots described above turn brown when heated to 550°C. Some researchers expressed the opinion that green spots on diamonds can turn brown with age without the high grade heat event (550°C) reported by Vance *et al*. (1973). However, the latter report was based upon laboratory experiments, while the former is only conjecture and does not take account, *e.g.* of the well known, very prolific green spots for which diamonds in the Witwatersrand sediments (with Archaean age) are noted. It is possible that green spots would turn brown at lower temperatures than in laboratory experiments, were heat to have been applied for a lengthy period, as in geologic time. Hence, a low-grade metamorphic event could suffice. Junner (1943) reported on diamonds in Ghana that survived a metamorphic event.

Robinson (pers. comm. 2002) stated that in the only three primary sources where he saw diamonds with brown spots these can be ascribed to contact metamorphism due to post-emplacement igneous activity, *i.e.* Premier (cross-cutting diabase sill), Maartensdrif (cross-cutting dolerite dykes) and the top of Argyle's sandy tuff unit (which is overlain by a basaltic flow). The Premier and Maartensdrif kimberlites all have pre-Karoo emplacement ages.

It is suggested that green-spotted diamonds could have spent time within a, probably sedimentary, environment more conducive to the infliction of radio-active damage to diamonds than would normally have been the case. It is thus possible that green-spotted diamonds could have enjoyed a common or similar history of radio-active attack as was the case with the brown-spotted ones, but missed out on the subsequent metamorphic event that would have converted the green spots into brown spots.

In the light of southern Africa's igneous and metamorphic history (Table 2.1) and the evidence discussed above, this study accepts the presence of brown spots on diamonds as proof of pre-Karoo kimberlite emplacement.



2 mm

Figure 4.6 Green- and brown-spotted diamond. Photo: courtesy Robinson, 1979.

***v. Nearly colourless*.**

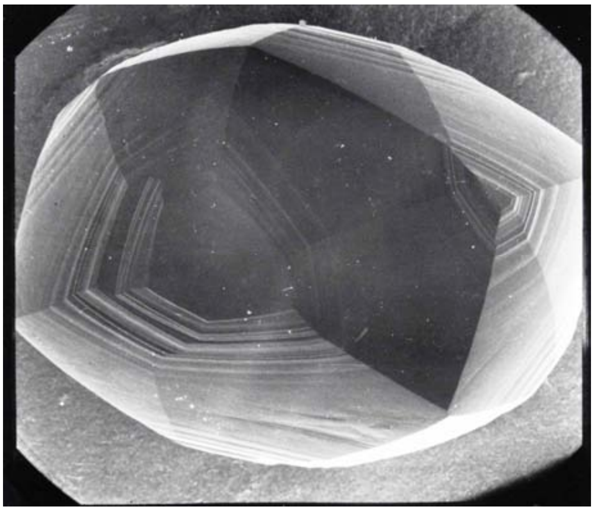
According to the work of Loubser and Wright (1973), Collins (1982), Evans (1992), and Fritsch (1998) these should all be very low in nitrogen (*i.e.* Type II) or they shall lack nitrogen in either the single substitutional or the N3 forms.

***vi. Brown and deformed diamonds*.**

The lamination lines that were shown to indicate plastic deformation followed by resorption (Urusovskaya and Orlov, 1964) are also displayed by these stones. De Vries (1975) demonstrated that temperatures higher than 1000°C are required for diamond to behave in a ductile rather than brittle manner. Since plastic deformation is supposed to accelerate N aggregation and break up platelets, enhanced aggregation states shall be exhibited by these diamonds. This has indeed been demonstrated by the work of Chinn (1995) on diamonds from George Creek, Colorado, Viljoen (2002) on diamonds from Venetia, George creek and the Argyle lamproite in Western Australia, and McKenna (in: Bowen *et al.*, 2004) on the Letseng diamond population.

***vii. Terracing*.**

The origin of these features, as is the case with micro disk- and zigzag-patterns, finely frosted and scratch-like markings (not illustrated here) is still a matter of conjecture (Orlov, 1973; Robinson, 1979).



3.3 mm

Figure 4.7 Terracing on diamond crystal. Photo: courtesy Robinson, 1979.

***viii. Appreciably Abraded*.**

Diamonds revealing appreciable abrasion of crystal edges could have experienced a transportation history different to that of associated diamonds, in which case a sub-population is indicated (Orlov, 1973; Robinson, 1979).

Alternatively, post-depositional conditions like those prevailing in a very torrid surf zone on hard, pothole-ridden bedrock, can impart abrasion features on diamonds as discussed in Section 4.1.5.

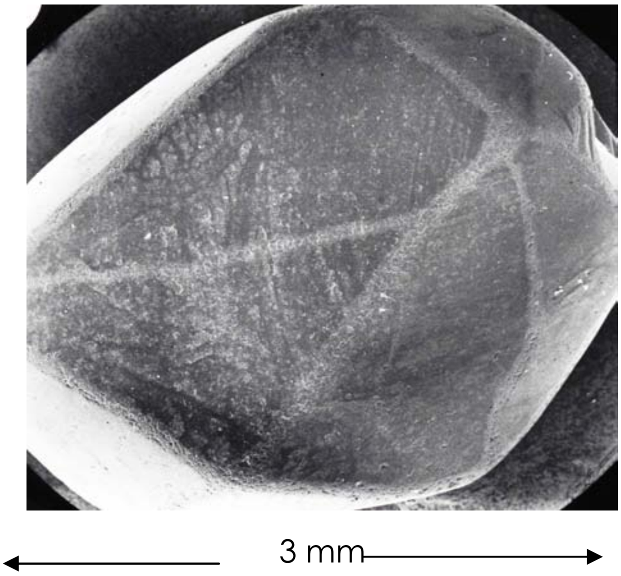


Figure 4.8 Appreciable abrasion evident as frosting of all crystal edges. Photo: courtesy Robinson, 1979.

4.1.5 Surface and near-surface features on diamonds in this study

In the preceding paragraphs the nature of the different surface features on diamonds in general was described. The origin of some of these features has been established, but some others remain a matter of conjecture.

There is no database of surface features from diamond populations of South African kimberlites available for a detailed comparison with the results of this study, and the very nature of most of the features has nothing to do with transport distance from primary source. For instance, brown spots on detrital diamonds give an idea of an emplacement age at least older than the Permian, but it does not tell us how far from the source those diamonds have travelled. The results of the surface feature study must therefore be used in conjunction with a study of the geographic location of diamondiferous kimberlites with known emplacement ages that meet that criterion.

Attention was focused on a number of features that are diagnostic with respect to provenance identification, compared to those common to most kimberlitic diamond populations. Since many of the surface features are secondary in origin, they allow the recognition of certain post-crystallization events affecting a diamond population.

The various localities from where the diamonds were collected for this study are listed in Table 1.3. They include 35 sample groups from 25 alluvial occurrences and 2 kimberlites. The surface features of some 1221 diamonds have been studied under the binocular microscope and were grouped into sub-populations that included: *brown-spotted, green-spotted, nearly colourless, deep yellow (these include medium yellow diamonds that either contain single substitutional N or are intermediate in terms of aggregation state), brown and deformed, terrace, micro disk-patterned, zigzag- patterned, finely frosted, scratched marked, appreciably abraded and polished surfaces (mechanically and not chemically polished). The "remainder" group* do not exhibit any features relevant to interpreting IR measurements, or to suggest that they might constitute a sub-population. They could still have had a common source, age and metamorphic history with, for example, the spotted ones (or some other sub-population), but were not affected by radio-active damage due to a different position in the kimberlite or sedimentary environment.

4.1.5.1 Discussion of results

In Table 4.4 the presence of a particular subpopulation is expressed as a percentage of the total population studied and n = number of diamonds in the sample population. Some diamonds display more than one of the surface features and as a result the total percentages for some populations do not add up to 100.

Diamond morphology of effectively all grains studied has the typical tetra-hexahedroid shape emanating from the partial resorption of octahedra, clearly conforming to the regional trend of southern African diamond deposits. Some rare cuboid, amber-coloured diamonds however, have been noted in the sample populations from the Helam Mine (kimberlite), Graauw Duinen (onshore marine) and one such diamond in that of Marine Concession 7A. This suggests that the provenance for portions of these two marine diamond populations is dissimilar to the regional trend and this aspect is regarded as significant in terms of provenance identification.

The full range of known microscopic surface features has been recorded. Only some of these, however, have diagnostic value in terms of provenance identification.

A correlation coefficient matrix was constructed for the populations depicted in Table 4.4 to define the interrelationships between surface features (Appendix 8.2.4). The strongest positive correlation (0.75) is between brown and green spotted diamonds in the matrix. This statistically means that if a diamond surface displays green spots there is a very good chance that it will also have or occur with diamonds having brown spots and vice versa. This supports the observations of Vance *et al.*, (1973) and Robinson (1979) discussed above, from which emanated the interpretation that brown spots represent thermally altered green spots.

TABLE 4.4 RELATIVE ABUNDANCE (%) OF SURFACE FEATURES IN THE DIAMOND POPULATIONS FROM THIS STUDY

	Brown Spotted (1)	Green Spotted (2)	Nearly Colourless (3)	Deep Yellow (4)	Brown and Deformed (5)	Terraced Group (6)	Micro Disk-patterned (7)	Zigzag (8)	Finely Frosted (9)	Scratch-marked (10)	Appreciably Abraded (11)	Polished (12)	Remainder (13)
Baken β Gravel n = 60	0	1.7	6.7	6.7	23.3	50.0	13.3	25.0	20.0	0	5.0	3.3	15.0
Bak. Up. Gravel n = 14	0	7.1	0	0	35.7	71.4	14.3	7.1	21.4	0	0	0	7.1
n = 39 Sax'drif & Brakfontein	0	2.6	35.9	0	5.1	28.2	10.3	12.8	0	2.6	2.6	0	48.7
3B n = 55	1.8	3.6	1.8	0	27.3	47.3	3.6	9.1	29.1	3.6	27.3	7.3	12.7
5A n = 46	4.4	6.5	2.2	0	17.4	26.1	0	8.7	8.7	2.2	8.7	8.7	54.3
H'Baai Surf Zone n = 31	4.4	6.7	8.9	2.2	26.7	26.7	2.2	0	8.9	0	11.1	0	46.7
HKB Mine n = 40	0	0	2.5	5.0	27.5	55.0	7.5	15.0	20.0	2.5	17.5	0	27.5
7A n =37	3.2	3.2	0	0	25.8	45.16	9.7	9.7	12.9	O	12.9	6.5	29.0
11A n = 21	30.0	22.5	27.5	0	40.0	62.5	0	5	0	2.5	5.0	2.5	15.0
12A GWK n = 39	23.1	10.3	0	0	15.4	43.6	0	10.3	7.7	0	0	0	30.8
12A Deep n=30	16.6	16.6	3.3	0	46.7	30.0	3.3	3.3	6.7	0	16.7	6.7	6.7
12A De Punt n = 60	21.7	20	3.3	0	26.7	43.3	5.0	10.0	5.0	0	0	8.3	20.0
13A n = 40	22.5	25.0	12.5	2.5	37.5	30.0	5.0	7.5	7.5	0	5.0	2.5	12.5
Bosluispan n = 58	1.7	15.5	3.5	1.7	32.8	44.8	10.3	13.8	17.2	5.2	19.0	3.5	13.8
Gr"Duinen n = 126	17.5	25.4	4.0	0.8	30.2	13.5	4.8	3.2	2.4	0	2.4	4.8	26.2
Klipgat n = 24	0	4.2	4.2	0	25.0	66.7	4.2	33.3	4.2	8.3	4.2	4.2	8.3
Nt'ged. n = 71	2.8	4.2	16.9	7.0	22.5	60.6	0	12.7	2.8	0	0	0	12.7
Buff'sbank n = 300	0.3	22	0	0	15	60	0	6	23	4	31	3	0
S-on-Vaal n = 60	0	1.7	6.67	0	13.3	46.7	11.7	8.3	3.3	0	0	1.7	40
Christiana n = 42	2.4	2.4	35.7	4.7	2.4	38.1	9.5	7.1	2.4	2.4	0	0	33.3
Samada n = 107	0	0	16.8	0	1.9	20.6	0	7.5	0.9	0	0	0	49.5
Holfontein n = 70	0	0	67.1	2.9	2.9	0	4.3	0	12.9	2.9	4.3	10.0	14.3
Cowpers n = 51	1.96	0	66.7	5.9	3.9	5.9	5.9	0	5.9	0	0	9.8	5.9
Skel' Coast n = 100	2.0	2.0	84.0	0	3.0	2.0	2.0	0	17.0	4.0	10.0	31.0	1.0

TABLE 4.5 LEGEND FOR LOCALITIES LISTED IN TABLE 4.4

Refer also to Figures 1.3 to 1.6 and Table 1.3

Abbreviations used in Table 4.4	*Description*
Baken β Gravel	*Basal, proto-Orange River gravel, Baken Mine*
Bak. Up. Gravel	*Upper, proto-Orange River gravel, Baken Mine*
Sax'drift & Brakfontein	*Combined parcel: Saxendrif and Brakfontein Mines, Mid-Orange River*
3B	*Marine Concession 3B*
5A	*Marine Concession 5A*
H'Baai Surf Zone	*Shallow marine environment, Hondeklipbaai*
HKB Mine	*Open cast mine, palaeo-channels with marine transgression, Hondeklipbaai land operations*
7A	*Marine Concession 7A*
11A	*Marine Concession 11A*
12A GWK	*Marine Concession 12A, shallow water zone opposite the farm Geelwal Karoo*
12A Deep	*Marine Concession 12A, near western boundary*
12A De Punt	*Marine Concession 12A, shallow water zone near De Punt*
13A	*Marine Concession 13A*
Bosluispan	*The farm Bosluispan in Bushmanland*
Gr'Duinen	*Open cast mine, raised beach on farm Graauw Duinen*
Klipgat	*Open cast mine, karstic depression on the farm Klipgat*
Nt'ged	*Open cast mine, karstic depression on farm Nooitgedacht*
Buff'sbank	*Open cast mine, palaeo-channel of Buffels River; this data extracted from Robinson, 1979.*
S. –on-Vaal	*Open cast mine, Vaal River palaeo-channel, Sydney-on-Vaal*
Christiana	*Open cast mine, Vaal River terrace near Christiana*
Samada	*Kimberlitic mine dumps, Samada Mine, farm Kaal Valley*
Holfontein	*Open cast mine, karstic depression, northwest of Randfontein*
Cowpers	*Open cast mine, karstic depression, NE part of Uitgevonden, 20 km north of Lichtenburg*
Skeleton Coast	*Open cast mine, raised beach, northern Skeleton Coast, Namibia*

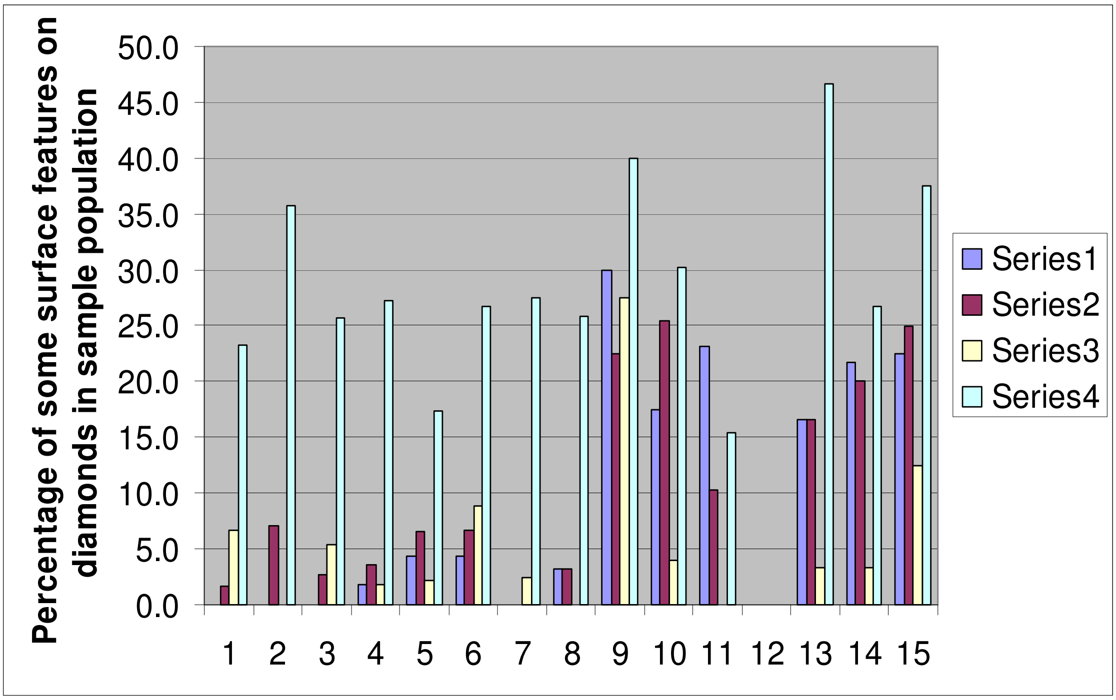


Figure 4.9 Relative abundance of certain diamond surface features: brown spots (**Series 1**), diamonds with green spots (**Series 2**) nearly colourless diamonds (Series 3) and brown, deformed diamonds (**Series 4**) in the sample populations studied between the Richtersveld and the Olifants River (horizontal bar not to scale). Details from Tables 4. 4 and 4.5.

LEGEND FOR LOCALITIES LISTED IN FIGURE 4.9

Number in Figure 4.9	Locality
1	Basal gravel, proto-Orange River, Baken Mine
2	Upper gravel, proto-Orange River, Baken Mine
3	Samples 1 and 2 combined
4	Marine Concession 3B
5	Marine Concession 5A
6	Hondeklipbaai Bay, Surf Zone
7	Hondeklipbaai Mine (onshore)
8	Marine Concession 7A
9	Marine Concession 11A
10	Graauw Duinen (Namakwa Diamonds, onshore)
11	Marine Concession 12A, Surf Zone at Geelwal Karoo
12: No study on surface features	Marine Concession 12A
13	Deeper part of Marine Concession 12A
14	Marine Concession 12A: vicinity of De Punt
15	Marine Concession 13A/Papendorp

Green and brown spots.

The presence of green and brown spots in the outer 20µm of natural diamonds was discussed in 4.1.4(iv). It has been shown that while green spots (the result of α-particle radiation) are common in many kimberlitic and alluvial diamond populations, brown spots are indicative of heat events that affected the diamond subsequent to the development of the green spots. In view of the geological history of southern Africa, it has been concluded that these brown spots confirm a pre-Karoo emplacement age for the source kimberlite(s). It stands to reason that all diamonds liberated from pre-Karoo kimberlites will not necessarily feature brown spots, only those that acquired green spots prior to being subjected to a heat event.

In Table 4.4 it can be seen that the Mid-Orange and Lower Orange populations (Saxendrif/Brakfontein and Baken) are devoid of brown-spotted diamonds. This could imply the absence of diamonds from pre-Karoo kimberlites from these populations, since green-spotted diamonds do occur in all the known diamondiferous pre-Karoo kimberlites in southern Africa (pers. comm., D.N. Robinson, 2002). However, diamonds with polished surfaces (that could also imply a Pre-Karoo emplacement age) do comprise 3.3% of the sample population from the basal gravel at Baken Mine.

The apparent absence of brown-spotted diamonds from the Orange River sample populations can also be a function of the drainage evolution of the Orange River. Jacob (2005) showed that the sedimentary clast population of the Orange River valley change from being Vaal River dominated in the Eocene to locally-dominated (his study area being from Vioolsdrif to Oranjemund) by the Mid-Oligocene. During the course of this study (Clast lithology and roundness tables in 8.1.2) abundant lydianite clasts (altered Karoo-aged mudstone) were found in the Miocene-aged samples. This implies that the incision of the Upper and Middle Orange River had during the Early Miocene not gone through the basal Karoo strata yet, and could therefore not have sampled diamondiferous debris from Dwyka Group glacial deposits in that region.

In comparison, the Lower Orange River transects the south-western edge of the Karoo-aged Nabas Basin in southern Namibia. Being very close to the study area of Jacob (2005), it is possible that incision by the palaeo-Orange River could have gone through the basal Karoo rocks of the Nabas Basin in Miocene times. This could account for the small percentage of diamonds with polished surfaces found at Baken Mine. Since it cannot be expected that the glacial rocks of the Dwyka Group occurring in different geographic regions contain diamonds from the same primary sources, it stands to reason that the Dwyka sediments in the Nabas Basin could harbour pre-Karoo emplaced diamonds that were never exposed to radio-active attack and consequently do not show green or brown spots, while their exposure to atmospheric erosion agents for a prolonged period of time did impart their polished surfaces.

Diamonds from Plio-Pleistocene deposits along the Upper and Middle Orange River valley, that would potentially have transported material during or after the incision through the basal Karoo rocks, were not available for this study.

Table 4.4 and Figure 4.9 show that brown-spotted diamonds comprise between 16.6 and 30% of the sample populations from Marine Concession 13A immediately south of the Olifants River, to Marine Concession 11A. There is a marked change in these percentages between Marine Concessions 11A (30%) and 7A (3.2%). The paucity of diamond samples from Concessions 8, 9 and 10 makes it impossible to determine whether this transition is abrupt or gradual. It is however clear that the sample populations southwards from Marine Concession 11A (and perhaps somewhat to the north thereof) were sourced from Dwyka Group glacial rocks and/or older conglomerates. The northern populations received only limited input from pre-Karoo secondary sources *via* relatively short drainages flowing down the Escarpment. These aspects are discussed further in Chapter 5.

The only alluvial diamond populations studied and found to be totally free from green and brown spots, are that of the Hondeklipbaai land operations and the Holfontein deposit near Randfontein. The Hondeklipbaai deposits are seen as equivalent to the neighbouring Koingnaas mine on the grounds of geographic location, diamond characteristics and the fact that both sets of deposits are found in palaeo-channels with kaolinized bedrock. The Koingnaas diamond population is also virtually free of green and brown spots (pers. comm., D.N Robinson, 2002). The sample population – 100 stones - from the northern Skeleton Coast contained only 2 green-spotted, and 2 brown-spotted diamonds (Figure 4.10).

Figure 4.10 Four diamonds with green or brown spots, northern Skeleton Coast, Namibia.

The Samada kimberlitic sample population reveals no green or brown spots, while the diamond samples from the two alluvial deposits Christiana and Sydney-on-Vaal, down-gradient and in close proximity (90 km as the crow flies) to Samada, are also virtually free from green and brown spots.

No diamonds from Lace and Voorspoed (proximal to Samada) were available for this study. Apart from the **non**-correspondence of surface features and NAD characteristics of a number of other well-known Free State and Northern Cape kimberlites or kimberlite clusters with those of Christiana and Sydney-on-Vaal, their localities also negate a link with these two Vaal River occurrences, as illustrated here:

Name	Shortest distance to Christiana
Kimberley Pool	105 km up gradient
Koffiefontein	175 km up gradient
Jagersfontein	212 km up gradient.

Appreciably abraded

It is difficult to scientifically quantify the degree of abrasion. The percentages shown in Table 4.4 merely reflect the number of diamonds revealing this feature, which is present in a specific population.

Detrital diamonds revealing appreciable abrasion of crystal edges probably experienced a transportation history different from that of unabraded diamonds, and the presence of abraded and unabraded diamonds in the same alluvial population could be indicative of more than one source.

Tappert *et al.* (2006) used this feature as an indication of transport distance in a provenance study of 68 alluvial diamonds in Brazil. During this study the author, apart from the other diamond samples listed in Table 1.3, also examined 100 diamonds in the size range 3 – 5 mm from the ROM production at the Konama Mine, Bafi River, Sierra Leone. Nearly 10% of these diamonds studied under the binocular microscope, revealed appreciable abrasion along the crystal edges. Of great interest is the fact that all of these also have fibrous coatings indicating a second crystallization event not affecting the unabraded diamonds. The diamonds from the Bafi River are thought to have been derived from the nearby Koidu kimberlite cluster, but this observation could indicate a different, more distant primary source for a portion of that alluvial population.

The results of the surface feature analyses of this study as listed in Table 4.4 reveal a general correlation between transport distance and abrasion, namely:

(i) The alluvial diamond populations of Christiana and Sydney-on-Vaal located in relative close proximity to their indicated kimberlite host (Samada) reveal no abrasion features, while
(ii) the populations at Bosluispan, Buffelsbank, Hondeklipbaai and some marine areas along the West Coast, distant from any known diamondiferous kimberlite and way off the craton edge, boast the highest percentages (5% to 31%) of diamonds with abraded edges.
(iii) Geographically in between (i) and (ii), only 2.6% of the diamond populations found in the Mid-Orange deposits of Saxendrif and Brakfontein - with indicated source regions in Lesotho, the western Free State and northern Cape – are comprised of abraded diamonds.

However, some distant deposits like the Upper Gravel at Baken, Concession 12A Surf Zone and De Punt are also totally free of abraded diamonds, contrary to the above model. It is therefore suggested that transport distance is not the only aspect to be considered here, but that other factors like transport and post-depositional environmental conditions (and the time spent in a more abrasive environment) would also play a part. Rouffaer (1988) likened the conditions prevailing inside a glacier to those inside a gigantic ball mill, while it is common knowledge that diamonds transported inside a moving solid ice sheet will enjoy a relatively calm journey. Likewise the probability for the infliction of abrasion features in a particular fluvial system will differ dramatically depending on the nature of the bedrock and velocity of flow. Also, larger diamonds should abrade more readily than small diamonds, as has been shown for quartz particles (Krinsley and Doornkamp, 1973). This aspect as well as the possibility of being transported inside a solid ice sheet, could account for the diamonds examined from 12A and De Punt seldom being abraded.

The diamond populations studied from Christiana and Sydney-on-Vaal also reveal no abrasion of crystal edges, and very little abrasion of crystal faces, reminiscent of the diamonds from the nearby Samada kimberlite with similar non-abraded characteristics.

Polished Surfaces

In Section 4.1.4.iii it has been shown that polished surfaces are suspected to be an indication of liberation from old, probably pre-Karoo, kimberlites.

In Section 2.2.6 geological evidence was presented for a source or sources different from the Orange River, for the diamonds occurring along the Skeleton Coast, north western Namibia. In the surface features study on the Skeleton Coast diamonds the most important observation made is that 31% of the population feature polished surfaces, and a further 2% reveal brown spots. This is in agreement with a similar study by D.N Robinson (pers. comm. 2008) on a small parcel of Skeleton Coast diamonds found at Rocky Point. The conclusion is drawn that while the geological and geomorphological evidence shows that the Skeleton Coast diamonds were not derived from the Orange River, the results of surface feature studies show that a significant proportion were derived from pre-Karoo primary sources. In this regard the presence of Dwyka Group outcrops east of the southern parts of the Skeleton Coast, could be significant. Dwyka Group outcrops are absent from the hinterland opposite the 300km stretch of coast line devoid of diamond deposits between Chameis Bay and the Huab River.

4.1.6 Nitrogen in diamond

Mendelssohn and Milledge (1995) pointed out that the intrinsic absorption (4000 – 1500 cm^{-1}) displayed by all diamonds in the mid-infrared range is the result of the inherent two- and three-phonon transitions associated with carbon (Lax and Burstein, 1955). The perfect symmetry of diamonds (diamond being a centrosymmetric crystal) prevents absorption within the one-phonon region of the IR range, in the case of pure (Type II) diamonds. Mendelssohn and Milledge (1995) then referred to the findings of Robertson *et al*. (1934), namely that some diamonds reveal ultraviolet and infrared absorption - classed as Type I (imperfect, nitrogen-bearing) whereas others - Type II (perfect, nitrogen-free) - do not. Type IIa diamonds are virtually free of any substitutional impurities because of the absence of lattice defects that would have afforded the incorporation of impurities, and therefore display only the intrinsic absorption mentioned above. Type IIb diamonds (blue, extremely rare) contain trace amounts of boron which is responsible for absorption in the 2-phonon region at 2460 cm^{-1}.

Navon (1998) pointed out that the most important information that we can derive directly from the diamond crystal itself (apart from its inclusions) are the following:

- Concentration and aggregation state of nitrogen impurities
- The isotopic compositions of carbon and nitrogen.

Subsequent to the work of Robertson *et al. (*1934) referred to above, continued research on diamonds resulted in further subdivisions as set out below. Observation of absorption spectra at different wavelengths when passing infra-red light through a diamond crystal allows the determination of numerous aspects including the total nitrogen content and the aggregation state (see below) of the nitrogen present. These features reveal important aspects about the history of the diamond and its mantle residence prior to being "sampled" by rising kimberlitic or lamproitic magma. Westerlund (2000) interpreted the presence of alternating zones of Type I and Type II compositions within individual diamonds from the Klipspringer kimberlite as the result of growth from alternating fluids (or magmas) comparatively enriched and depleted respectively in C, N and H.

Woods (1986), Harris (1987) and Wilks and Wilks (1991) discussed a further subdivision of Type I diamonds according to the state of nitrogen aggregation in the crystal lattice of the diamonds. Thus in Type Ib the nitrogen is present as single atoms substituting for carbon atoms in the lattice of the diamond crystal. The single nitrogen atom is said to occupy a "C" centre (Evans, 1992). With increasing temperature and/or mantle residence time, the nitrogen atoms diffuse through the crystal, come into contact with other single nitrogen atoms and aggregate to form 2-atom molecules. These are termed "A" aggregates, occupying "A" centres (Davies, 1976). In laboratory experiments it was found that the conversion from "C" to "A" is relatively fast and is controlled by activation energy of ~ 6eV for nitrogen in the cubic growth zones and ~ 4 eV for the octahedral zones (Taylor *et al*., 1996). Collins (1980) stated that aggregation is speedier with increasing N content. J. Gurney (personal communication, July 2005) ascribes this phenomenon to the fact that at higher concentrations single N atoms finds a mate more easily. An idea of the difference in aggregation rate at different N concentrations was given by Evans (1992). Experimentally derived aggregation constants were used to illustrate that heat treatment for 400 minutes at 1500°C would result in an aggregation state of 24% if the initial concentration was 100 ppm and 43% if the initial concentration was 250 ppm.

As soon as aggregation commences the diamond no longer belongs to the Type Ib group, but becomes part of the Type Ia group (small letter "a" for "aggregated"). If 100% of the nitrogen present is in the form of "A" aggregates the diamond is classified as Type IaA (Kiflawi and Bruley, 2000; Woods *et al.,* 1990).

From electron paramagnetic resonance properties Loubser and Van Wyk (1981) suggested that with prolonged mantle residence time and/or increasing temperature further aggregation takes place as pairs of "A" aggregates join to form "B" aggregates each one consisting of 2 pairs of 2-atom molecules or four nitrogen atoms. This observation was supported by the work of Kiflawi and Bruley (2000). If all the nitrogen is present in the form of "B" aggregates, the diamond is classified as Type IaB. Local-density-functional theory was used by Jones *et al.* (1992) to evaluate the structure, vibrational bands and electronic properties for the two point defects seen as possible models of the "A" and "B" centres. These authors reported that their calculations strongly support the Davies and Loubser-Van Wyk models of the "A" and "B" centres respectively as their predicted vibrational and electronic properties are consistent with those observed. Conversion from "A" to "B" centres was shown experimentally to take longer than the conversion from "C" to "A" and seems to be controlled by an activation energy of ~ 7 eV (Evans and Qi, 1982; Evans and Harris, 1989; Taylor *et al.,* 1990; Evans, 1992).

In natural systems variations ranging between Types IaA (characteristic absorption peak at 1282 cm^{-1} with a subsidiary peak at 1215 cm^{-1}) and IaB (displaying absorption at 1174 cm^{-1} and, to a lesser extent, at 1282 cm^{-1}) are common, reflecting the different post-crystallization histories of the Type I diamonds studied. Most natural Type I diamonds seem to have an aggregation state between the above mentioned two types and the term Type IaA-B is applied to these. Thus the following continuum is indicated:

Type Ib $\Rightarrow$ IaA $\Rightarrow$ IaA-B $\Rightarrow$ IaB.

Davies *et al* (1999) disagree with the idea that high temperature and mantle residence time are responsible for aggregation into "mixes of paired and tetrahedral sites" which would constitute the IaA-B state. They see this as the result of deformation, as suggested *inter alia* by Evans (1992). However, these phenomena occur in both undeformed and deformed diamonds and it would rather appear as if deformation is responsible for structural features that are conducive to aggregation.

Occasionally so-called N3 centres developed (Loubser and Wright, 1973). Davies *et al.* (1998) suggested that this was the result of the clustering of small amounts of nitrogen on {111} planes during annealing events in the mantle. N3 centres show no absorption in the one-phonon region of the IR spectrum, but they do exhibit distinctive absorption in the visible and UV ranges and are thought to be responsible for pale yellow ("Cape Yellow") colouration in diamonds.

Raman and Nilakantan (1940) and Lonsdale (1941) observed anomalous spikes in X-ray diffraction patterns of diamonds. Planar structures (platelets) on the cubic planes ({001}), identified under the electron microscope, were found to be responsible for this phenomenon, as well as for IR absorption at 1359 – 1378 cm^{-1} (Evans and Phaal, 1962; Sobolev *et al.*, 1968). These authors also found that the position of the so-called "platelet peak" (on the spectral graph) seems to be dependant on the size of the platelets, with the larger platelets being associated with lower wave numbers. According to Evans and Qi (1982) platelets vary in size from 8nm to a few µm. The formation of the "B" aggregate seems to provide the mechanism for their formation (Loubser and Van Wyk, 1981), and thus the degree of platelet development generally reflects the aggregation state. Platelet development can be measured by the area of the platelets per unit volume. A smaller percentage of the diamonds studied by Loubser and Van Wyk (1981) did not reveal such a correlation and were termed "irregular", as illustrated in Figure 4.1.

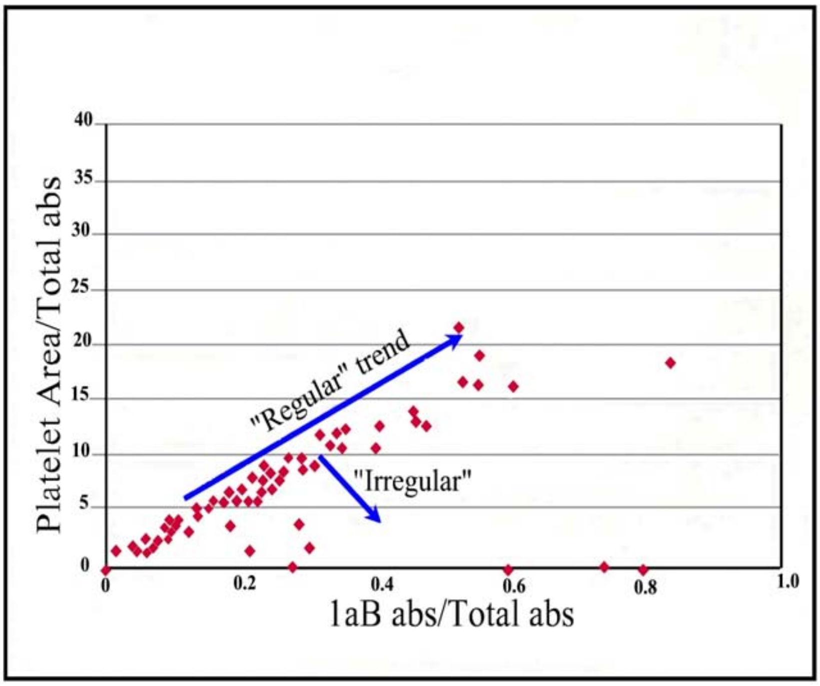


Figure 4.11 Graphic distinction between "regular" and "irregular" diamonds, using the ratio's between the Platelet Area/Total absorption at 1282 cm^{-1} and Total 1aB absorption/Total Absorption at 1282 cm^{-1} (composed from data in McKenna , 2004).

It was suggested that secondary processes such as plastic deformation were responsible for the destruction of the platelets, and such diamonds could be indicative of kimberlite emplacement at or near a craton margin (Viljoen, 2002). While Mendelsohn and Milledge (1995) ascribed the destruction of platelets to catastrophic heat events, it is also true that higher temperature would have been conducive to plastic deformation. Thus the presence of "irregular" diamonds seems to indicate a post-crystallization process and since they are not ubiquitous among different diamond populations, the presence of irregular diamonds may have a diagnostic value in terms of provenance recognition (Viljoen, 2002). Among the known diamondiferous kimberlites in southern Africa, only Letseng (Viljoen, pers. comm., 2008) and Samada (this study) reveal the presence of irregular diamonds as a significant percentage of their diamond populations.

Finally, high-temperature annealing of type IaB diamonds containing platelets apparently causes the conversion of the platelets to dislocation loops and voidites; this process represents the ultimate stage of nitrogen aggregation in diamond (Kiflawi and Bruley, 2000).

In summary:

- In Type I (nitrogen-bearing) diamonds single N atoms occupy defect positions and the diamond is termed type Ib. They are very rare in nature, but most synthetic diamonds belong to this group, probably because these diamonds do not reside for prolonged periods of time in a high temperature environment after crystallization.
- Due to the high temperatures prevailing in the mantle the single N atoms migrate and combine to form 2-atom pairs, called "A" aggregates. A diamond in which all the nitrogen is in this form is termed Type IaA (the small letter "a" here denotes "aggregated").
- With prolonged residence time, "B" aggregates form by the combination of two "A" aggregates. A diamond in which all the nitrogen is present in this form is termed Type IaB.
- Since most natural diamonds underwent some degree of nitrogen aggregation, but few reached the final stages, the majority of natural Type I diamonds contain an intermediate mixture of the A and B aggregates and belong to Type IaAB. McKenna (2001) reported the presence of both types Ib and IaA components in a single, zoned diamond from the Helam Mine near Swartruggens.

- In Type IaB diamonds containing platelets, the conversion of the platelets to dislocation loops and voidites can occur because of high-temperature annealing.

Diamonds free or virtually free of substitutional trace elements are termed Type IIa (the small letter "a" in this instance has nothing to do with aggregation). Type IIb is also free or virtually free of nitrogen, but contains trace amounts of boron which is thought to impart the colouration to blue diamonds as mentioned in 4.1.2.

4.1.7 Infra-red Analyses

Most methods used for analytical work on rocks and minerals are of a destructive nature. A non-destructive method entailing the use of infra-red light to measure among others the quantity and state of molecule aggregation of nitrogen in diamond (discussed in Section 4.1.5) was developed during the latter half of the 20^{th} century.

Kaiser and Bond (1959) demonstrated a positive correlation between the "A" defect absorption peak at 1282 cm^{-1} and nitrogen content determined by mass spectrometry. The presence of "B" defects (Boyd *et al.,* 1995) causes IR absorption at 1174 cm^{-1} and also contributes to the absorption peak at 1282 cm^{-1}. These are obtained by subjecting the optical features obtained when passing IR light through the diamond to certain mathematical manipulations. Fourier's transform features prominently, hence the term Fourier Transform Infrared (FTIR) analyses. The method can be further illuminated by observation of the definitions offered by Parker (1989), namely

Fourier transform: For a function f(t), the function F(x) equal to $1/\sqrt{2\pi}$ times the integral over t from $^{-x}$ to ^{x} of f(t) exp (it); and

Fourier Transform Spectroscopy: A spectroscopic technique in which all pertinent wavelengths simultaneously irradiate the sample for a short period of time, and the absorption spectra is found by mathematical manipulation of the Fourier transform so obtained.

Because of limited penetrative capability of infrared (IR) light, as well as the cumulative effect that high nitrogen concentrations in a thick diamond section has on the nitrogen spectral peak, only very small diamonds (preferably < 0.1ct) are suitable for these analyses and the samples to be analyzed should also not be so full of impurities that they become totally opaque.

Mendelsohn and Milledge (1995) and Taylor *et al.* (1990) suggested that experimentally-derived activation energies for the various stages in the sequence of nitrogen aggregation can be used in conjunction with the nitrogen concentration in the diamond under investigation to estimate the residence time and/or temperature involved. Since the range of temperatures prevailing in the mantle is reasonably well known, *e.g.* as estimated from mineral inclusions in diamonds, the time that a diamond spent after crystallization in the mantle can be arrived at. There are, however, a number of uncertainties involved, namely:

- The method assumes that the aggregation proceeded in accordance with second order kinetics.
- Calculated temperatures are time-averaged.
- Evans (1992) suggested that plastic deformation of diamonds may enhance the rate of nitrogen aggregation.
- The results are very sensitive to the temperature assumed.

A useful method for characterizing the diamonds in a population is found in the ratio between the total nitrogen present and the percentage of that total that is present in the form of the "B" aggregate. When such ratios are plotted on a diagram (called the Nitrogen Aggregation Diagram, from here on referred to as NAD) specific fields may become apparent. Quite understandably much overlap is to be expected between different populations. In this study therefore, the Fourier Transform Infrared analyses are used essentially to characterize the diamond populations from different occurrences, and to compare these with the characteristics reflected in similar parameters for diamond populations from known kimberlites.

Diamonds from a particular primary source reveal a wide range of total nitrogen content and nitrogen aggregation state and therefore a primary population is not characterized by any single analysis, but rather describes a specific field on the nitrogen aggregation diagram (NAD). Similarly single diamond analyses from an alluvial source cannot be used to indicate a possible primary source, neither should one expect to find an alluvial deposit that received diamonds from various primary sources that mirrors the NAD characteristics of any individual primary source. As a result groupings on the NAD's will be used to assist in the correlation. In addition microscopic surface features and rare properties such as elevated nitrogen content (> 1600 ppm among the populations studied), amber-coloured cubo-octahedral diamonds, highly aggregated low-N diamonds like those found at Venetia and the presence of "irregular" diamonds will contribute to characterize diamond populations and provenance identification.

4.1.8 FTIR analyses of diamonds in this study

The processing of the raw IR data is described fully in Section 8.2. To elucidate the interpretations applied in this study, a brief résumé of the criteria used in scrutinizing the results is presented here. The deconvolution programme, kindly provided by Dr David Fisher of the Diamond Trading Company Research Centre, Maidenhead, England, uses a pre-programmed formula with some of the acquired data to model an ideal spectrum for the particular analysis. It then uses all the acquired data to construct the actual spectrum.

Concordance between the ideal spectra and the actual model is required for the result to be acceptable. In addition, the curve should be smooth; an irregular, saw-tooth appearance (often caused by over-saturation of nitrogen in the diamond section analyzed) is unacceptable. Visual observation of the spectra generated by a particular analysis allows this distinction (Figure 4.12).

During this study up to 12 analyses were performed on a single diamond before an acceptable result was obtained, or it was realized that the particular diamond had to be omitted from the FTIR study. After scrutiny of more than 6000 spectra, 15.63% of the diamonds analysed were thus omitted, essentially, because of the cumulative effect of thick diamond sections (not enough <0.1ct diamonds available) and inherent high nitrogen values that caused over- saturated nitrogen peaks.

In Figures 4.12A, 4.12B and 4.12C the principles underlying the visual distinction between ideal and unacceptable spectra are graphically illustrated.

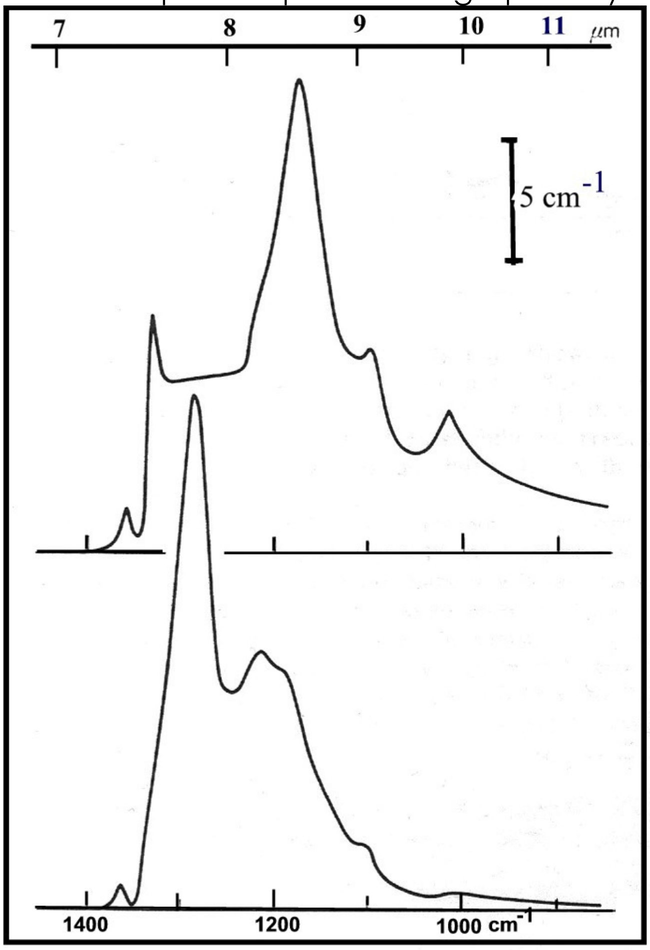
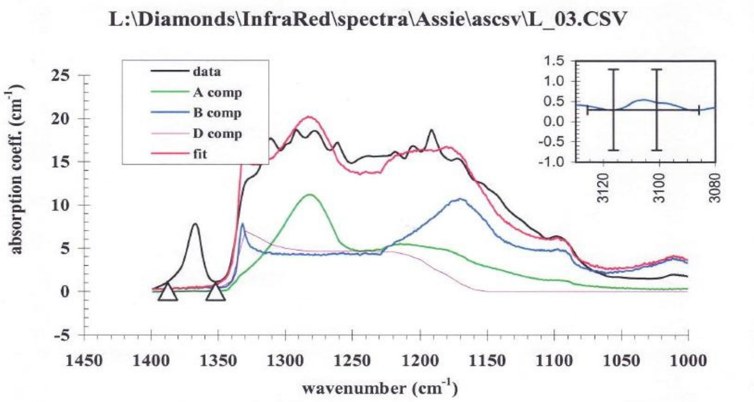


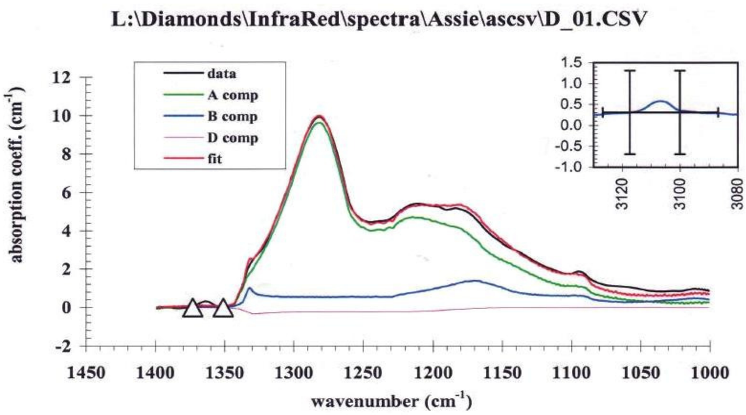
Figure 4.12A: Ideal infrared absorption spectra of diamonds. The upper part of this figure illustrates a situation where the extreme B component causes absorption spectra at 1174 cm^{-1} and, to a lesser extent, at 1282cm^{-1}. The extreme A component (bottom) reveals a characteristic absorption peak at 1282cm^{-1} with a subordinate peak at 1215 cm^{-1} (Davies, 1980).



Area statistics	Lower limit	Upper limit	Base	Area
Platelet peak	1351.90	1387.60	1.10	92.00
Hydrogen peak	3101.00	3116.50	0.29	2.50

IaA u(1282)	11.21	IaA NA	185.00	P. Peak	1367.31
IaB u(1282)	4.21	IaB NB	334.60	P. Area	92.03
D u(1282)	4.69	NT	519.60	H. Peak	3105.80
fit u(1344)	1.71	%B	64.40%	H. Area	2.50

Figure 4.12B: Example of unacceptable spectra with ill-defined, ragged peaks (the "data" line, in black) and discordant "fit" (red line). (This study, sample L_03 from proto-Orange River gravel, Reuning Mine).



Area statistics	Lower limit	Upper limit	Base	Area
Platelet peak	1350.90	1373.10 .		3.40
Hydrogen peak	3100.10	3117.40	0.31	2.60

IaA u(1282)	9.65	IaA NA	159.23	P. Peak	1363.45
IaB u(1282)	0.55	IaB NB	43.77	P. Area	3.44
D u(1282)	-0.22	NT	202.99	H. Peak	3106.80
fit u(1344)	0.19	%B	21.56%	H. Area	2.60

Figure 4.12C: Example of acceptable spectra obtained during this study (Sample D_01, diamond from basal proto-Orange River gravel In Trench PK46, Baken Mine).

The development and significance of irregular diamonds as deduced from the FTIR analyses are discussed in 4.1.6: Nitrogen in Diamond. The results of all the FTIR analyses are depicted and fully discussed in Section 8.2 (on CD), while those from the Graauw Duinen diamond population is presented here to illustrate some salient points with respect to the FTIR analyses, and their interpretation.

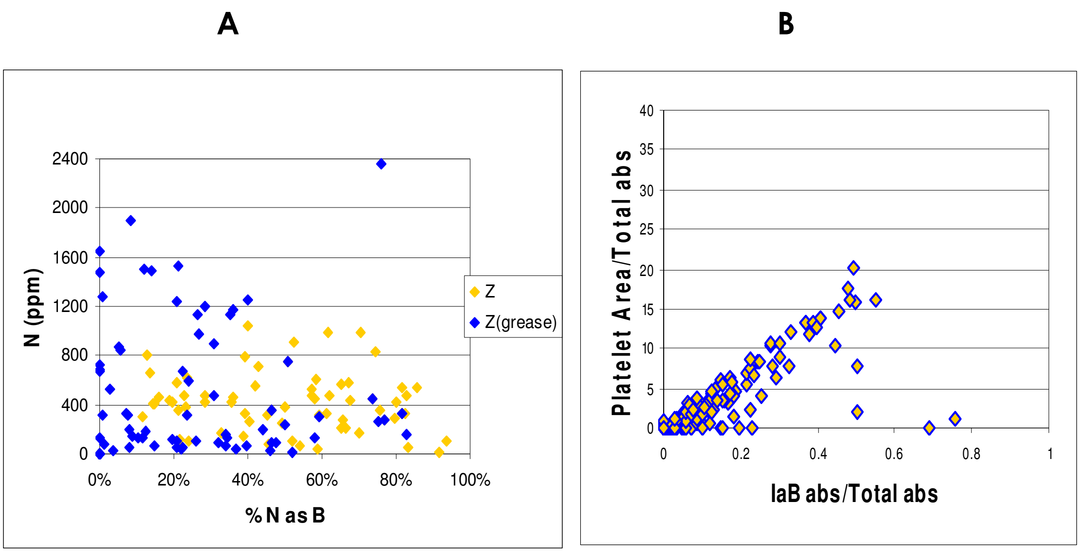


Figure 4.13: NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Graauw Duinen (raised marine beach).

This NAD demonstrates the difference between diamond recoveries made from the same alluvial deposit using X-ray technology only (gold coloured symbols) and those recovered by grease from the X-ray tailings (blue).

The blue dots represent diamonds produced from a tailings dump generated over a period of more than a year, comprising a much larger run-of-mine gravel resource than the week's production represented by the gold-coloured dots on the NAD. Therefore the relative abundance of blue dots on the NAD may be biased.

While it is to be expected that low-nitrogen diamonds would tend to evade X-ray recovery and be preferentially recovered by the grease system, an important observation on this NAD is that a significant number of diamonds with >800ppm nitrogen initially evaded recovery by X-ray technology. The most likely explanation for this phenomenon is:

- Nitrogen content is only one of the parameters that determine the probability for the diamond to be recovered by X-ray technology; of greater importance is the state of nitrogen aggregation because an aggregate of nitrogen molecules would be responsible for a more obvious luminescent signal than single nitrogen atoms or molecules. Some nitrogen molecules are also arranged in platelets which would enhance the possibility of its luminescent signal to be picked up by the optical sensor of the X-ray recovery equipment. In Figure 4.13 it can be seen that with one exception all the diamonds containing more than 800ppm nitrogen but missed by the X-ray machine, have nitrogen aggregation states of only 40% or less.

- Nitrogen molecules and aggregates are not disseminated evenly through the crystal lattice of the diamond, as illustrated by the results of single particle analyses performed by the author on 723 diamonds from the Lower Orange River (Van der Westhuizen, 2003b). Significant differences in the strength of the luminescent signal were recorded by examining the same diamond from different sides. Thus a diamond emanating a strong luminescent signal can go through the X-ray machine undetected, if the side not harbouring the nitrogen platelet or molecule cluster faces the sensor. While the short wave x-rays can penetrate up to 25 mm into the subject matter, the electro magnetic waves responsible for the luminescent "glow" detected by the optical sensor of the X-ray recovery system comprise long wave rays with limited penetrative abilities that will not always be detectable from all sides of the crystal.

Interpretation of the results from the Graauwduinen NAD with respect to provenance identification follows in 8.2.2 with the rest of the sample populations.

4.1.9 Overview of the results of the diamond study

The most outstanding observation made when comparing the various nitrogen aggregation diagrams with microscopic features of diamonds, is a definite correlation between deformed, brown diamonds in these sample populations and total nitrogen content. At each locality the deformed, brown diamonds seem to be restricted to a total nitrogen content of ≤ 500 (< 400 in the majority of cases) ppm. The aggregation state of the brown diamonds under discussion shows no concomitant relationship. It would thus appear that the brown colouration tends to appear as soon as deformation occurs regardless of the state of aggregation achieved, although aggregation will be enhanced by the plastic deformation, as noted by Evans (1992). At the same time this observation supports the suggestion by Wilks (1958) that nitrogen in diamond tends to prohibit plastic deformation. A predisposition of low-nitrogen diamonds to the effects of deformation has been suggested for certain Australian diamonds by Davies *et al.* (1999). Similar observations were made among the diamonds from the Helam Mine by McKenna (2001).

Figure 4.9 shows that, especially in terms of the relative abundance of brown-spotted diamonds in the different West Coast populations, two distinct groups are present, *viz.* a southern group depicted by the samples from Marine Concessions 13A, 12A, 11A and Graauw Duinen with a somewhat variable, but generally high (16% – 30%) content of brown-spotted diamonds and a northern group (~4% - <2% brown spotted diamonds) depicted by samples from Marine Concessions 7A, 7A Hondeklipbaai Surf Zone, 5A at the Buffels River estuary, 3B and the Arrisdrif Gravel Formation at the Baken Mine with Marine Concession 7A located near its southern end. If the coastal stretch covered by Concessions 8, 9 and 10 from where no diamonds were available for this study should be ignored, a steady decline in the relative abundance of brown-spotted diamonds from south to north is indicated. Whether this transition is gradual or sharp, the presence of at least two distinct populations has been established.

It is concluded that the most prolific supply of brown-spotted diamonds reached the Atlantic Ocean between Marine Concessions 13 and a point or region between Concessions 11 and 7. It has already been shown that brown spots are, in the context of southern Africa, proof of pre-Karoo emplacement.

Should the percentage of non-spotted diamonds revealing polished surfaces also be taken into account, the indicated percentage of pre-Karoo emplaced diamonds in the southern group is significantly higher. It is suggested that the high incidence of diamonds with a pre-Karoo emplacement age in this region is the result of glacial transport of such diamonds from the northeast to the southwest of the subcontinent. The role of post-Karoo drainages like the postulated Gamoep River of Malherbe *et al.* (1986) in the south- to southwesterly transportation of diamonds liberated from Jurassic and Cretaceous kimberlites, contributed towards the mixed nature of the diamond population at, *e.g.,* Graauw Duinen.

The sample populations south of Marine Concession 7A not only received a much higher input from pre-Karoo kimberlites, but derivation from primary sources from diverse cratonic settings is also indicated. Thus a portion of the Graauw Duinen population, including some amber-yellow cuboid diamonds, is linked to the poorly aggregated field described by the Helam (Swartruggens) population of this study. This postulated link is based upon the said overlap of a part of the nitrogen aggregation field, as well as the fact that Helam has an anomalously high – in the context of southern African kimberlites - incidence of cuboid, amber-yellow diamonds.

The aspects discussed above are graphically illustrated in section 8.2.2, where the Graauwduinen and Orange River NAD's are compared with those of mixed sample populations from different primary sources.

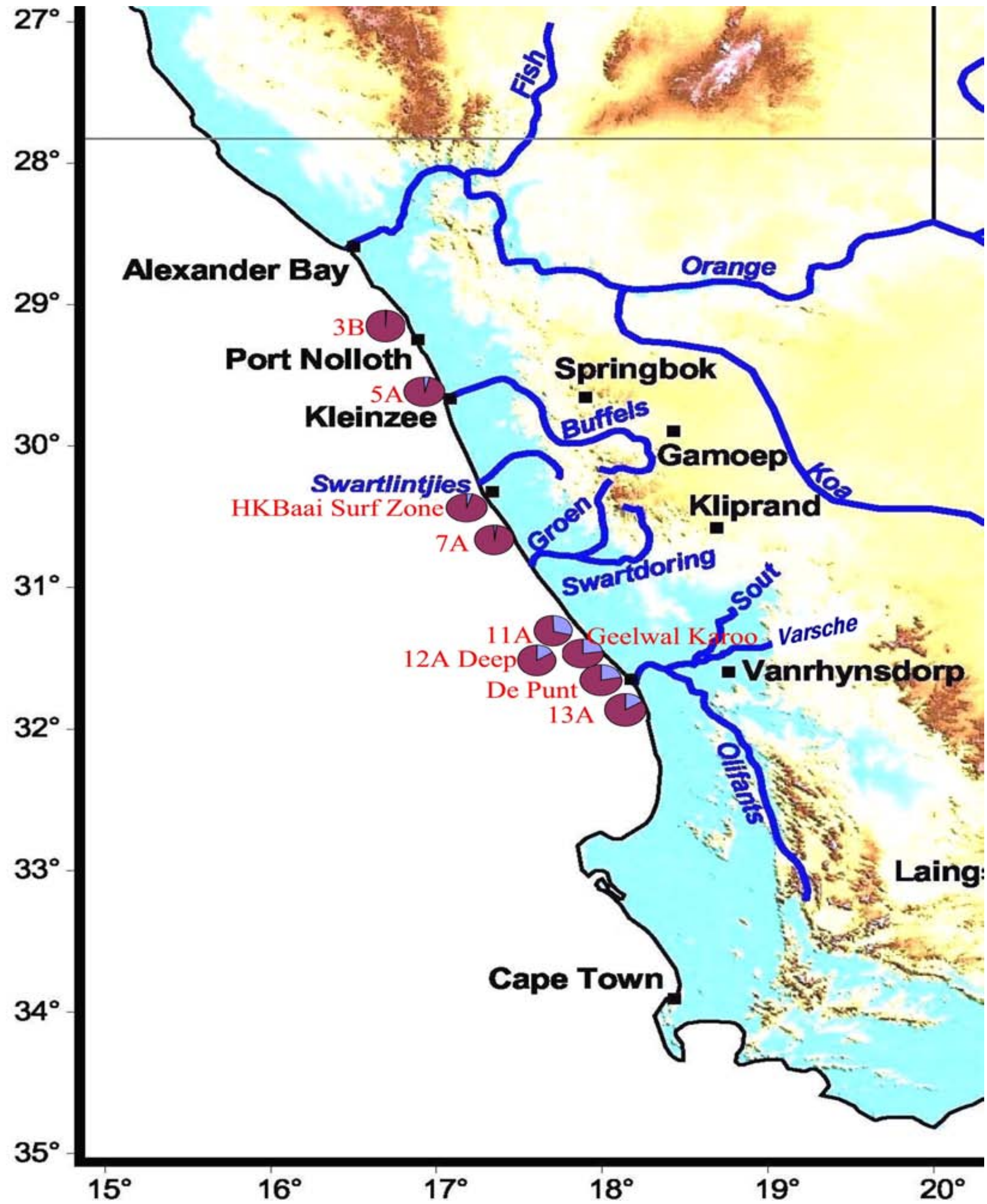


Figure 4.14 South African West Coast with pie charts showing percentage of brown spotted diamonds (blue-grey) versus other diamonds (maroon) at sampling localities between Marine Concessions 13A and 3B

A further observation regarding the southern population is the apparent negative correlation between total nitrogen content and nitrogen aggregation state observed at Graauw Duinen. A similar pattern has only been observed in the diagrams of Roberts Victor, Jagersfontein and Letseng. Letseng and Samada are the only two primary sources included in this study where significant numbers of irregular diamonds occur. The presence of irregular diamonds, with very restricted primary source regions as mentioned above, links Letseng and Samada to a portion of the Graauw Duinen diamond population.

The deposits from either side of the Olifants River (12A-De Punt, 12A Deep and 13A) are characterized by the almost total absence of diamonds with a nitrogen aggregation state of less than 25% - 30%. After elimination on the basis of the indicated pre-Karoo age of the diamonds and the features of the nitrogen aggregation diagrams, it has been concluded that among the known kimberlites in southern Africa only Premier could be considered as a likely primary source for these diamonds. The absence of poorly aggregated diamonds at 12A De Punt, 12A Deep and to a lesser extent 13A however then needed to be explained. This aspect was addressed in terms of the geology of the Premier Mine, in Section 8.2.3, but it must be conceded that diamonds (no sample population available for this study) liberated from the basal marine conglomerate of the Table Mountain Group northeast of Van Rhynsdorp (Baxter-Brown, 1963b) could also have contributed to this peculiar population.

In the discussions of the various nitrogen aggregation diagrams attention was drawn to the fact that the diagram of the Hondeklipbaai land operations (Figure 8.46, Section 8.2.3) differs quite conspicuously from that of the Hondeklipbaai Surf Zone (Figure 8.49), while the latter reveals great similarity with those from the Orange River samples, Marine Concession 3B and Marine Concession 5A (with an additional input from the Buffels River indicated). From this similarity and the difference in the content of brown-spotted diamonds, it is concluded that the primary sources for most of the diamonds in the above-mentioned alluvial deposits with the exception of the Hondeklipbaai land operations have similar cratonic settings, but belong to different age groups.

The absence of green- and brown-spotted diamonds as well as the nature of the nitrogen aggregation diagrams put the Hondeklipbaai land operations apart from the other sample localities. The only other localities that formed part of this study from which brown-spotted diamonds are absent are Klipgat north of Ventersdorp, the Mid- and Lower Orange River and the kimberlitic population of Samada, where both green and brown spots are absent, which is not uncommon among kimberlites. The Klipgat sample population was however extremely small, and nearby Nooitgedacht, with a sample population of 122, does contain a low percentage of brown-spotted diamonds. All these alluvial localities do contain green-spotted diamonds, leaving Hondeklipbaai Land Operations as the only alluvial sample locality lacking both green- and brown-spotted diamonds. A different source is indicated.

Alternatively, it could be reasoned, these diamond populations came from mutual kimberlite hosts, but subsequent to being liberated from the kimberlite, the diamond population of the Hondeklipbaai land operations escaped the type of sedimentary environment where the other diamonds developed green spots in reaction to α-particle bombardment. However, the NAD which indicates mantle residence time and conditions, also distinguishes this particular population from the rest and so does the zircon evidence from the neighbouring Koingnaas, as reported by Rozendaal *et al.* (2002).

It is proposed that these diamonds were transported to this region by a non-marine route and accumulated in deeply incised channels. In Miocene times the area was bevelled and reworked during a marine transgression. While this transgression was responsible for the distribution of lighter marine clasts, shells, shark's teeth and other typical marine components over the area under discussion, it was not vigorous enough to move heavy minerals like diamond to those elevations, otherwise the diamond populations of the Hondeklipbaai surf zone and the land operations would not have differed so dramatically from each other. This view finds support in the fact that the diamond population of the channel deposits on the neighbouring Koingnaas is characterized by an almost complete absence of green and brown spots, reminiscent of those from the Hondeklipbaai Mine. Clasts of banded iron formation were found in the basal parts of one of these deeply kaolinized features.

The Hondeklipbaai surf zone and Marine Concession 5A have comparable concentrations of brown- and green-spotted diamonds, with a conspicuous decline discernible from 5A further north to 3B.

While the NAD of Concession 5A's diamond population reveals a significant similarity to that of the Richtersveld population (Miocene Orange River), it does also contain some brown spotted and non-spotted, polished diamonds (1.8% and 8.7% respectively of population studied) which are conspicuously absent from the Orange River samples except for 3.3% polished stones at Baken Mine. This seems to indicate a mixed diamond population transported seaward by the Buffels River (0.3% and 1% brown spotted diamonds at Buffelsbank and Langhoogte respectively – Robinson, 1979). The Buffels River has its headwaters in the Kamiesberg while its major tributary, the Schaapf/Doring River, originates on the northern extension of the Western Escarp, and one of the most likely sources for some of its diamonds would be the Dwyka glacials that once covered this part of the subcontinent, with a possible contribution from the Bosluispan deposit as described in the next paragraph.

While the landscape was being denuded palaeo-drainages like the palaeo-Gamoep River of Malherbe *et al.* (1986) could also have transported diamonds from Cretaceous kimberlites in the hinterland to the catchment area of the Buffels, giving rise to a mixed population derived from both pre-Karoo and Cretaceous kimberlites.

The results of the study on the Bosluispan diamonds provide further evidence in support of a link between the Buffels and Koa River diamond populations. The link with the Cretaceous kimberlites of Letseng and Samada indicated by the presence of irregular (8.6%) diamonds supports the observations by De Wit (1993) concerning the occurrence of diamonds in the Sak River and Carnavonleegte south of Brandvlei and Van Wyksvlei resting on top of Karoo Supergroup sediments, as is expected of diamonds liberated from kimberlites with a post-Karoo emplacement age. He also remarked on the similarity between the Sak River and Bosluispan diamond populations. One important difference between these two populations however, is the presence of a small percentage (1.7%) of brown-spotted and 3.5% polished stones at Bosluispan (this study), which are completely absent from the Sak River population (pers. comm. D.N. Robinson, 2007). Bosluispan is located topographically lower than the surrounding exhumed Dwyka Group glacial deposits, the obvious source for this small percentage of pre-Karoo emplaced diamonds. This mixed population is reminiscent of the diamond populations found along the valley of the Buffels River and at the Buffels River estuary in Marine Concession 5A. The latter occurrence contains diamonds common to Bosluispan and the Buffels River, but foreign to the rest of the West Coast as studied north of Marine Concession 8A.

The diamond populations from Holfontein, Uitgevonden and the Skeleton Coast were available for surface feature studies only since logistic constraints precluded FTIR analyses on these. The results of their surface feature studies are included in Tables 4.4 and 4.7.

Interpreting the results of the different alluvial diamond populations studied the possible link between Jwaneng and Orapa with some of these alluvial deposits were noted. This indicated relationship with the diamond populations in the Lower Orange River and Marine Concessions 3B to 7A could be seen as support for the former existence of a palaeo-Kalahari River as suggested by Behr (1989) and De Wit (1993). However, the presence of diamonds with similar characteristics in the Middle Orange River, Bosluispan and Graauw Duinen would argue against the existence of a major Kalahari River as postulated, because such a major drainage would have acted as a barrier for south-bound Botswana diamonds. Their presence in the above-mentioned three localities proves that they reached the catchment of the Gamoep River. Transportation for these diamonds *via* a former south-bound drainage and the Gamoep River to all the localities where they are currently found could have taken place in the absence of a Kalahari River, and it is concluded that the postulated Kalahari River either never existed, or that it developed at a much later stage, after significant quantities of Botswana diamonds were transported by south-bound drainages to the catchment area of the Gamoep River.

The above conclusions, summarized in Table 4.7 find strong support in the results of a study by Phillips & Harris (2008) referred to in Section 1.2. Their "Namaqualand" sample comprised 48 diamonds from the Buffels River valley and Dreyer's Pan immediately north of the Buffels River estuary (Phillips, pers. comm. August 2009), and - in terms of a long shore distribution - geographically corresponds to the sample from Marine Concession 5A of this study. (They also studied a small parcel of diamonds from Oranjemund, which is not included in this study). A comparison of results shows the following:

TABLE 4.6 COMPARISON BETWEEN RESEARCH RESULTS OF PHILLIPS AND HARRIS (2008) ON A COMBINED DIAMOND SAMPLE FROM CONCESSION 5A AND THE BUFFELS RIVER, AND THAT OF CONCESSION 5A FROM THIS STUDY

Locality	**% Pre-Karoo diamonds**	***Remarks by the authors***
Phillips and Harris (2008)	"< 14"	*Similarity to Orapa mentioned, but with a significant >220 Ma component not present in the Orapa population*
Concession 5A (this study)	*4.4 brown-spotted and additional 8.7 with polished surfaces = 13.1%*	*Derivation from Kimberley area, as well as from Jwaneng and Orapa concluded*

In this study the possible link between Orapa-Jwaneng and Concession 5A was postulated on the basis of NAD characteristics. The fact that such a link is also suggested by the results of a different analytical method by different researchers provides supportive evidence to the results of this study.

The comparison of indicated pre-Karoo kimberlite emplacement ages between the two populations also yields an acceptable result. The $^{40}Ar/^{39}Ar$ analyses of clino-pyroxene inclusions would identify all such diamonds that came from pre-Karoo kimberlites, but it is not sure what percentage of the total population is comprised of stones with clinopyroxene inclusions. The surface feature studies again, can only identify those containing brown spots and/or polished surfaces. Thus the percentage diamonds liberated from pre-Karoo kimberlites (13.1%) indicated by this study compares well with the "less than 14%" reported by Phillips and Harris (2008), but it must be conceded that, in the light of the points raised above, the actual correspondence between the gross populations may differ.

Of great importance when assessing the West Coast as a whole, is the fact that while the correspondence between the results of the two methods described above was obtained for the 5A area, this study, for the +260 km sector stretching from south of the Olifants River (Marine Concession 13) to Marine Concession 3, comprised 735 diamonds compared to the 48 studied by Phillips and Harris (2008).

A pronounced transition in the number of diamonds with indicated pre-Karoo kimberlite association occurs between Marine Concessions 11A and 7A, with the southern population having orders of magnitude more of these diamonds than the northern population that includes Marine Concession 5A (see Figure 4.14).

Mutual support between the results obtained by Phillips and Harris (2008) and this study has thus been demonstrated for the geographic locality where sample sites overlap. However, their conclusion that "pre-Karoo kimberlite sources provided only minor or negligible quantities of diamonds to the West

Coast deposits" as a whole, is unacceptable in the light of the fact that their sample position is geographically - in the south-north distribution - only a single point sample that cannot be extrapolated over the entire West coast.

TABLE 4.7 SUMMARY OF CONCLUSIONS DRAWN WITH RESPECT TO THE PROVENANCE REGIONS FOR THE DIFFERENT ALLUVIAL DEPOSITS STUDIED.

LOCALITY	*PROVENANCE REGIONS CONCLUDED FROM RESULTS OF FTIR ANALYSES AND SURFACE FEATURE STUDIES*
Mid- and Lower Orange River	*Letseng, De Beers Pool (Kimberley), Rovic, Koffiefontein, Jagersfontein, Samada. Primary sources conspicuously absent: those with a pre-Karoo emplacement age, and Botswana*
Marine Conc. 3B	*Reminiscent of Orange River populations, but with Jwaneng, Orapa and 1.8% pre-Karoo*
Marine Conc. 5A	*Reminiscent of Orange River populations, but with Jwaneng, Orapa and 4.4% pre-Karoo*
Marine Conc. 7A	*Jwaneng, Orapa, Letseng, and to a lesser extent, Koffiefontein and Jagersfontein*
Marine Conc. 7A Hondeklip Surf Zone	*Best comparisons with Jwaneng, Orapa and to a lesser extent, Premier*
Marine Conc. 11A	*Mainly Letseng as well as Helam, Koffiefontein, Jagersfontein, Klipspringer and subordinate contributions from Jwaneng and Orapa; 30% pre-Karoo, probably Premier, and Venetia*
Marine Conc. 12A	*Letseng, Jagersfontein, Klipspringer and 23% from Pre-Karoo: Venetia, Premier*
Marine Conc. 12A De Punt and 13A	*Mainly Premier, with contributions from Letseng and/or Samada*
Hondeklipbaai land	*Unidentified*
Graauw Duinen	*Mainly Samada, Letseng, Helam, Orapa, Kimberley, Finsch; lesser contributions from Jwaneng, Premier, Koffiefontein and Jagersfontein*
Bosluispan	*Letseng and/or Samada, subordinate contributions from Koffiefontein, Venetia and Premier*
Klipgat	*Helam, Orapa (no pre-Karoo stones identified)*
Nooitgedacht *alias* Vetpan	*Helam, Jwaneng, Orapa, Klipspringer Main Fissure*
Christiana	*Samada*
Sydney-on-Vaal	*Samada plus subordinate contribution from unknown source (either via Harts River or the Riverton-Barkly West occurrences)*
Holfontein	*Unidentified sources to NE; 10% with polished surfaces could indicate pre-Karoo sources*
Uitgevonden	*Unidentified sources to the north-northeast; 9.8% with polished surfaces and presence of one stone with brown spots indicate contribution from pre-Karoo sources*
Skeleton Coast	*Average stone size and geology preclude link with Orange River population. High incidence of stones with polished surfaces suggest major contribution from pre-Karoo sources*

4.2 GARNET

4.2.1 General

Garnets crystallize in a wide variety of metamorphic rock types, as well as in some granites, pegmatites, acid volcanic rocks, kimberlites (Deer, Howie and Zussman, 1992) and some lamproites and lamprophyres (Kornilova *et al.*, 1998). Since the mineral chemistry of garnet is determined by the physio-chemical environment in which it crystallizes the above species can to a large extent be used to identify the parent rock. Gurney *et al.* (1993) have shown that the mineral chemistry of garnet can be used not only to distinguish between garnets derived from mantle rocks and non-mantle garnets, but in the case of the former to make qualitative predictions regarding the diamond potential of their source rock. Because of their high resistance to chemical weathering garnets are quite commonly found as detrital grains in sedimentary packages. This aspect makes garnet a natural choice for provenance studies as emphasized by Mange (2002).

TABLE 4.8 TYPICAL PARENT ROCKS OF MORE COMMON GARNET SPECIES Deer, Howie & Zussman (1992)

Garnet species	Typical parent rock	Reference
Pyrope	peridotite, eclogite, kimberlite,	Deer, Howie & Zussman (1992)
Almandine	schist, metamorphosed BIF, granitic aplite, pegmatite, calc-alkali granite and rhyolite	
Spessartine	Skarn deposits, granite pegmatite, aplite	
Grossular	thermally and regionally metamorphosed calcareous rocks, zeolite-bearing vesicles in metamorphosed basaltic lava	
Andradite	contact or thermally metamorphosed impure calcareous (e.g. metasomatic skarn deposits) and igneous rocks such as andesites	
Uvarovite	serpentinite, metamorphosed limestones and skarns	
Hydrogrossular	metamorphosed marls, altered gabbroic rocks, pyroxenite horizons in the BIC	

TABLE 4.9: THE 15 NATURAL AND 14 HYPOTHETICAL (IN ITALICS) GARNET END MEMBERS RECOGNIZED BY LOCOCK (2008)

Henritermierite	$\{Ca_3\}[Mn_2](SiO_4)_2(OH)_4$
Blythite	$\{Mn_3\}[Mn_2](Si_3)O_{12}$
Katoite	$\{Ca_3\}[\ [Al_2](OH)_{12}$
FCa garnet	$\{Ca_3\}[Al_2]()_3F_{12}$
FMn garnet	$\{Mn_3\}[Al_2]()_3F_{12}$
Yttrogarnet	$\{Y_3\}[Al_2](Al_3)O_{12}$
Kimzeyite	$\{Ca_3\}[Zr_2](SiAl_2)O_{12}$
Kimzeyite-Fe	$\{Ca_3\}[Zr_2](SiFe_2)O_{12}$
Tin garnet	$\{Ca_3\}[SnFe](Si3)O_{12}$
Schorlomite	$\{Ca3\}[Ti_2](SiFe_2)O_{12}$
Schorlomite-Al	$\{Ca_3\}[Ti_2](SiAl_2)O_{12}$
Morimotoite	$\{Ca3\}[TiFe](Si_3)O_{12}$
NaTi garnet	$\{Na_2Ca\}[Ti_2](Si_3)O_{12}$
Morimotoite-Mg	$\{Ca_3\}[TiMg](Si_3)O_{12}$
Morimotoite-Fe	$\{Fe_3\}[TiFe](Si_3)O_{12}$
Majorite	$\{Mg_3\}[SiMg](Si_3)O_{12}$
Sc garnet	$\{Ca_3\}[Sc_2](Si_3)O_{12}$
Goldmanite	$\{Ca_3\}[V_2](Si_3)O_{12}$
Yamatoite	$\{Mn_3\}[V_2](Si_3)O_{12}$
Uvarovite	$\{Ca_3\}[Cr_2](Si_3)O_{12}$
Knorringite	$\{Mg_3\}[Cr_2](Si_3)O_{12}$
Spessartine	$\{Mn_3\}[Al_2](Si_3)O_{12}$
Pyrope	$\{Mg_3\}[Al_2](Si_3)O_{12}$
Almandine	$\{Fe3\}[Al_2](Si_3)O_{12}$
Grossular	$\{Ca_3\}[Al_2](Si_3)O_{12}$
Andradite	$\{Ca_3\}[Fe_2](Si_3)O_{12}$
Calderite	$\{Mn_3\}[Fe_2](Si_3)O_{12}$
Skiagite	$\{Fe_3\}[Fe_2](Si_3)O_{12}$
Khoharite	$\{Mg_3\}[Fe_2](Si_3)O_{12}$

Using the oxides of Ti, Cr, Fe, Mg and Ca, Dawson and Stephens (1975, 1976) conducted a statistical (cluster) analysis on garnets from kimberlites and associated xenoliths which allowed them to classify mantle derived garnets into 12 different groups numbered G1 to G12 as listed in Table 4.10.

TABLE 4.10: STATISTICAL GROUPING OF MANTLE-DERIVED GARNETS ACCORDING TO DAWSON AND STEPHENS, 1975, 1976

Grp	Name	TiO_2	Cr_2O_3	FeO	MgO	CaO	Assoc. lithology
1	Titanian pyrope	0.58	1.34	9.32	20.00	4.82	K, GL, GOW, D
2	High–titanium pyrope	1.09	0.91	9.84	20.30	4.52	K
3	Calcic pyrope-almandine	0.31	0.30	16.49	13.35	6.51	K, GL, GOW, D, EC
4	Ti-, Ca-, Mg-almandine	0.90	0.08	17.88	9.87	9.41	K, EC, D
5	Magnesian almandine	0.05	0.03	28.33	7.83	2.44	K, EC, D
6	Pyrope-grossular almandine	0.24	0.27	10.77	10.38	14.87	GP, EC, GR
7	Ferro-Mg uvarovite-grossular	0.29	11.52	5.25	8.61	21.60	K, GS
8	Ferro-Mg grossular	0.25	0.04	6.91	4.69	24.77	GR
9	Chrome pyrope	0.17	3.47	8.01	20.01	5.17	K, GL, GOW, EC, D
10	Low-Ca chrome-pyrope	0.04	7.73	6.11	23.16	2.13	K, GS, D
11	Titanian uvarovite pyrope	0.51	9.55	7.54	15.89	10.27	K, GL, GW, D
12	Knorringitic uvarovite-pyrope	0.18	15.94	7.47	15.40	9.51	K, GS

LEGEND FOR ABBREVIATIONS

K	Kimberlite	GOW	Garnet-olivine websterite
GL	Garnet lherzolite	GP	Garnet pyroxenite
GH	Garnet harzburgite	GR	Grospydite
GD	Garnet dunite	EC	Eclogite
GW	Garnet wehrlite	D	Diamond inclusion
GS	Garnet serpentinite		

Grütter *et al.* (2004) explained how currently known thermo-barometry techniques based on analyses from mantle-derived xenoliths allowed them to assign such mantle xenoliths to the stability fields of graphite ($P < 16.4 + 0.025 *T$) and diamond ($P > 22.4 + 0.025 *T$) with a "relatively high" degree of confidence. This enabled Grütter *et al.* (*op cit.*) to identify two geochemical parameters to distinguish between garnets that formed within the diamond stability field from other garnets:

1. a critical value ≥ 0.15 for Cr/(Cr + Al), and
2. a MnO content of < 0.36 wt.%.

In addition, the work of Gurney and Switzer (1973) and Gurney (1984) indicated that the ratio between Cr_2O_3 and CaO in garnet can be used to identify the pressure-temperature conditions in the portion of the mantle where these garnets crystallized. Grütter *et al.* (2004) suggested that a Caintercept (CA_INT) value (*i.e.* CaO – (0.25 x Cr_2O_3) of 4.3 be used in the case of lherzolitic garnets to distinguish between on-craton (potentially diamondiferous) and off-craton (non-diamondiferous mantle sources) populations.

Gurney (1984) found that 85% of peridotitic garnet inclusions in diamonds worldwide correlates with the low-calcium, high-chromium harzburgitic pyrope cluster G10 of Dawson and Stephens (1975, 1976). This identified G10 garnets as prime indicator minerals in the search for diamondiferous kimberlites. From the foregoing, Grütter *et al.* (2004) concluded that G10 garnets can be identified geochemically by:

Cr_2O_3 (wt.%) : $\geq$1.0 to <22.0

CA_INT (wt%): 0 to <3.375

MGNUM: $\geq$0.75 to <0.95,

where MGNUM = (MgO/40.3)/(MgO/40.3 + FeO_t/71.85) (oxides in wt%).

The new classification scheme of Grütter *et al.* (2004) differs more profoundly from that of Dawson and Stephens (1975, 1976) as well as from that of Schultze (2003) in respect of pyroxenitic, websteritic and eclogitic garnets. These have been left mostly unclassified by the earlier workers, while the moderate- to low-chrome pyroxenitic garnets have a distinct association with diamond (Gurney, 1984; Aulbach *et al.*, 2002) and as such are important in diamond exploration.

4.2.2 The garnets from this study

Separation, analytical procedures and results with respect to the garnets studied, are described in Section 8.3. Some 224 garnet grains (*e.g.* Figure 4.15) from five localities along the Lower Orange River have been analyzed by SEM. The data were normalized. Fourteen analyses conform to stoichiometric parameters of between 5.98 and 6.02 ions per structure. A further 41 were good enough (but at lower confidence limits) to calculate end members according to Locock (2008) which facilitated the construction of ternary diagrams of end members.

Figure 4.15 Photomicrograph of <0.5mm garnet: fine fraction of proto-Orange River gravel from this study

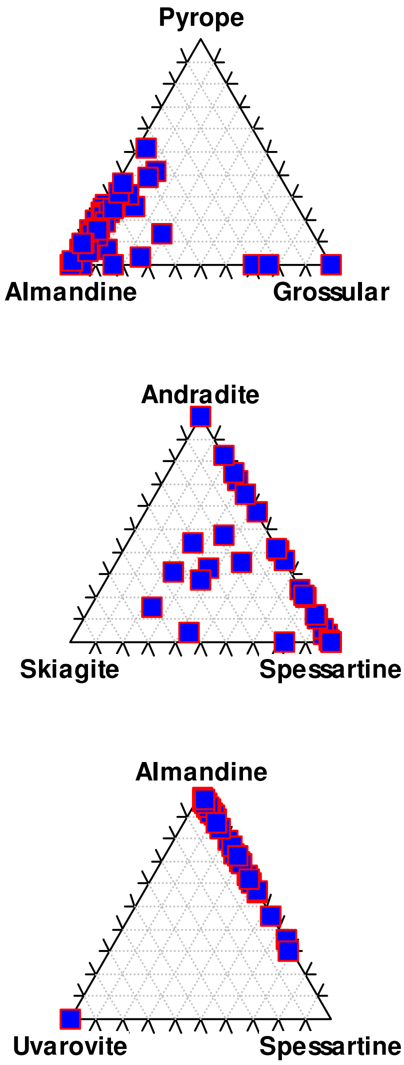


Figure 4.16 Ternary diagrams of garnet end-members, this study.

The TriPlot programme of Todd Thompson Software was used to construct the ternary diagrams. This program also normalizes the relative end member percentages to 100. The minimum and maximum percentage of the different end members as detected in the samples are listed in Table 4.11.

TABLE 4.11 MINIMUM AND MAXIMUM PERCENTAGES OF GARNET END MEMBERS DETECTED IN SAMPLES ANALYZED DURING THIS STUDY

END MEMBER	%
Katoite	*0.09*
Schorlomite-Al	*0.02 – 0.69*
Morimotoite	*0.18 – 2.23*
Morimotoite-Mg	*0.03*
Majorite	*0.17 – 3.87*
Uvarovite	*0.03 - 0.55*
Spessartine	*1.18 – 61.17*
Pyrope	*0.82 – 46.79*
Almandine	*6.46 – 82.15*
Grossular	*0.04 – 66.67*
Andradite	*0.44 – 51.61*
Skiagite	*1.00 – 24.20*

In Figure 4.16 and Table 4.11 it can be seen that none of the analyses showed more than 46.79% of pyrope in the structure. This observation would support the results of De Wit (1993) where pyrope is reported from Miocene deposits at Bosluispan in the upper reaches of the Koa Valley, but the conclusion is drawn from other evidence that the Orange River never flowed through the Koa Valley, an important aspect in the reconstruction of the drainage evolution and diamond distribution. The Koa River valley is currently connected to the Orange River, but this was not the case during the Miocene.

A further observation is the dominance of almandine. Only one of the analyses failed to report the presence of this end member, and in one sample it only constitutes 6.46%. In the other 53 analyses, it averages 63.58%. Of the predominantly almandine analyses, 87% plot along the almandine-pyrope line. Garnets with such a composition were described from the aluminous gneisses, schists and granites of western Namaqualand (Kröner 1973a; Zelt, 1975; Joubert, 1976; Jack, 1980 and Albat, 1984), as well as from detrital deposits along the West Coast by Cilliers (1995), Philander (2001) and McDonald (1996).

In addition, all the predominantly almandine analyses plot along the almandine-spessartine line. This combination of end-members was attributed to granite and pegmatite source rocks by Blatt *et al.* (1980). Both the almandine-pyrope and almandine-spessartine garnets, comprising the bulk of the analyses, could therefore be derived from the rocks of the Namaqualand Metamorphic Complex which had been metamorphosed to granulite and upper amphibolite grade.

A subordinate percentage of the predominantly almandine analyses plots along the almandine-grossular line. Garnets in which grossular is the dominant molecule are especially characteristic of both thermally and regionally metamorphosed impure calcareous rocks, but are also known from zeolite-bearing vesicles in metamorphosed basaltic lavas (Deer, Howie and Zussman, 1992). Zeolites weathered out from vesicles in the Karoo basalts are common in some sediments of the palaeo-Orange River, but these lavas are generally unmetamorphosed and therefore not a possible source of the garnets in this study.

Grossular garnet has been reported from the almandine zone of metamorphism (Deer, Howie and Zussman, 1992) which could explain the almandine-grossular relationship of this subordinate sub-population. The proximal Namaqua Province with its polymetamorphic history (Joubert, 1971; Zelt, 1980a,b) therefore seems the most likely provenance for these garnets.

Garnets with the combined almandine-pyrope composition occur along the west coast at Kleinzee (Philander, 2001) and Geelwal Karoo (McDonald, 1996), but at Geelwal Karoo those with a grossular-andradite composition are also found (McDonald, *op. cit.*). This latter locality is due west from and at lower topographic levels than the Kliprand area where Albat (1984) reported grossular-andradite garnet in calc-silicate gneisses. This composition is absent from the garnets of this study, supporting the view that the bulk of the garnets studied probably was derived from the Namaqua Province and the Richtersveld, although it is theoretically possible that some of the garnets may have been sourced from more distal metamorphic terrains in the Vaal-Orange drainage system.

Application of the parameters proposed by Grütter *et al.* (Section 4.2.1) to the garnet analyses obtained during this study, failed to identify any mantle-derived species, only those associated with crustal parent rocks. This could be due to selective survival, for the following reasons: Kimberlitic garnets crystallize under very high pressure conditions, from where they are moved to the surface in rapidly ascending kimberlite magma. This pressure release takes place during a matter of hours and is evident in the presence of abundant internal flaws and fractures which make these garnets very prone to both chemical and mechanical destruction (Figure 4.17). Metamorphic garnets, to the contrary, crystallize in crustal rocks at higher elevations, and their movement into the surface environment takes place gradually over prolonged periods of uplift and erosion. Not only are these conditions less conducive to internal fracturing of the garnets, but the Orange River transects the Namaqua Metamorphic Complex from immediately upstream from Upington, affording a considerably shorter distance for the metamorphic garnets to be transported along the palaeo-Orange River.

The fact that kimberlitic garnets do occur at Bosluispan in the upper reaches of the Koa River valley, could be ascribed to a less destructive journey from their source region, either in the palaeo-Gamoep River flowing over soft Karoo sediments, or as passengers within a solid Dwyka ice sheet.

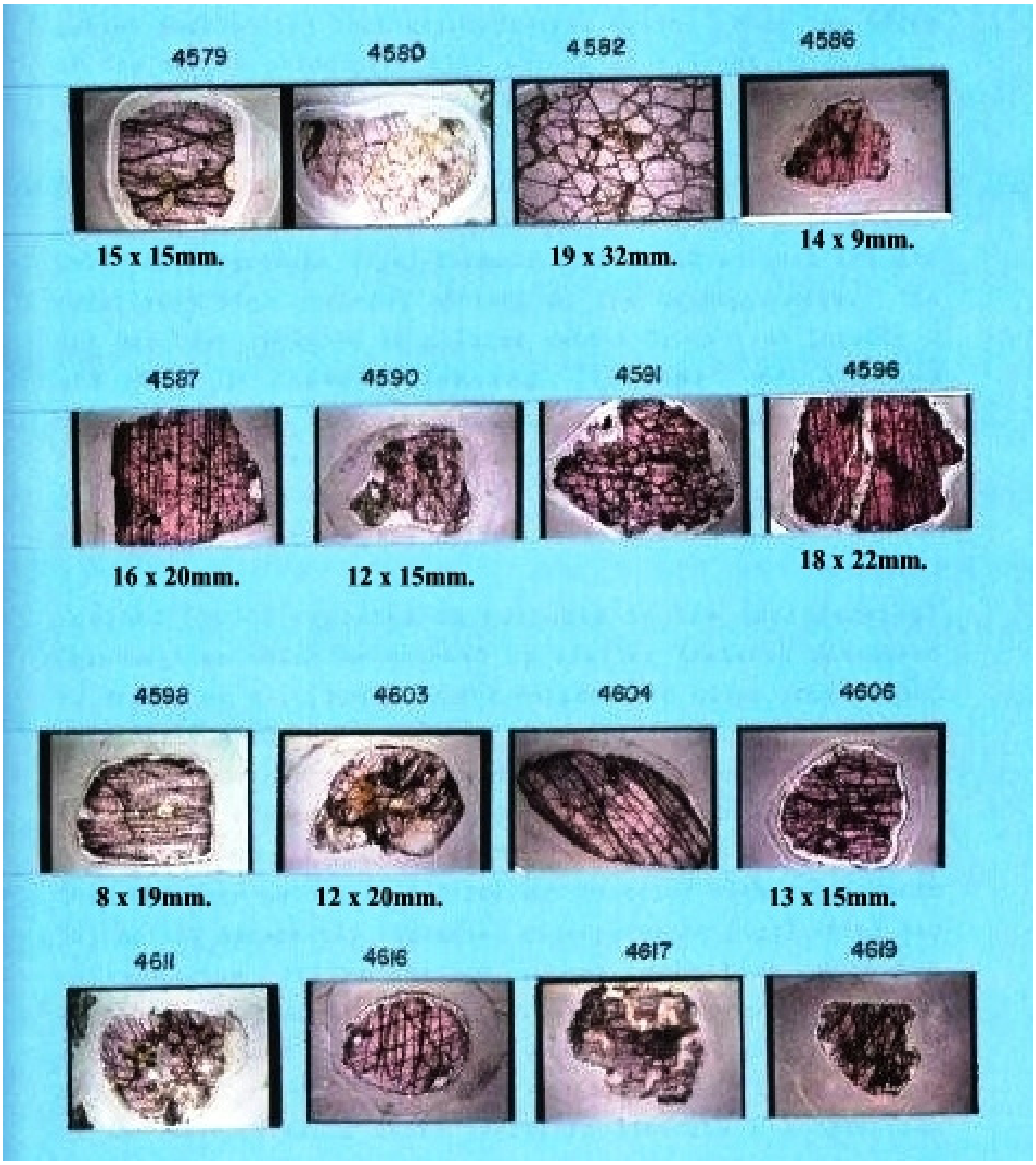


Figure 4.17 Selection of fractured garnet megacrysts from the Bobbejaan Mine (Van der Westhuizen, 1992).

4.3 ZIRCON

4.3.1 The mineral zircon

Zircon ($ZrSiO_4$) is a common accessory mineral of igneous rocks, especially sodium-rich plutonic rocks. It is generally present as small early-formed crystals within later minerals. Zircon can also form larger well-developed crystals in granite pegmatites, particularly those associated with nepheline syenites (Deer, Howie and Zussman, 1992).

Because of its remarkable resistance to abrasion and weathering, zircon can survive numerous cycles of erosion and sedimentation and is often found as an accessory mineral in most clastic sediments. The length/breadth ratio of individual crystals does not vary significantly throughout a body of magmatic granite and if such a variation does occur it may indicate that the particular intrusion is complex (Deer, Howie and Zussman, 1992). Quite conceivably then, if a significant variation in the length/breadth ratio is noted among the zircon crystals found in a detrital deposit, it could be an early indication of multiple source regions in addition to the possibility of a single, but complex provenance. Pupin (1980) recognizing the fact that zircon morphology reflects the physio-chemical conditions under which they crystallize, devised a classification scheme featuring indices A – development of pyramidal faces (101) and (211) – and T, reflecting the development of prismatic faces (100) and (110). However, a significant percentage of the detrital zircon grains available for this study were broken or rounded through abrasion, as one would expect to be the case in a high-energy fluvial system like the palaeo-Orange River. Therefore the typological classification of Pupin (1980) and the breadth/length ratio parameters of Deer, Howie and Zussman (1992) were unsuitable for the detrital zircons used in this study.

Zircon has the ability to retain its isotopic integrity, thus allowing the determination of its original age as well as those of subsequent metamorphic events reflected in zoned crystals. Williams (1998) cites numerous case histories where separate analyses (see discussion of U-Pb age determinations) on multiple crystallographic features such as overgrowths in single zircon grains allowed the reconstruction of various thermal events that influenced the geochronology of a particular region.

In a geographically widespread geological unit like the Karoo Supergroup in southern Africa, it is possible to find zircon of similar ages to be present in time-equivalent formations a few thousand kilometres apart. In such instances age determinations alone can only recognize a particular grain or population of grains as being of e.g. "Karoo" age, without the identification of the relevant geographical source region for the Orange River sediments. In other words, zircon age reveals something with respect to the parent rock, but not the sedimentary host in which it is found.

4.3.2 Zircon in geochronology

The pioneers in geology already recognized the value and importance of field observations in establishing relative ages between different geological formations and events. Such observations, however, do not provide an absolute measure of the relevant ages of the formations or events studied. A piece of petrified wood with well-preserved year rings can reveal how many years the particular tree had lived, but it does not tell us *when* the tree lived. The determination of absolute ages is thus especially helpful in the identification of provenance for minerals, fossils and other clasts found in sediments. In order to achieve this, a continuous, uni-directional process that was (and still is) in existence in nature, is needed. Such a process, and the one most widely utilized for this purpose, is natural radio-activity.

The probability that a given isotope will decay in any given time period is a constant, so the number of decays occurring per unit time is proportional to the number of atoms of the particular isotope present. Radioactive decay can thus be described as follows:

$$D = P_0 (1 - e^{-\lambda t})$$

where D = number of daughter atoms produced after a period of time (t) from an original number of radio-active parent atoms (P_0) and λ is the decay constant for the isotope concerned. In practice the equation is more conveniently expressed (Williams, 1998) in terms of the ratio between daughter atoms produced (D) and parent atoms *remaining* (P) after a given period of time (t):

$$\frac{D}{P} = e^{\lambda t} - 1$$

TABLE 4.12 HALF-LIFE AND DAUGHTER ISOTOPES OF SOME PARENT ISOTOPES

PARENT ISOTOPE	DECAYS TO	HALF-LIFE (years)
^{40}K	^{40}Ar (and ^{40}Ca)	1.25×10^9
^{87}Rb	^{87}Sr	48.8×10^9
^{238}U	^{206}Pb	4.47×10^9
^{235}U	^{207}Pb	0.704×10^9
^{147}Sm	^{143}Nd	106.0×10^9

Armstrong *et al*. (2004) label the U-Pb method as the "premier geochronometer currently available and the natural benchmark for all other techniques" because of the unique advantages of the paired ^{238}U – ^{206}Pb and ^{235}U – ^{207}Pb decay scheme; this is helped by the high precision measurement of the isotopic compositions afforded by modern analytical equipment.

The application of the U-Pb dating technique to zircon and other accessory minerals is the one where the most dramatic advancement in recent years occurred. The SHRIMP (Sensitive High Resolution Ion Microprobe) with its ability to accurately analyze U-Pb *in situ* on a scale of a few microns within individual grains can be applied to determine multiple ages within a zircon population which might have inherited cores and rims of metamorphic overgrowths.

4.3.3 Geochronology by SHRIMP analyses of zircon grains in this study

As mentioned in Section 8 all the zircon analyses of this study were done by the author at the Australian National University (ANU) in Canberra, while the processing of the raw data was done by Dr Richard Armstrong of the ANU.

While the zircons extracted from the gravel samples were examined as part of the heavy mineral suite of the palaeo-Orange River sediments, available drill core samples from Ecca Group turbidite fans, Laingsburg district, were also included to establish the possible role of the Ecca in provenance identification. Prior to SHRIMP analyses, cathodoluminescence (CL) or transmitted light optical images of the zircons to be analyzed were used to:

- Recognize different zones within the crystals so that these could be analyzed separately to afford the mapping out of the thermal history of the crystal, and

- Identify fractures and impurities to be avoided during analysis.

This procedure is illustrated in Figure 4.18 and the technical details pertaining to the sample preparation and analyses appear in Section 8.4.1 – 8.4.3. The unedited raw data appears in Section 8.4.4, on CD. In Section 8.4.5 images pertaining to the analyses, with grains and sample spots marked as illustrated in Figure 4.18, are followed by comprehensive discussions of results and corrected data. Histograms showing the concentration of different age groups are followed by Concordia Diagrams of $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ values.

As an illustration of the above, the data obtained from the sample population at Lorelei are presented in the following paragraphs.

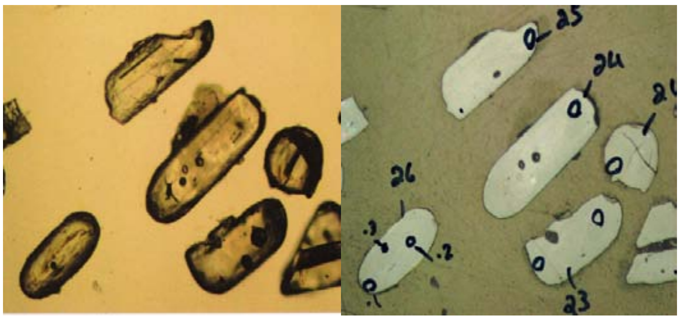
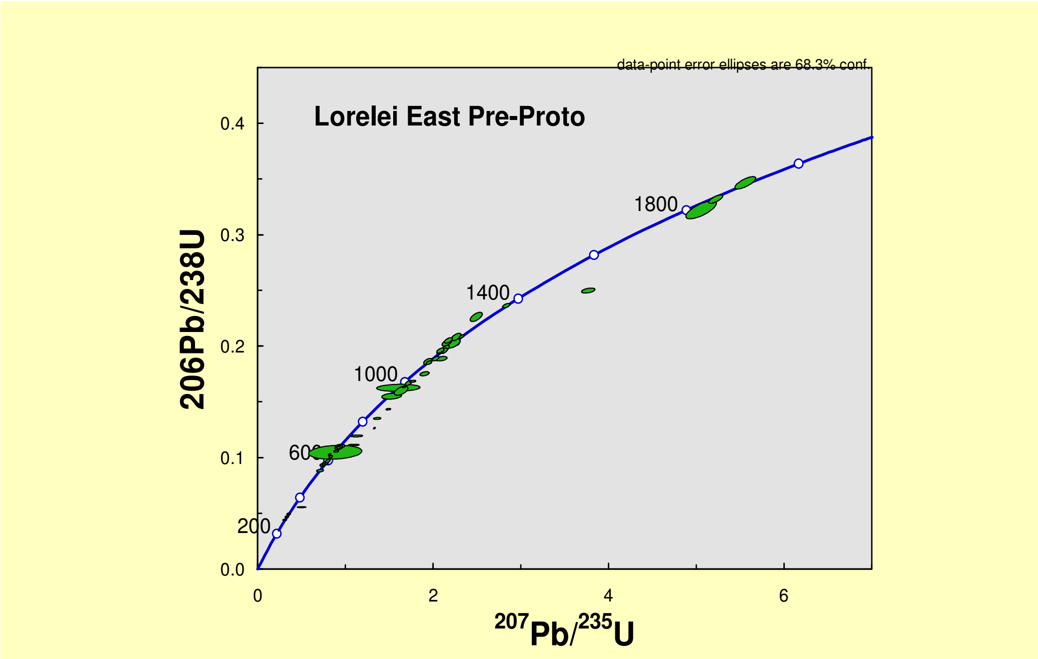


Figure 4.18 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

TABLE 4.13 RESULTS OF LORELEI ZIRCON ANALYSES

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
LOR-13.1	197.5	1.5	186	53	-6	197.5	1.5
LOR-42.1	259.1	2.2	242	91	-7	259.1	2.2
LOR-11.1	276.4	2.6	234	116	-18	276.4	2.6
LOR-8.1	291.3	3.9	311	70	6	291.3	3.9
LOR-23.1	292.6	3.1	221	57	-33	292.6	3.1
LOR-41.1	530.0	4.3	543	64	2	530.0	4.3
LOR-15.1	559.6	5.2	529	67	-6	559.6	5.2
LOR-24.1	563.0	4.3	559	37	-1	563.0	4.3
LOR-32.1	569.2	5.9	560	55	-2	569.2	5.9
LOR-36.1	580.5	5.2	598	38	3	580.5	5.2
LOR-18.1	604.7	4.8	609	33	1	604.7	4.8
LOR-30.1	616.6	3.3	527	24	-17	616.6	3.3
LOR-50.1	630.5	24.3	651	496	3	630.5	24.3
LOR-22.1	635.6	3.3	656	43	3	635.6	3.3
LOR-26.1	653.3	6.2	664	58	2	653.3	6.2
LOR-21.1	657.5	7.1	671	42	2	657.5	7.1
LOR-37.1	660.2	7.2	681	82	3	660.2	7.2
LOR-6.1	662.3	2.7	652	14	-2	662.3	2.7
LOR-19.1	668.1	2.8	975	74	31	668.1	2.8
LOR-2.1	921.0	10.7	970	100	5	970	100
LOR-49.1	962.7	11.7	975	212	1	975	212
LOR-5.1	968.0	4.0	1045	13	7	1045	13
LOR-3.1	947.4	15.2	1047	53	10	1047	53
LOR-14.1	988.8	7.9	1059	25	7	1059	25
LOR-16.1	1094.7	9.2	1083	25	-1	1083	25
LOR-27.1	995.8	4.1	1099	24	9	1099	24
LOR-48.1	1087.6	5.8	1112	21	2	1112	21
LOR-17.1	1149.0	7.7	1118	20	-3	1118	20
LOR-20.1	1197.7	8.7	1118	21	-7	1118	21
LOR-34.1	1186.8	10.8	1122	26	-6	1122	26
LOR-7.1	1144.2	7.7	1127	19	-2	1127	19
LOR-40.1	1108.0	7.7	1149	20	4	1149	20
LOR-46.1	1157.1	9.8	1160	25	0	1160	25
LOR-45.1	1148.2	8.6	1161	22	1	1161	22
LOR-10.1	1215.0	11.4	1169	26	-4	1169	26
LOR-35.1	1312.9	14.0	1189	29	-10	1189	29
LOR-33.1	1184.3	14.7	1199	36	1	1199	36
LOR-29.1	1108.1	7.6	1206	39	8	1206	39
LOR-1.1	1217.6	5.5	1218	12	0	1218	12
LOR-12.1	1365.4	6.8	1358	16	-1	1358	16
LOR-38.1	1804.8	26.2	1859	29	3	1859	29
LOR-43.1	1852.7	12.1	1862	13	0	1862	13
LOR-4.1	1923.5	17.4	1898	17	-1	1898	17



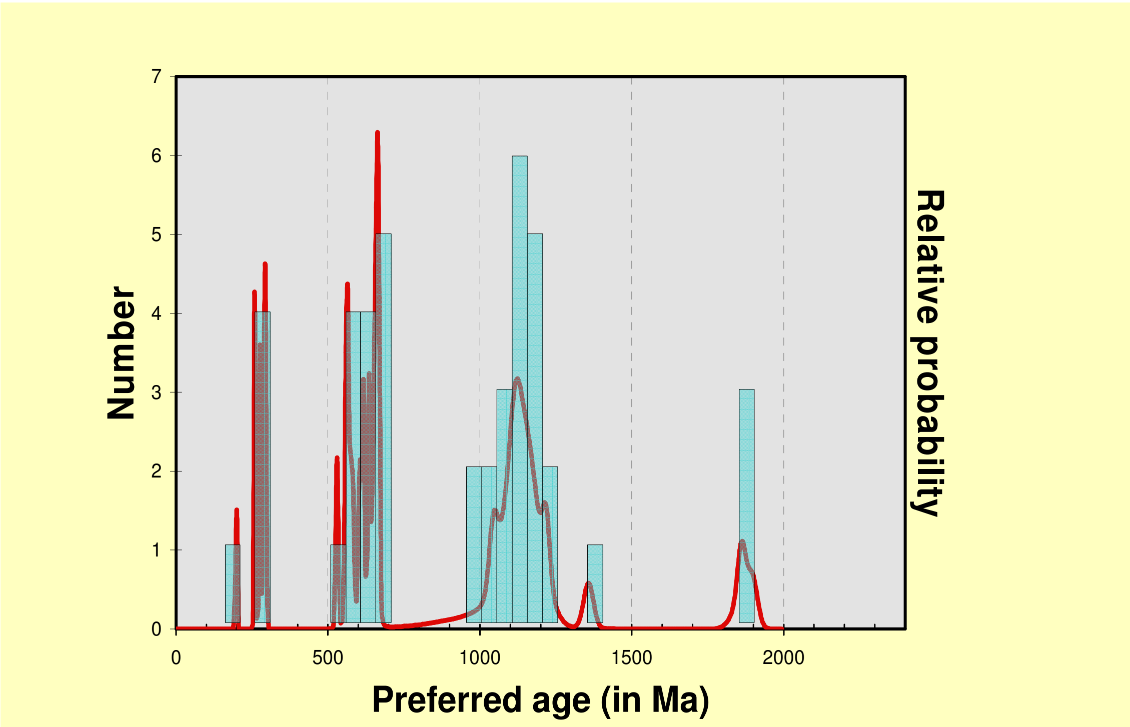


Figure 4.19 Lorelei. Concordia diagram and histogram of preferred ages Analyses by this author; samples collected by J.R. Jacob.

Lorelei is located immediately upstream from AACE (Figure 1.3), but along the right flank of the Orange River valley. The gravel sample from which these zircons were extracted, came from a local scour feature harbouring sediments that, on the basis of bedrock elevation and field relations, are thought to be of pre-proto age. As shown in Table 4.13, and with reference to Table 2.1, the entire thermal history of the Kaapvaal Craton, with the exception of the Archaean, is reflected in this zircon population with ages ranging from 197.5 ± 1.5 Ma to 1898.0 ± 17.4 Ma. The older ages among this zircon population reflect the fact that the Orange River valley transects the Vioolsdrif and Richtersveld Suites (Section 2.2.3) over a distance of about 30 kilometres before reaching Lorelei. East-bound drainages from the Kuboos pluton would have been responsible for the input of zircons of Cape Granite Suite age in the region of Grasdrif, about 21 kilometres upstream from Lorelei.

The age of 197.5 ± 1.5 Ma however is seen as significant in terms of the denudation and drainage history of the subcontinent. Table 2.1 shows that this age can only be correlated with those reported from the Lebombo range in northern Kwazulu-Natal, immediately east of the current headwaters of the Orange/Senqu River in northern Lesotho (Figure 2.29). The oldest age exposed in the Lesotho Highlands is only ± 182 Ma and this would indicate that the early Orange River drainage could have reached farther east than today, prior to the development of the Drakensberg Escarpment. The fact that this juvenile zircon occurred in pre-proto Orange River sediments, is in harmony with a denudation history that would have resulted in the erosion products from the highest region (youngest rocks) in the catchment area being deposited in some of the oldest sediments transported by the relevant drainage.

TABLE 4.14 SUMMARY OF ZIRCON MODEL AGES FROM DIFFERENT SAMPLE LOCALITIES OF THIS STUDY

Possible Correlations (see Table 2.1 for S. Afr., and those for S. Am. & Patagonia cited below)		Lebombo Acid Volcanics	Choiyoi Volcanism	Granites of Argentina and Patagonia**	Deseado Massif & Patagonia *	Cape Granites	Malmesbury & Gariep	Malmesbury Group	Unknown	Rich'sveld Suite	Nam-Nat	Vioolsdrif Suite & Orange River Group	Kheis Orogeny & Hartley Form.	Tvl ign. act. Griqualand West depo-centres	Archaean (Ventersdorp)
		190-194	210-290	371-403	460-495	496-594	594-668	706-790	815 -892	771-833	905-1370	1750-2000	1800 - 1930	2400-2500	>2500
Pre-Proto	Lorelei	197.5	259-292	-	-	530-580	605 -668	-	-		970-1358	-	1859-1898	-	-
	Snake	-	274	-	-	503-594	638-662	704-791	852-862		972-1219	1750	1871-1925	-	-
Pre-Proto to Proto		-	-	-	-	526-547	606 -661	-	870		1060-1284	1555-1818	1845-2111	-	2661& 2719
Ren'kop Prot		-	251.6	395.1	475.6	502-594	612-657	755-769	815-892		953-1244	1719	-	-	-
Baken Proto		-	291.5	-	490.8	523-565	632-655	-	866		1040-1235	-	1891-2000	2473	2677
Modern River		-	-	-	-	528-585	614-691-	-	846-874		1019-1344	1786	1821-2132	-	2596 & 2919
63a, Tanqua Fans 3, 4 & 5, Laingsburg		-	253 - 310	374 – 415	474 - 492	509-589	595-619	-	-		1054 -1119	-	-	-	-
64: : Fan F Laingsburg		-	264 -274	-	-	518	-	-	-		1356	-	-	-	-
65: Slope Sandstone, Laingsburg		-	263- 287	-	459 - 472	497	-	756	-		-	-	-	-	-
66:Fan A, Laingsburg		-	260-309	364-386	458-496	531-564	-	694	822		985-1250	-	-	-	2669

*Pankhurst *et al*. (2003); Stuart-Smith *et al.* (1999); Tickj *et al.* (2001); ** Pankhurst *et al.* (2001, 2003); Kay *et al.*, (1989).

4.3.4 Discussion of detrital zircon geochronology

4.3.4.1 Ecca detrital grains

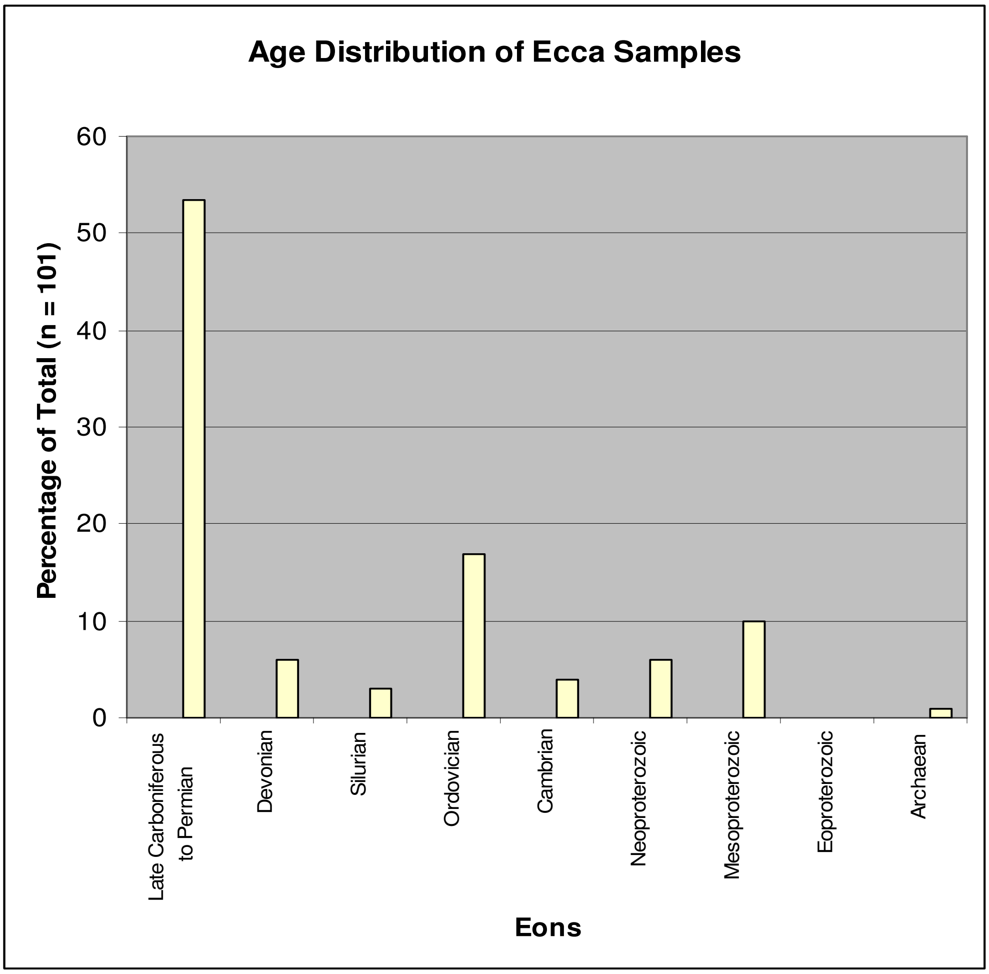


Figure 4.20 Graphic illustration of model ages of all Ecca zircon samples.

The most likely source rocks for these zircons are indicated in Table 4.15 with the exception of one anomalous Archaean-aged zircon which was found in the sample population of Fan A, Laingsburg. This particular grain was analysed in two different spots, namely numbers 66-2.1 and 66-2.2. The model ages obtained were 2667 ± 11 Ma and 2671 ± 11 Ma respectively (averaged to 2669 Ma in Table 4.15). It is suggested that this zircon originally crystallized in rocks of the Ventersdorp Supergroup and reached the Laingsburg area as part of glacial till during the Dwyka glaciation, as illustrated in Figure 5.1. This aspect implies that the use of zircon ages with respect to palaeo-drainage reconstruction when dealing with sediments that may have an Ecca component in its provenance regions should be done with caution.

4.3.4.2 Comments on zircon ages from diamondiferous gravel samples

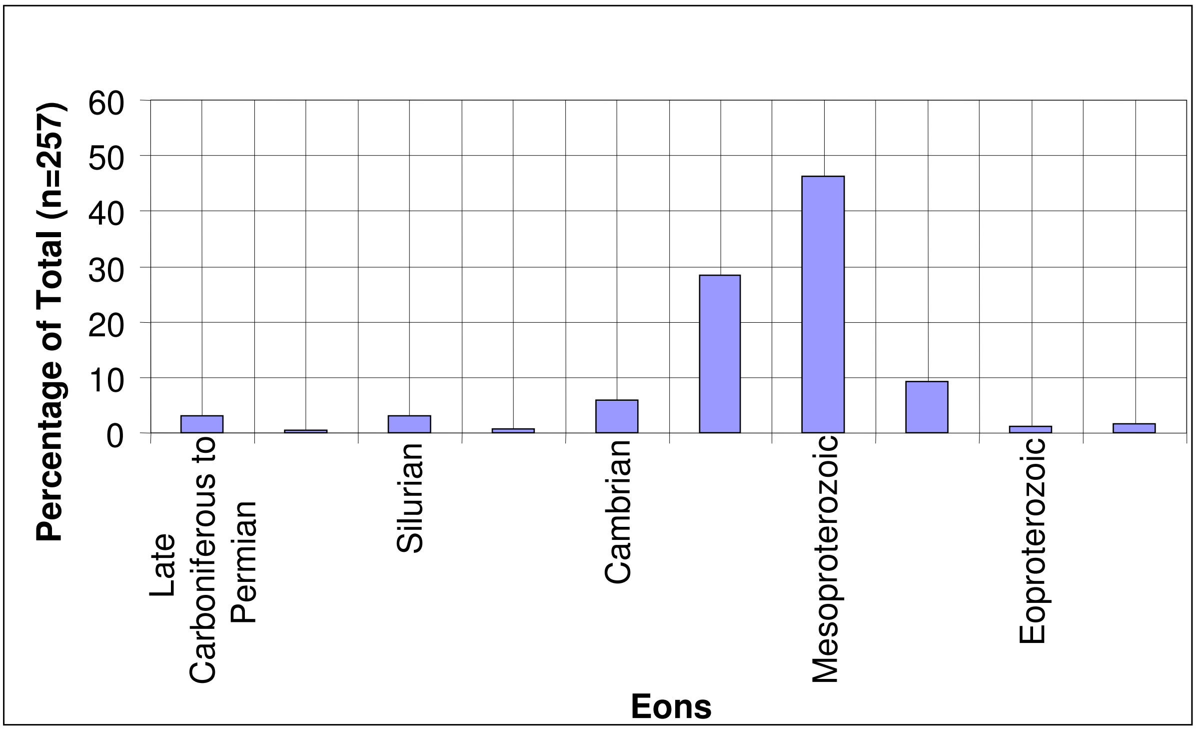


Figure 4.21 Graphic illustration of model ages obtained from zircon in gravel samples.

Among the gravel samples studied the youngest zircon age, 197.5 Ma, was found in the Lower Orange River valley in some of the earlier members of the Arrisdrif Gravel Formation, *viz.* the Lorelei deposit with an indicated pre-proto (Late Oligocene) age. In the discussion of the Lorelei analyses it has been pointed out that the most likely source region for this zircon is the Lebombo Mountains in northern Kwazulu-Natal.

A single grain with an age of 251.6 Ma was found in the Renosterkop sample. Its geographic location and age correlation with a 252 Ma zircon from Laingsburg would indicate that this grain could have been transported down either the Hartebeest or the Brak Rivers, since both these tributaries have their headwaters in the central Karoo basin. Alternatively it could have been derived from Ecca Group rocks along the Orange River valley upstream from Hopetown, or from the eastern part of the Nabas Basin. Bangert *et al.* (1999) did report on the presence of zircons from the Ecca in Namibia, but the drainage history of the subcontinent makes a Namibian source for this zircon unlikely.

Zircons with Archaean ages (indicating that incision had eventually gone through the Karoo cover of the hinterland) only appear in the Early - Middle Miocene, culminating in the highest zircon age (deepest incision in the hinterland) present in the youngest sediments, namely the modern river. This observation is in line with the evidence from sedimentary clasts found in the various gravel deposits in the Lower Orange River. In the sector of the Orange River immediately downstream from the point where it transects the Nabas Basin, clasts of Karoo sediments have their highest incidence in the proto (Early to Middle Miocene) deposits, with a dramatic decrease in the number of these clasts noted in the younger (meso and modern river) deposits (Jacob, 2005). It would therefore appear that the Orange River in the Early Miocene was still actively down-cutting through the Nabas Basin, but by the time the meso-Orange deposits were laid down incision through the Karoo rocks had been completed. Only after incision had gone through the relatively smooth, flat-lying Karoo sediments into hard and variable Precambrian lithologies, a micro-topography conducive to the retention of heavy minerals like diamond, developed. The close relationship between this aspect of river morphology and the presence of economic concentrations of diamond was mentioned in Section 2.1.

Zircons reflecting Proterozoic ages (up to about 2 Ga) are present in all the age groups of sediments from the oldest (Snake) to the modern river, including the Miocene deposit at Renosterkop where an age corresponding to the Kheis Orogeny was found. The presence of zircons with these ages in the sediments of the Lower Orange confirms that the rocks of the Orange River Group were already exposed in Early Miocene times. The presence of the 1719 Ma zircon at Renosterkop shows that Proterozoic outcrops, probably dating back to the Kheisian Orogeny, were also exposed upstream from Renosterkop during the Early Miocene.

None of the >1356 Ma Proterozoic zircon ages that can be correlated with the Vioolsdrif Suite, the Kheis Orogeny, the Hartley Formation of the Olifantshoek Sequence or the Griqualand West depocentres of the Transvaal Supergroup, were found among the Ecca samples of the Laingsburg region. The geographic location, drainage and glacial history of the subcontinent confirms this observation, and therefore the Proterozoic ages reported from the gravel samples referred to in the above discussion, can be accepted as indeed reflecting the drainage evolution of the region, and should not be seen as the recycling of >1356 Ma Proterozoic zircons *via* the Ecca. The presence of a single Archaean zircon reported from sample 66 (Laingsburg Fan A) has been shown to be most probably linked to the Dwyka glacial period.

The absence of Archaean-aged zircons from Renosterkop and the older (pre-proto) deposits along the Lower Orange is regarded as significant. De Wit (1993) cited evidence from fission track analyses along the western section of the subcontinent (preserved crater facies of ultrabasic intrusions in Bushmanland and Namaqualand and offshore drilling records) to demonstrate that the bulk of the landscape denudation of the subcontinent was complete by the end of the Cretaceous. Probably the best time constraint in this regard is the evidence from the ultrabasic intrusions in western Bushmanland (Moore and Verwoerd, 1985). Their radiometric ages for these intrusions range from 54.1 Ma to 77 ±3 Ma. The modest amount of erosion indicated by the present surface expressions of these intrusions as mentioned by De Wit (1993) confirms the Early Eocene as the minimum age for the denudation to current levels of this part of the subcontinent. The results of this study also reveal zircon ages associated with the Namaqua Metamorphic event to be present in the Lower Orange gravel samples from the Oligocene to the Plio-Pleistocene.

The earliest appearance of pre-Proterozoic zircons in the gravels sampled came from the transition between pre-proto and proto gravel at Bloeddrif, *viz.* 2.661 and 2.719 Ga. Scrutinizing the catchment area of the Orange River valley in an upstream direction, the first outcrop that approaches this age is the Schalkseput Granite southeast of Upington (2.640 Ga), and the Zeekoebaart Formation of the Ventersdorp Supergroup between Groblershoop and Prieska (2.690 Ga, Hartzer *et al.,* 1998). This seems to imply that at the time when the Snake and Lorelei sediments were deposited (indicated age of Snake = Late-Eocene, Lorelei 23 Ma) the Orange River drainage system did not have access to these Archaean-aged rocks yet, as was the case in the Early Miocene. This would imply that the Karoo cover in the hinterland persisted longer into the Cenozoic than previously envisaged.

The model outlined above requires an explanation for the presence of rare Archaean-aged zircons (article in preparation, NAMDEB geological department), found in the Eocene (Stocken, 1978) Buntfeldschuh deposit along the southern coast of Namibia, which is characterized by the presence (Figures 2.25, 2.26) of abundant siliceous clasts from the upper Vaal-Orange system. Among this zircon population (which revealed mostly an age of about 500 Ma) two grains with rare Archaean ages were noticed. Their small number, compared to the total sample population, would indicate a very restricted source. Their presence at this locality can be attributed to recycling *via* either the Ecca or Cretaceous kimberlites. However, during the course of this study the presence of Archaean material among the crustal xenoliths found in the kimberlite diatreme at Letseng, Lesotho, was noted (Figure 4.22). The emplacement age of these kimberlites ensured that material liberated from the upper reaches of the diatreme was available for transport by the Orange/Senqu drainage system since the Late Cretaceous. It is suggested that the occurrence of rare zircons of Archaean age found at Buntfeldschuh can be explained in this way.

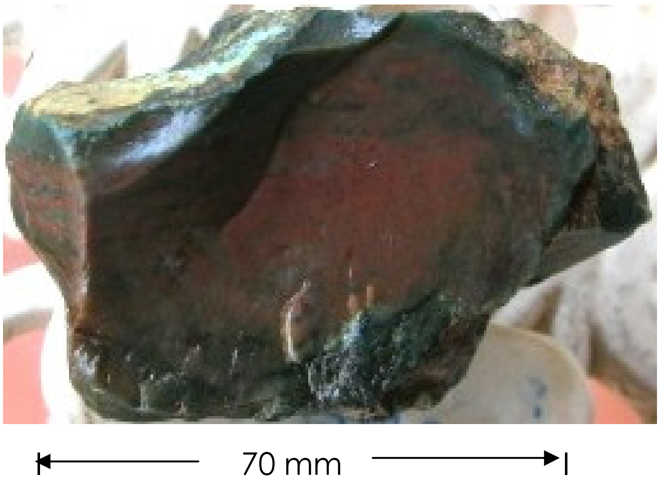


Figure 4.22 Angular piece of red and greenish-grey chert found *in situ* in diamondiferous eluvium next to satellite kimberlite pipe at Letseng. *Its most likely provenance is the Witwatersrand Supergroup rocks (Beukes and Strauss, 1995) locally underlying the Karoo sediments from where it was transported upward as a crustal xenolith in ascending kimberlite magma. Liberated from the decomposing kimberlite it became incorporated in the eluvial placer deposit adjacent to the diatreme, where the author found it in an opencast mining face.*

4.3.5 Summary and Conclusions with respect to the zircon analyses

The zircon analyses yielded information that throws light on the drainage history of the subcontinent. The zircon data acquired from the Ecca samples confirmed the conclusions drawn by earlier workers with respect to the indicated provenance history of the Ecca Group near Laingsburg, namely derivation from Argentina and Patagonia for zircons dated between 210 and 497 Ma BP and the Cape Granite Suite, Malmesbury Group and the Namaqua-Natal Metamorphic Province for the older ones. It also confirmed the input of Archaean–aged material that could have reached the Laingsburg region only *via* the Dwyka glacials.

The zircon data acquired from the gravel samples suggest a model whereby the youngest zircons were transported and deposited by the early Orange River, and the progressively older zircons are seen in younger sediments, reflecting the gradual incision of the hinterland to expose ever older formations. This is convincingly demonstrated by the presence of the oldest zircon in the total sample population, namely 2.919 Ga being found in the gravel of the modern river, and the youngest zircon, 197.5 Ma, found in some of the oldest sediment packages, namely the pre-proto deposit at Lorelei. The only possible source region for this juvenile zircon was identified as the acid volcanics of the Lebombo Mountains east of the Drakensberg, implying that the initial head-waters of the Orange/Senqu River was further east, prior to the development of the Drakensberg Escarpment, than its current location in the Lesotho Highlands would indicate.

CHAPTER 5 DIAMOND DISTRIBUTION IN SOUTHERN AFRICA

5.1 General

Immediately after the cooling down and solidification of the kimberlite or lamproite rocks at the surface of the earth it comes under attack by atmospheric weathering. The matrix minerals of the volcanic rocks tend to decompose fairly rapidly (in geologic time), leaving behind the chemically resistant minerals like garnet, ilmenite, chromite and diamond which eventually become part of the heavy mineral suite in glacial till, fluvial or marine sedimentary packages. From these hosts they can again be liberated by chemical weathering or by reworking and concentration by fluvial, marine or aeolian processes.

As illustrated in Table 4.2 three main age groups of known kimberlitic sources have supplied diamonds to the secondary environment in southern Africa. These are:

- The pre-Karoo kimberlites in the NNE part of the RSA and southern Zimbabwe.
- The Jurassic kimberlites of Jwaneng, Dokolwayo, Dullstroom/Alkmaar, Helam (Swartruggens) and Klipspringer.
- The Cretaceous kimberlites of Lesotho, the so-called Kimberley province in the central part of the RSA and parts of Botswana.

To the pre-Karoo group, must be added a number of unknown sources of the following alluvial diamond occurrences:

- The >2.78 Ga (Kositcin *et al.*, 2003) Witwatersrand Supergroup.
  Regional sedimentary structures in the WWR basin indicate transportation from the southwest, west, northwest and north (Pretorius, 1981; Minter and Loen, 1991 and Viljoen and Viljoen, 2002). Eglington and Armstrong (2004) showed that these fit very well with the known

location of rock suites older than the WWR, with matching lithologies among the WWR sedimentary clasts.

- The Table Mountain Group.
  Asam Minerals recovered diamonds from the basal marine conglomerate of the Table Mountain Group at the foot of the escarpment upstream from Grootdrif, north-east of Van Rhynsdorp (Baxter-Brown, 1963b).

- The Nama Group.
  The basal conglomerate of the Nama Group (the Kuibis Formation) is known to contain diamonds, albeit in small quantities (Baxter-Brown, 2000).

- The Namibian Skeleton Coast.

- Somabula in SW Zimbabwe.

- Marange, SE Zimbabwe.
  The recently discovered Marange alluvial diamond field in south-eastern Zimbabwe comprises layers of diamondiferous conglomerate within a Proterozoic sedimentary package, while some diamonds reveal a fused contact with red granite.

Subsequent to the emplacement of the known Cretaceous diamondiferous kimberlites in the hinterland of South Africa, there was a hiatus of up to 35 million years during which chemical weathering was responsible for the liberation of diamonds from some of these kimberlites prior to the development of the Vaal-Orange drainage system. This caused the early fluvial sediments of this drainage system to harbour some high grade deposits. The observed diminishing in diamond content as the age of the fluvial deposits approaches that of the modern day Orange River for instance, probably reflects the fact that especially since the Late Cretaceous the rate of mechanical erosion outstripped that of the liberation of diamonds from kimberlites.

The presence of numerous small diamondiferous kimberlite occurrences in close proximity to the Vaal River is responsible for the fact that economic concentrations of diamonds are found in the modern Vaal River and terraces/palaeo-channels relatively close to it.

It is clear that diamonds were available for distribution and concentration into secondary deposits in southern Africa over a substantial period of time. Being highly resistant to both chemical and mechanical erosion, they could survive numerous cycles of erosion and sedimentation. The aims and objectives of this dissertation (Section 1.4) were to unravel at least part of this history by presenting evidence that would link diamonds from various alluvial occurrences to known "primary" sources.

5.2 Diamond distribution

5.2.1 The role of glacial events

Several authors listed below have in the past drawn attention to the potential importance of major glaciation events in the dispersion of alluvial diamonds and the formation of diamond placers in southern Africa.

Crowell (1983) listed several glacial events that affected southern Gondwanaland prior to the advent of the Dwyka. These events are recorded, *e.g.*, in the:

- Witwatersrand (Wiebols, 1955; Harland, 1981; Tankard *et al.*, 1982);
- Griqualand West and Transvaal Basins (Visser, 1971; De Villiers and Visser, 1977; Visser, 1981);

- Numees Diamictite of the Gariep Group and the Nosib Group (Martin, 1965; De Villiers and Söhnge, 1959; Kröner, 1981; Bond, 1981; Tankard *et al.*, 1982);
- Nama Diamictites (Tankard *et al.*, 1982; Martin, 1965; Germs, 1974);
- Table Mountain Group (Rogers, 1902, 1904; Rust, 1973, 1981; Daily and Cooper, 1976).

Comparing the ages, geographic locations and cratonic setting of these pre-Karoo glacials with the ages and locations of the known diamondiferous kimberlites in southern Africa (Tables 2.1 and 4.2) none of them comes forward as a likely transport conduit for diamonds liberated from these currently known pre-Karoo kimberlites like the Premier-National group, the Marnitz kimberlite cluster, Venetia, Klipspringer-Maarsfontein and the Beit Bridge cluster in southern Zimbabwe. The mystery regarding the primary source(es) for the detrital diamonds found in the conglomerates of the >2.7 Ga Witwatersrand Super Group, the TMS, the Nama Group, the Namibian Skeleton Coast and the Somabula and Chiadzwa/Marange deposits in Zimbabwe remains unsolved.

Harger (1909, 1910) ascribed the occurrence of some alluvial diamonds at Klipdam near Barkly West to the Dwyka Tillite. Du Toit (1954) remarked favourably on this view, citing the correlation between alluvial diamonds and the Carboniferous glacials in western Brazil and Bolivia, as well as those found in glacial drift in North America, in support. In his response to Harger's *(op cit.)* views, Wagner (1914) said: "It is of interest in this connection that the only diamonds ever found in Natal were discovered in the bed of a small stream at the foot of the Itala Mountain, the lower portion of which is built of Dwyka tillite".

Maree (1987) submitted a comprehensive discussion on the subject, pointing out the close proximity of all major alluvial diamond diggings in the Republic of South Africa to regions where the Dwyka Tillite had been exposed to near-surface erosion for a prolonged period of time. Tompkins and Gonzaga (1989) and Gonzaga *et al.* (1994) described the derivation of alluvial diamond deposits from glacial outcrops in Brazil. Field evidence in north-central Brazil that supports the views of Tompkins and Gonzaga referred to above, has been observed by this author. Stratten (1979), Van Wyk and Pienaar (1986), Rouffaer (1988) and more recently Moore and Moore (2004) presented convincing arguments in favour of this model in South Africa. Further support is found in the work of Von Gottberg (1970) and Wilkins *et al.* (1987) on the deposition and occurrence of Dwyka sediments in the former south-western Transvaal, and in karstic depressions south of Pretoria, respectively. Von Gottberg (2006) stated that the results of his fieldwork referred to above convinced him that the Dwyka Diamictite was the "immediate source of alluvial diamonds in the south-western Transvaal (now the North West Province), but that his employers at the time agreed to the publication of his research results only on the condition that no mention was made of diamonds.

De Wit (1996) argued that the occurrence of economic concentrations of diamonds in close proximity to regions where Dwyka Tillite underwent prolonged periods of weathering, can merely be ascribed to decomposition of boulder beds in the tillite which caused local influxes of large boulders and cobbles into the palaeo-drainages, creating ideal conditions for the trapping of heavy minerals. While this is a valid point, it does not preclude the possibility of diamonds liberated from the same tillite to be added locally to the sediment load of the river.

Objections against the possible dispersion of diamonds by the Dwyka glacials also came from other researchers who would point out that there are alluvial diamond deposits in the North-West Province and the south-western Karoo that rest upon a floor of Dwyka Tillite or Ecca sediments. This observation does not however prove that the relevant alluvial diamond deposit did not derive at least part of its diamond content through the reworking of a lag deposit that developed as a result of the decomposition of Dwyka Tillite initially located at a higher elevation either vertically above (in the case of the North-West Province occurrences), or laterally removed. Furthermore, while the fact that diamond distribution by the Dwyka is suggested and implied by a number of facts pointed out in this study and the references cited above, it is not alleged that every alluvial diamond deposit found in southern Africa is supposed to have reached its current locality *via* the Dwyka.

While it must be conceded that no diamond recoveries directly from Dwyka rocks have thus far been recorded, it is also true that the recovery of diamonds from low grade deposits require very large volumes of material to be treated, which had not been done on the Dwyka yet. The Dwyka should not be seen as a high or medium grade, ubiquitously mineralized resource. It is only suggested to be diamondiferous in those portions of the glacial till that acquired at least part of its transport load over areas where diamondiferous debris was present, for instance the immediate surroundings of a weathered pre-Karoo primary source (of which there are a considerable number in southern Africa as pointed out above), or a nearby valley.

Recent discoveries of rich diamondiferous kimberlites in Canada were made after trails of kimberlitic minerals in glacial sediments were followed for up to 1200 kilometres to the source regions (Levinson *et al.*, 1992; Fipke *et al.*, 1995; Kong *et al.*, 1998). Similar results were achieved in Russia (Golubev, 1995).

In southern Africa the following facts point towards glacial dispersal of some of the diamonds derived from pre-Karoo primary sources:

- Rich diamondiferous kimberlites with a pre-Karoo emplacement age a few hundred million years older (Table 4.2) than the Dwyka glaciation, still exist, apart from the unknown sources of the diamonds in the older sedimentary packages mentioned earlier. This left enough time for chemical and mechanical erosion to liberate large quantities of diamonds from these volcanic host rocks into the surface environment, prior to the advent of the Dwyka glaciation.

- The mapped-out route of at least some of the Dwyka glaciation events (Figure 5.1 and Visser, 1985, 1996; Visser *et al*., 1997) shows that its general direction of movement was from the north-eastern parts of the subcontinent, in a south-south-westerly direction crossing the palaeo- and present routes of the Orange River at an oblique angle. Further proof of glacial activities in Bushmanland (apart from the subdued outcrops of Dwyka Tillite around the present day perimeter of the Karoo Supergroup in Bushmanland), comes from the presence of *roches moutonées* and a huge block (approximately 1m x 2 m x 2 m) of corundum-sillimanite (Rozendaal, 1975) on top of Gamsberg. These features are accompanied by glacial striations in polished surfaces that should not be confused with nearby pervasive slickensides. The most likely provenance for this block of corundum-sillimanite is the site of the now defunct Klein Pella corundum-sillimanite mine situated about 15 kilometres NE of Gamsberg, on strike with the measured directions of the said striations.

- Deeply incised channels along the South African west coast hosting diamondiferous sediments are of early Gondwana age – 180 Ma and younger – pre-dating the Cretaceous kimberlites and fluvial systems. Transportation by the Dwyka glacials, as also envisaged for some alluvial diamond deposits in Brazil (Gonzaga *et al.*, 1994) is concluded.

- At the Kwaggaskop alluvial diamond mine along the valley of the Sout River 25 kilometres north of Van Rhynsdorp, two diamonds with kimberlite emplacement ages ($^{39}Ar/^{40}Ar$ analyses of clino-pyroxene inclusions) of approximately 1200 Ma were discovered in recent years (M. Truter, pers.

comm., 2002). This is very close to the emplacement age of the Premier kimberlite, nearly 1300 kilometres to the northeast. Its movement from Cullinan over the (present day) water divide of the Witwatersrand to the head waters of the postulated Karoo (De Wit, 1993) or Gamoep (Malherbe *et al.*, 1986) Rivers can be attributed either to an unidentified, now obliterated palaeo-drainage at a much higher level, or by ice sheets moving from the NE to the SW. Surface features observed on the Sout River diamonds, *e.g.* the percentage of brown-spotted diamonds (D.N Robinson, pers. comm., 2002) suggest that this diamond population is virtually identical to that found on either side of the Olifants River in Concessions 12A De Punt, 12 A and 13A during the course of this study.

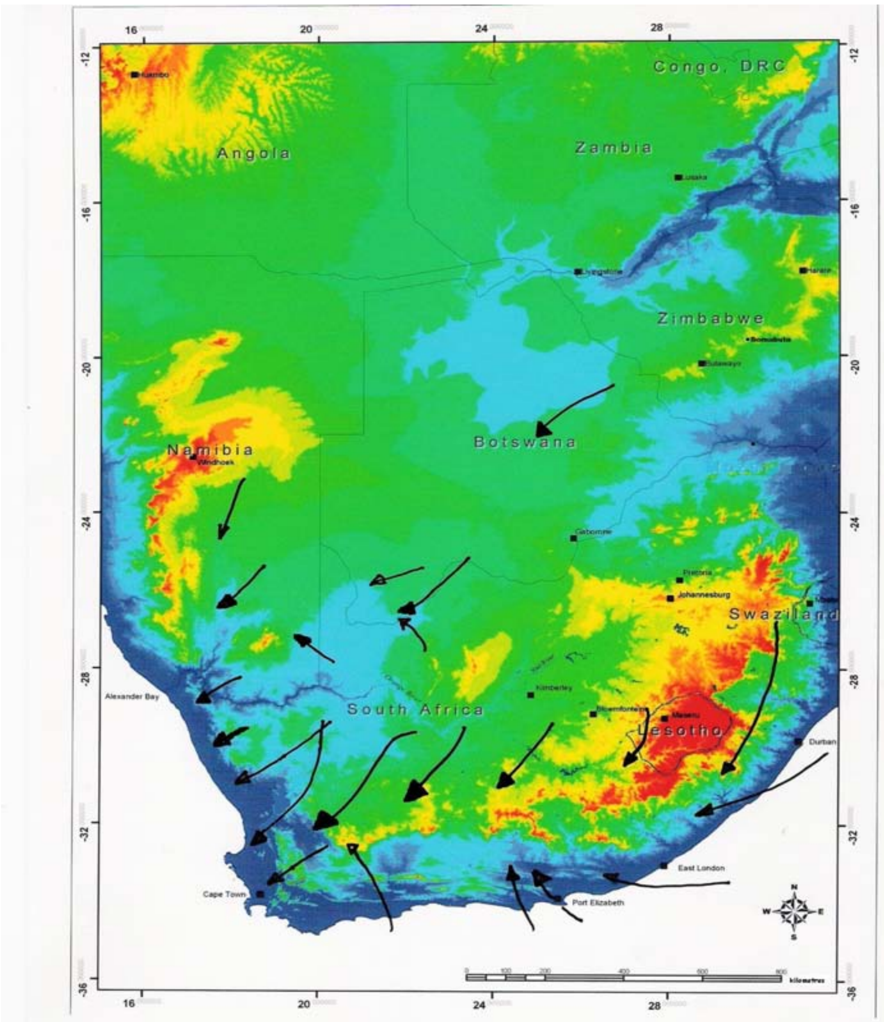


Figure 5.1 Digital Elevation Model of southern Africa (courtesy Sean Johnson, Trans Hex Group) with ice-transport vectors after Moore and Moore (2004)

- Hallam (1959) noted a significant increase in both diamond concentration and average stone size in the vicinity of the estuaries of the major rivers draining the western escarpment in Namaqualand. This phenomenon, strongly suggesting that these rivers were conduits for the transportation of diamonds to the sea, is borne out by the presence of alluvial diamond deposits along the Buffels, Swartlintjies, Horees, Spoeg, Swartdoring and Groen Rivers. Some of these drainages are far removed from the influence area of the Orange and postulated Karoo/Sout Rivers. A point in case is the Doring River with its headwaters near Steinkopf, about 40km north of Springbok. Botha (2003) reported on alluvial diamonds in the valley of the Doring River which ultimately joins the Buffels *via* the Schaapf River. The gravel associated with the small river that drains eastwards from the Kamiesberg to Bosluispan, is diamondiferous - albeit low grade - over its entire strike length (H. Jenner-Clarke, pers. comm., 2007). All the known para-kimberlites that occur in the Kamiesberg range and neighbouring Bushmanland were in the past tested for diamonds and found wanting, as one can expect from off-craton intrusives (Figure 4.4; Clifford, 1966; Helmstaedt, 1993). At least portions of the Kamiesberg range and the Western Escarpment were once covered by Dwyka Tillite which had in the meantime been removed by weathering, thus liberating resistant heavy minerals like diamond to the headwaters of the rivers draining from the escarpment.

- It could be argued that rich deposits of alluvial diamonds should occur along the Limpopo valley, the subcontinent's geomorphologic "mirror image" of the Orange River (Figures 1.2 and 2.30). This is not the case, even though the Venetia, Marnitz and Beit Bridge diamondiferous kimberlite clusters are situated in proximal positions in its catchment area. These are all pre-Karoo kimberlites and it is suggested that the diamondiferous debris derived from them by weathering processes were removed by fast-flowing east bound drainages that did not leave a legacy of diamondiferous sediments behind, or by south-westerly-moving palaeo-drainages and ice sheets prior to the advent of the Limpopo. The small secondary occurrences like Seta on the farm Riedel 48 MS along the right bank of the Limpopo and those near Pafuri would then have developed as a result of diamonds liberated from some of these kimberlites in post-Karoo times, after exhumation of the kimberlites, with a possible contribution from the weathering of Dwyka Group rocks located at higher elevations. This suggestion finds support in the fact that the bedrock at the Seta deposit, topographically lower than the present day surface elevation of the pre-Karoo kimberlites of the area, is comprised of Upper Karoo Clarence Formation sandstone. There is also a possibility that the Pafuri diamonds were derived from pre-Karoo kimberlites located to the north, in SE Zimbabwe.

- A further line of evidence for the Dwyka glaciation as a possible means of transport for diamonds liberated from pre-Karoo kimberlites is offered by the gravel occurrences at Somabula, immediately SW of Gweru in Zimbabwe. This follows visual observations by the author during a bulk sampling programme at this locality which revealed, as also reported by Du Toit (1954) that these deposits comprise a basal fluvial gravel bed overlain by gritty, feldspathic sandstone, fining upward to include clay beds. The gravel consists of sub-rounded to sub-angular pebbles and cobbles of quartz, quartzite, granite, serpentine and banded iron formation, including lutite and jaspilite.

An outstanding feature of the Somabula gravel deposits is the heavy mineral suite, comprising chromite, chrysoberyl, corundum (both ruby and sapphire varieties), kyanite, abundant staurolite, various types of garnet (but none of kimberlitic derivation), gold nuggets, topaz, tourmaline, diamond and gorceixite, the rare phosphate of barium which was also found in the Miocene gravel of the Komaggas Mine along the Buffels River, Namaqualand (Gurney, 1972). Due to the absence of boart diamond and the wide variety of provenance areas (scattered virtually all over Zimbabwe) indicated by the diverse heavy mineral suite, this author concluded (in Moore and Moore, 2006) that this deposit is a long-lived lag deposit concentrated at the base of this Karoo-aged fluvial sedimentary package. Moore and Moore (2006) see the Somabula deposits as a condensed sequence, relatively proximal to the edge of the original Karoo basin, and concluded that the basal gravels are comprised of material transported there by glaciers; these (Permian) tillites were subsequently reworked prior to the deposition of the upper (Triassic) fluvial sedimentary sequence.

- Figure 4.14 illustrates the concentration of diamond populations with significant contributions from pre-Karoo kimberlites, in Marine Concessions 11A, 12A and 13A. Considering the location of the known pre-Karoo diamondiferous kimberlites in the northeastern parts of the subcontinent and the mapped-out ice vectors of the Dwyka glaciation, these concessions are ideally positioned to serve as "depocentres" for diamonds moved along this postulated transport route.

- The surface feature study done on the Skeleton Coast diamonds (Section 4.1.4) also supports the conclusion drawn on geological and geomorphic grounds, namely that sources (most probably hosting diamonds liberated from pre-Karoo kimberlites) to the east of the Skeleton Coast, and not the Sperrgebiet, is the provenance for the bulk of the Skeleton Coast diamonds. In 2.2.6 reference has been made to the fact that the 300km stretch between Chameis Bay and the Huab River that is devoid of diamond deposits, coincide with a paucity in the presence of Dwyka Group outcrops (on or close to the Western Escarpment) which reappear immediately east of the Huab mouth.

Field relations and the results of this study on surface features and FTIR characteristics discussed in the preceding paragraphs thus comprise substantial evidence pointing to the Dwyka glaciers and ice sheets as possible and indeed probable modes of transport of diamonds liberated from pre-Karoo kimberlites in southern Africa.

5.2.2 Fluvial processes

Since the development of the oldest alluvial diamond occurrences known in southern Africa, rivers played an important part in their existence. Diamonds occur as a clastic heavy mineral component in Witwatersrand conglomerates located in the Klerksdorp and East Rand basins (Minter and Loen, 1991).

During the fluvial transportation of diamondiferous debris from the vicinity of the host kimberlite (or from the region where diamonds were liberated from decomposing tillite) three important factors become involved.

Firstly, poor quality diamonds do not survive the torrid conditions prevalent in most fluvial systems, resulting in an increase in the average quality of the surviving diamond population. Secondly it is well known that fluvial processes tend to concentrate heavy minerals like diamond in suitable trap sites, creating rich deposits often with a higher diamond grade than the original source. Thirdly, especially in southern Africa, fluvial systems were responsible for the transportation of alluvial diamonds to the Atlantic Ocean where they were concentrated by wave action to form high grade marine deposits.

Any model seeking to unravel the drainage evolution of this part of the subcontinent must satisfy the evidence supplied by resilient minerals like diamond and zircon since these were able to survive numerous stages of erosion, transportation and sedimentation, while their mineral chemistry and other physical properties allow the identification of most probable source regions within specific time frames. The results of this study on alluvial diamond populations allowed the compilation of Table 4.8 in which the most likely provenance regions for these alluvial deposits are summarized. In addition the work done on zircon grains from gravel deposits hosting some of the alluvial diamonds as well as drill core from the Ecca Group, facilitated the construction of Figures 4.20 and 4.21 summarizing the results of these geochronological studies. In the light of this new information three important existing hypotheses on the drainage evolution of southern Africa and its role in diamond distribution, are discussed.

5.2.2.1 The palaeo-Karoo River and a dual exit for the Orange River

This hypothesis (Dingle & Hendey, 1984) was expanded by De Wit (1993, 1999), and De Wit *et al., (*2000) who disagreed on the postulated drainage switching of Dingle & Hendey (*op. cit.)*. However, together with the work of McCarthy *et al.* (1985); Partridge and Maud (1987) and Behr (1989), a model was accepted comprising the former existence (Figure 1.1) of:

- A **Karoo River** in the south that was thought to be comprised of the Upper Orange/Vaal River system that linked up with the present Olifants River *via* the Sout River.
- The Lower Orange River which drained southern Namibia and Botswana and linked up with the proto-Molopo River and formed the northern palaeo-drainage system, referred to as the **Kalahari River**.

Initially, the hypothesis for the former existence of a major Karoo River apparently found support from Brown *et al.* (1995) who reported on the relative ages recorded in the two main depocentres in the off-shore Orange River basin, *viz.* 117,5 to 103 Ma in the south (Olifants River) and what they called "post-103 Ma" in the north (vicinity of the present Orange River mouth).

Du Toit's (1910) suggestion that the presence of jasper pebbles near Britstown could be seen as evidence that the upper Vaal/Orange River once entered the Karoo south of Prieska was seen as possible support for this theory. With added input from his geomorphologic investigations De Wit (*op. cit.)* interpreted the presence of diamonds in the Koa River valley to a link between the upper portion (also known as the Geelvloer River) of the Koa with the palaeo-Sak River valley during the Miocene.

This study showed that the diamond population found at the mouth of the Olifants River does not reflect a theoretical population transported by a Cretaceous-aged system draining, *inter alia*, the Cretaceous kimberlite field of Griqualand West and the western Free State. If the Orange/Vaal drainage ever utilized the 31° South exit point the diamond population found near the Olifants River mouth should reflect derivation from essentially Cretaceous kimberlites, with the possibility of some stones derived from pre-Karoo kimberlites and winnowed from the Dwyka (Moore and Moore, 2004) to be present as well. This is not the case. As indicated in the relevant paragraphs in Section 4.1 the diamond sample population from 12A-De Punt and 13A, located on either side of the present Olifants River mouth, seems to be unique with a pronounced pre-Karoo age based on the presence of brown spots, and showing a paucity of nitrogen aggregation of less than 25-30%. The diamond population at Graauw Duinen (about 20 km north of the Olifants River mouth) reflects diverse sources, including the Late Jurassic Helam kimberlite at Swartruggens as indicated by corresponding NAD fields and the presence of significant numbers of amber-coloured cuboid diamonds which enjoy an abnormally high concentration at Helam.

There is also a major time discrepancy involved with Dingle and Hendey (1984*)* allocating a Palaeogene age to their proposed southern exit of the Orange, while Brown *et al.* (1995) showed that the Orange River already deposited its sediment load into the Atlantic at its present latitude during that period. As mentioned in Chapter 2, Buntfeldschuh on the Skeleton Coast comprises a sedimentary package of Eocene age, rich in well-rounded clasts typical of the Vaal-Orange System, thus confirming the findings by Brown *et al.* (*op. cit.*), for the Eocene as well.

Wigley (2005) studied the sediments in the off-shore Cape Canyon located south-west of the Olifants River mouth. The results of her research revealed a Pliocene-Pleistocene age for the incision and not the Oligocene as suggested by Dingle and Hendey (1984). The work by Wigley (*op. cit.*) supports the conclusion above, namely that the Orange River already entered the Atlantic at its present latitude since before the Eocene.

As a result it is proposed that the vast majority of the sediments contained in the southern of the two depocentres referred to above were derived from the Cape Fold Belt *via* the Olifants River, with some input from decomposing Dwyka (including diamonds from pre-Karoo sources) and only Karoo sediments transported by the Sout River drainage system. This proposal is supported by the following arguments:

Wigley (2005) found that the material contained in the Cape Canyon is essentially comprised of clean, mature sand deposits with no evidence of exotic clasts as one would have expected from the postulated major Karoo River. It could be argued that the part of the depo-centre investigated by Wigley (*op. cit.*) represents the more distal part of the sediment package, with the coarse clastic material having been deposited closer to shore. However, it remains highly unlikely that all <2mm particles of exotic material were also deposited closer to the shore since jasper, for example, has the same SG as quartz. Should one look at the Clarence Formation as a provenance for the mature sand deposits in the Olifants River depo-centre, a highly selective bed-load of the postulated Karoo River reflected in the composition of the Olifants River depo-centre is implied. The pure white sand banks visible in the modern Olifants River valley next to highway N7, derived from amongst others the Graaffwater Formation of the Table Mountain Group flanking the valley, are indicative of a provenance that not only answers to the mineralogical composition, but is also in terms of geographic location the preferred choice.

According to D. N. Robinson (pers. comm., 2003) no brown spotted diamonds were found among the sample population studied from the Sak River. This fact is in agreement with the stratigraphic position of these deposits (resting upon Karoo sediments while brown-spotted diamonds were derived from pre-Karoo kimberlites), and distinguishes this diamond population from that found along the Sout River (Kwaggaskop) and at the mouth of the Olifants River (section 4.1.8 above). De Wit (1993) stated that there is a marked similarity between the Sak River diamond population and that found at Bosluispan. During the cause of the present study a small percentage of brown-spotted diamonds (indicative of derivation from kimberlites with a pre-Karoo emplacement age) was also identified in the Bosluispan population, located topographically below the base of the nearby Dwyka glacials. It is suggested here that the proposed link between the palaeo-Sak and Koa Rivers (De Wit, 1993) is supported by these results, with a limited contribution of diamonds from pre-Karoo kimberlites subsequently being added to the Bosluispan diamond population through the weathering of proximal Dwyka glacials.

Most of the other evidence submitted in support of the Karoo River hypothesis applies equally well to the Gamoep River proposed by Malherbe *et al.* (1986) referred to in the following paragraphs. The Sout and its main tributary the Varsche River is just another west-bound system draining the western escarpment, without being part of a major system transecting the Karoo geographic province. Its capacity to incise the coastal region was enhanced after the confluence with the Olifants River.

In rejecting the hypothesis of a palaeo-Karoo River having transported vast quantities of diamonds from the Cretaceous kimberlites of the Kimberley region to the vicinity of the present day Olifants River estuary, there are two aspects concerning the Cenozoic geology of the West Coast and some associated diamond deposits that were apparently accounted for by the said Karoo River, that now need to be explained:

i. the presence of large quantities of jasper and banded iron formation clasts, so-called exotics, (Figure 5.3) that are present in the marine gravel between Doringbaai and at least to the northern boundary of Concession 11A as well as in the onshore deposits on Graauw Duinen, and

ii. also on Graauw Duinen, the presence of diamonds with IR characteristics reminiscent of Cretaceous kimberlites of the Northern Cape and Lesotho, as well as diamonds with **IR characteristics <u>and</u> crystallographic features** (Figure 5.2) strongly indicating possible derivation from the ~147 Ma Swartruggens (Helam) kimberlite in the North West Province.

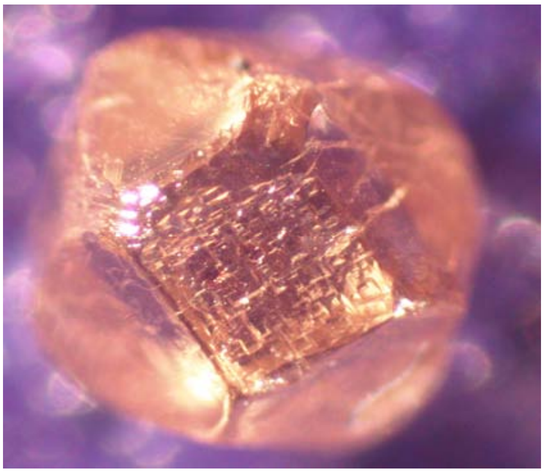


Figure 5.2 Photo-micrograph of 2 mm Type 1b amber-coloured diamond (a cubo-octahedron) from Graauw Duinen. *The remnant of an original cube plane faces the camera. These diamonds constitute an abnormally high (compared to other South African kimberlites) concentration in the Swartruggens population, and with the exception of one Type 1b stone in the sample population of Marine Concession 7A, they were* ***only*** *found at Graauw Duinen where they comprise just over 4% of the sample population. This is regarded as significant with respect to provenance identification, considering their absence from the other populations studied.*

As mentioned in preceding paragraphs the two marine concessions on either side of the Olifants River mouth, 12A-De Punt and 13A, boast unique diamond populations that imply, on the grounds of brown-spotted and highly polished diamonds, a significant contribution from kimberlites with pre-Karoo emplacement ages. It is suggested that these diamonds were transported from the interior to the southwestern parts of the subcontinent by pre-Karoo fluvial systems and the Dwyka glaciers. Their presence and that of the exotic clasts, in the shallow marine environment can be ascribed to either:

i. being winnowed out of the decomposing Dwyka sediments and washed down to the coast by rivers draining westward from the escarpment, or

ii. direct spillage from disrupted Dwyka sediments near the continental margin during continental break-up, or

iii. a combination of these two processes, with the former contributing such resistates to the ocean over a prolonged period of time during erosion of the escarpment.

This model offers an explanation for the presence of diamonds with an indicated pre-Karoo emplacement age accompanied by exotic clasts in present-day marine gravel in the vicinity of the Olifants River mouth.

The diamond population of the marine concessions immediately north of the De Punt area, as well as that of the onshore Miocene deposits on Graauw Duinen, are different from those of 12A-De Punt/13A. It would appear as if the "transport channel" for the "Graauw Duinen" diamonds did not utilize the Sout/Olifants River system. It is suggested that these diamonds were transported to the SW parts of the subcontinent *via* the Late Cretaceous to Palaeocene Gamoep River of Malherbe *et al.* (1986). In this regard it is of interest to note that the IR characteristics of the diamond populations from Ventersdorp (this study), resemble those from kimberlites northwest, north and northeast from Ventersdorp. This would indicate a drainage system with a generally north-to-south vector that could have transported diamonds from some of those source regions (Botswana, Venetia, Helam, Klipspringer, and Premier) to the catchment area of the palaeo-Gamoep River. A study of the course of the postulated Gamoep River (Figure 5.4) reveals that it could have collected diamonds liberated from numerous Cretaceous kimberlites apart from the diverse population from the north (including Helam). This would account for the diverse diamond population accompanied by exotic clasts found at Graauw Duinen.

The absence of exotic clasts from the mature sand in the "headwaters" of the Cape Canyon as reported by Wigley (2005), while such clasts abound in the near-shore environment and even in the raised beach deposits on Graauw Duinen and Annexe Blaauwklip (see paragraph below), still calls for an explanation. Following the above line of reasoning we assume that these exotic clasts were present in the near-shore environment, at the time when the incision of the Cape Canyon took place. A fluvial system that was able to do the amount of incision illustrated by the Cape Canyon must have been energetic enough to pick up all debris in its way and deposit it at the continental margin way beyond the confines of the Cape Canyon. Clasts that were too big to be transported by that river had very little chance at all to be moved towards the Cape Canyon. All (moveable) traces of the exotics strewn over the shore and sea floor in the way of this juvenile Olifants River were thus removed and by the time the river went into an aggradation phase, it was the mature sand of the Table Mountain Group (its 'normal' bed-load) that was deposited.

Further evidence that the exotic clasts characterizing the Graauw Duinen deposit were transported to the southwestern past of the subcontinent by the Dwyka glaciers and not by a postulated Karoo River, is found in the presence of similar deposits on the farm Annexe Blaauwklip 433, about 30 km south of the Olifants River estuary. The most likely route for these clasts to have reached the Atlantic prior to being concentrated in beach deposits would have been *via* west-bound rivers located south of the Olifants, draining the escarpment.

Figure 5.3 Naturally polished sedimentary clasts characterizing on-shore Miocene deposits at Graauw Duinen, 20 km north of the Olifants River estuary, and Annexe Blaauwklip 433, roughly 30 km south of the Olifants River.

5.2.2.2 The "Early Tertiary" Gamoep River hypothesis.

Although the term "Tertiary" is becoming obsolete, it is retained here as reference to the title of the original paper by Malherbe *et al*. (1986).

The postulated presence of this palaeo-drainage was proposed by Malherbe *et al*. (1986). While some of the points raised by these authors (Section 1.2) are open to debate, the aspect concerning the possible palaeo-Gamoep River deserves special attention. This drainage system is said to have reached the sea *via* the Swartlintjies River. With the headwaters of the Buffels River located in the Kamiesberg immediately to the west of the Koa Valley (Figures 1.3 and 1.4), the Buffels River also qualifies as a possible conduit for diamonds brought to this region by a postulated palaeo-Gamoep River. This palaeo-drainage, (Figure 5.4) has been identified on the basis of the following parameters:

i. the regional distribution of salt pans as mapped out by Hugo (1974) and

ii. geological mapping, LANDSAT imagery and observations in wells and borehole cuttings by Malherbe *et al*. (*op. cit.*).

The mapped out route of this palaeo-drainage commences immediately west of Odendaalsrus, crossing the present-day Orange River upstream from its confluence with the Vaal River and currently ending up east of Springbok in the valley of the Koa River in Bushmanland.

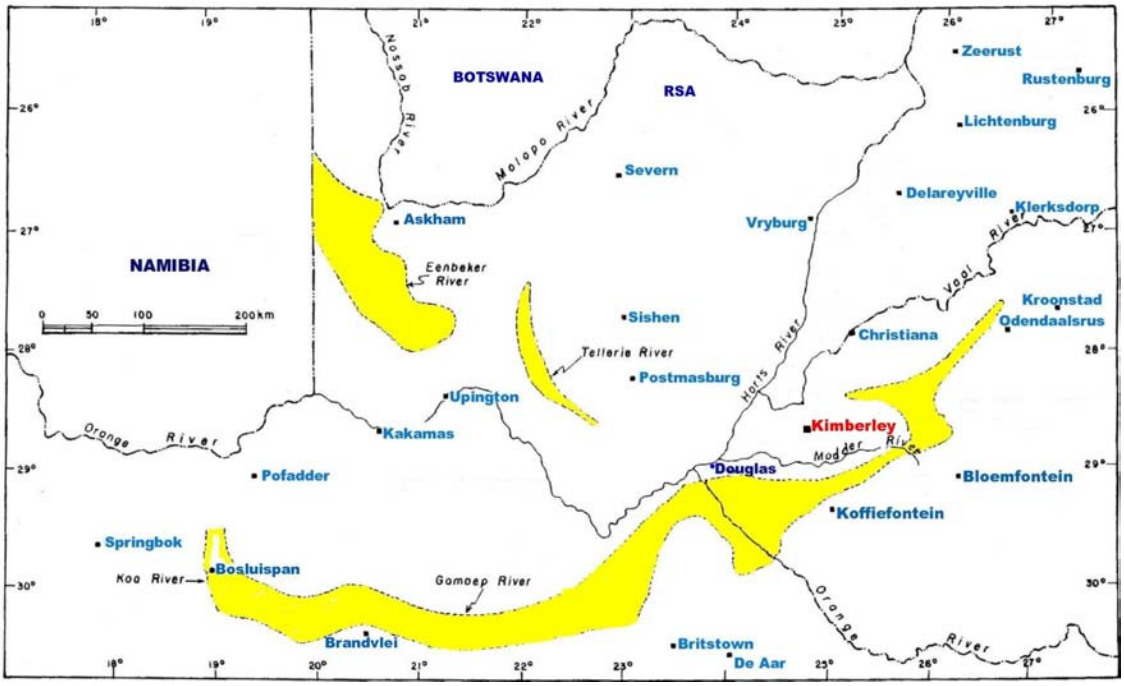


Figure 5.4 Portions of the palaeo-courses (yellow areas) of the Gamoep and other extinct (Eenbeker, Tellerie, and Koa) Rivers (After Malherbe *et al.*, 1986).

In the light of its postulated age, location of its headwaters and its general course, this postulated river would have drained an area where it could collect diamondiferous debris from Cretaceous kimberlites only, since at that time its incision would not have gone through the basal Karoo rocks. The diamond population from the Sak River attests to this.

If one considers the present day geomorphology of the region, it seems unlikely for a river to have flowed from the Koa Valley westwards over the Kamiesberg, currently the highest topographic region in Namaqualand. However, De Wit (1993) suggested that up to 600 metres of the crust in this region had been stripped off by erosion and it is therefore conceivable that such a drainage system could have existed prior to the exhumation of the competent rocks of the pre-Karoo Namaqua Metamorphic Complex providing that it was old enough, *e.g.* Late Cretaceous to Palaeocene. Evidence from zircon model ages submitted in Section 4.3.4 indicates that exhumation of Archaean rocks above the escarpment was initiated between Eocene and Early Miocene times.

Support for this view is also found in the present topography of the region, as discussed below.

There are areas where the current Koa River valley is separated from the head waters of the Buffels River by a relatively narrow water divide comprising a portion of the eastern foothills of the Kamiesberg with a maximum surface elevation of 1000 metres above mean sea level. From this point eastwards the surface elevation drops steadily to 887 metres above mean sea level in the Koa valley, only 113 metres lower than the water divide described above.

This scenario is illustrated in Figure 5.5, a Google Earth image appropriately annotated.

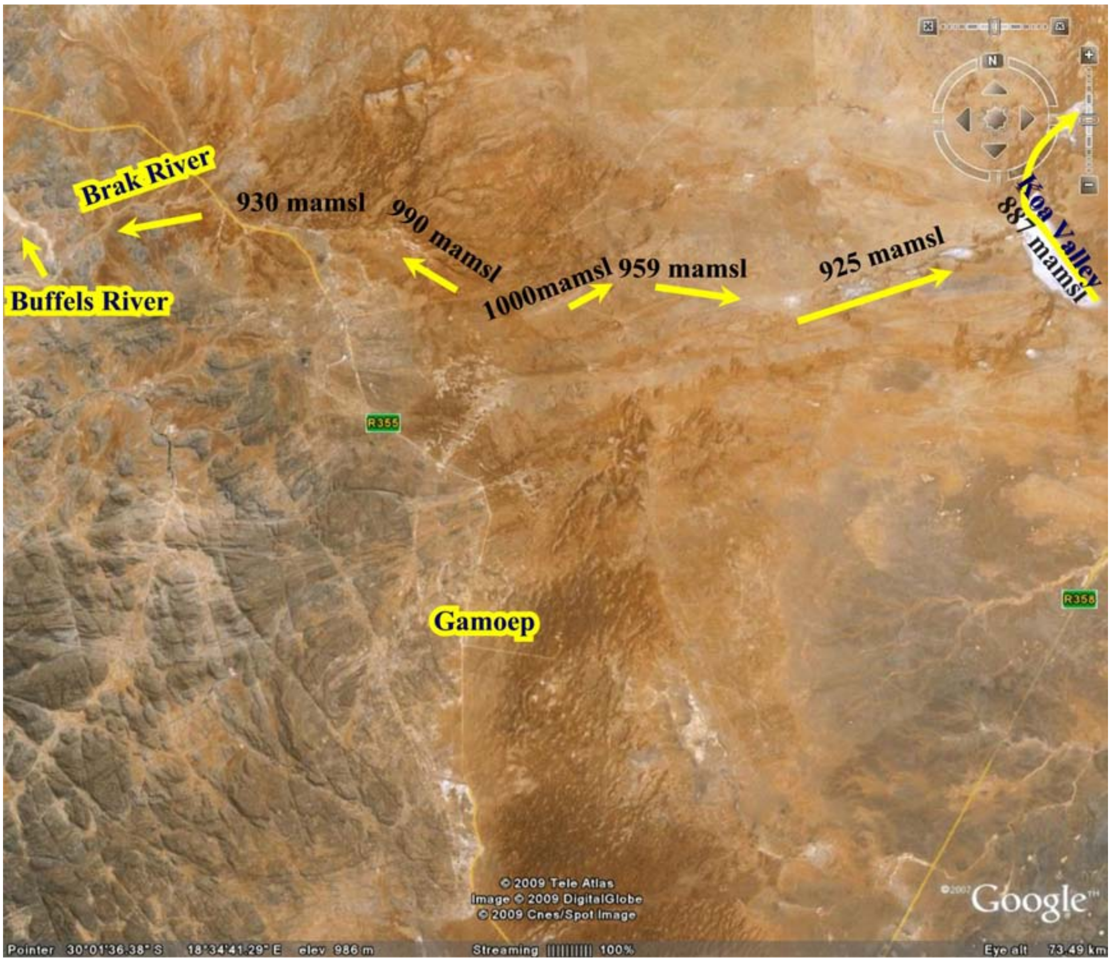


Figure 5.5 Surface features of the Bushmanland/Kamiesberg transition north of Gamoep. Surface elevations: SRTM90 *via* Google earth.

In the same region (Figure 5.6) a major east-west flowing head water tributary of the Buffels River can be seen following a superimposed course across an exhumed geologic structure.

Figure 5.6 Superimposed river course: head waters of Buffels River

The field evidence for the region between Odendaalsrus and the Bushmanland submitted by Malherbe *et al.* (1986), supported by the diamond study results discussed above (indicated link between the Sak River diamonds and Bosluispan, but no link between the Sak River population and that of the Sout River) cannot be ignored. Furthermore, the diamond population found in the Miocene deposits of the Buffels River valley reveals similarity with that of Bosluispan, including the small percentage of brown-spotted stones. De Wit (1993) also reported the presence of pyrope garnets at Bosluispan but concluded that the Orange River never ran through the Koa Valley. Support for this conclusion is seen in the absence of pyropes and brown-spotted diamonds in the Miocene sediments of the Lower Orange River valley in this study.

A link between Bosluispan and the Buffels River is also indicated by the Platelet Preservation Index (PPI) of the diamonds. The Bosluispan population boasts an abnormally high percentage (8.8% vs zero at most of the other alluvial deposits studied) of irregular diamonds. While PPI data for the Buffels River population were not available for this study the diamond population found in Marine Concession 5A which straddles the Buffels River estuary, is the only occurrence sampled along the ± 100 km coastal stretch between Concession 8A and 2B where irregular diamonds are present. While it is conceded that, ideally some of the sample populations could have been larger, it is inconceivable that irregular diamonds would have been repeatedly missed during sample selection from ROM production parcels, had they been present. It is therefore suggested here that the Miocene deposits in Bosluispan and the Buffels River valley sourced their diamond populations from material brought to this region by the palaeo-Gamoep River probably during the Palaeocene, supplemented by diamonds from pre-Karoo kimberlites winnowed out from Dwyka glacials that previously covered the Kamiesberg and part of the Bushmanland.

Two important events that saw the demise of this palaeo-drainage, were the beheading of the Gamoep River by the Orange upstream from Douglas, and the exhumation of the Kamiesberg that severed the link between the palaeo-Koa and Buffels Rivers.

While the evidence regarding the former existence of a Gamoep River is supported by the diamond data of this study, the suggestion by Malherbe *et al.* (1986) that the Orange River had to "re-emerge as the major drainage system during Quaternary times…" is not acceptable. Field observations made during this study support the views of Van Wyk & Pienaar (1986, on the Lower Orange) and Gresse (2003, for the Mid-Orange) indicating a continuous meandering and incising river more or less along the present Orange River valley (or relatively close to it) from the Eocene to the Pliocene-Pleistocene. It is concluded that the Gamoep River must have been:

- Not Tertiary, but Mid- to Late Cretaceous to Palaeocene in age.
- First beheaded by the advent of the Vaal River north of Kroonstad, while its middle and lower stretches remained active.
- Finally cut off by the advent of the Orange River, immediately upstream from Douglas, as indicated in Figure 5.4.
- Having been cut off from the high rainfall area afforded by Late Cretaceous tropical conditions in the northeast and east, the Karoo stretch of this river quickly drowned in its own sediments. Where protected from erosion its course became covered by calcrete or duricrust and aeolian sand, as described by Malherbe *et al.* (1986). In its lower reaches this drainage could have been kept alive by its link with the Krom River until exhumation of the Kamiesberg put an end to its exit *via* the Swartlintjies or Buffels River courses. Both the Swartlintjies and Buffels River valleys host basal diamondiferous palaeo-channel sediments.

5.2.2.3 Postulated palaeo-Kalahari River

The former existence of this river (Figure 1.1) was proposed *inter alia* by Behr (1989) and De Wit (1993). It was said to represent the forerunner of the Lower Orange River and drained southern Namibia and Botswana, linking up with the proto-Molopo River.

In Section 4.1.8 an interpretation of the results of the diamond study showed that this postulated palaeo-drainage either never existed, or it evolved much later after significant quantities of Botswana diamonds had been moved in south-bound drainages across the route where the Kalahari River was thought to have developed.

5.2.2.4 Postulated major palaeo-northwesterly drainage system

In Section 5.2.1 evidence and arguments by Moore and Moore (2004) were submitted in support of the view that Dwyka glaciation played a major role in the distribution of diamonds from pre-Karoo "primary" source regions, especially toward the south-western, western and north-western parts of the sub-continent. They also suggested the former presence of a series of equidistant, sub parallel rivers draining from the southeast to the northwest into a postulated palaeo-Kalahari River and suggested that these rivers were responsible for the formation of the series of alluvial diamond deposits found to the north and northwest of the major "Kimberley-Barkley West" Cretaceous kimberlite province (Figure 5.7).

Apparent support for this view could be seen in the conclusion by De Wit (2004) that the diamondiferous deposits at Nooitgedacht north of Kimberley were brought there by a drainage consequent to a surface gradient inclined from the southeast, the Kimberley region, but De Wit (pers. comm., 2007) added that the Nooitgedacht deposits could have been the result of a localized valley slope.

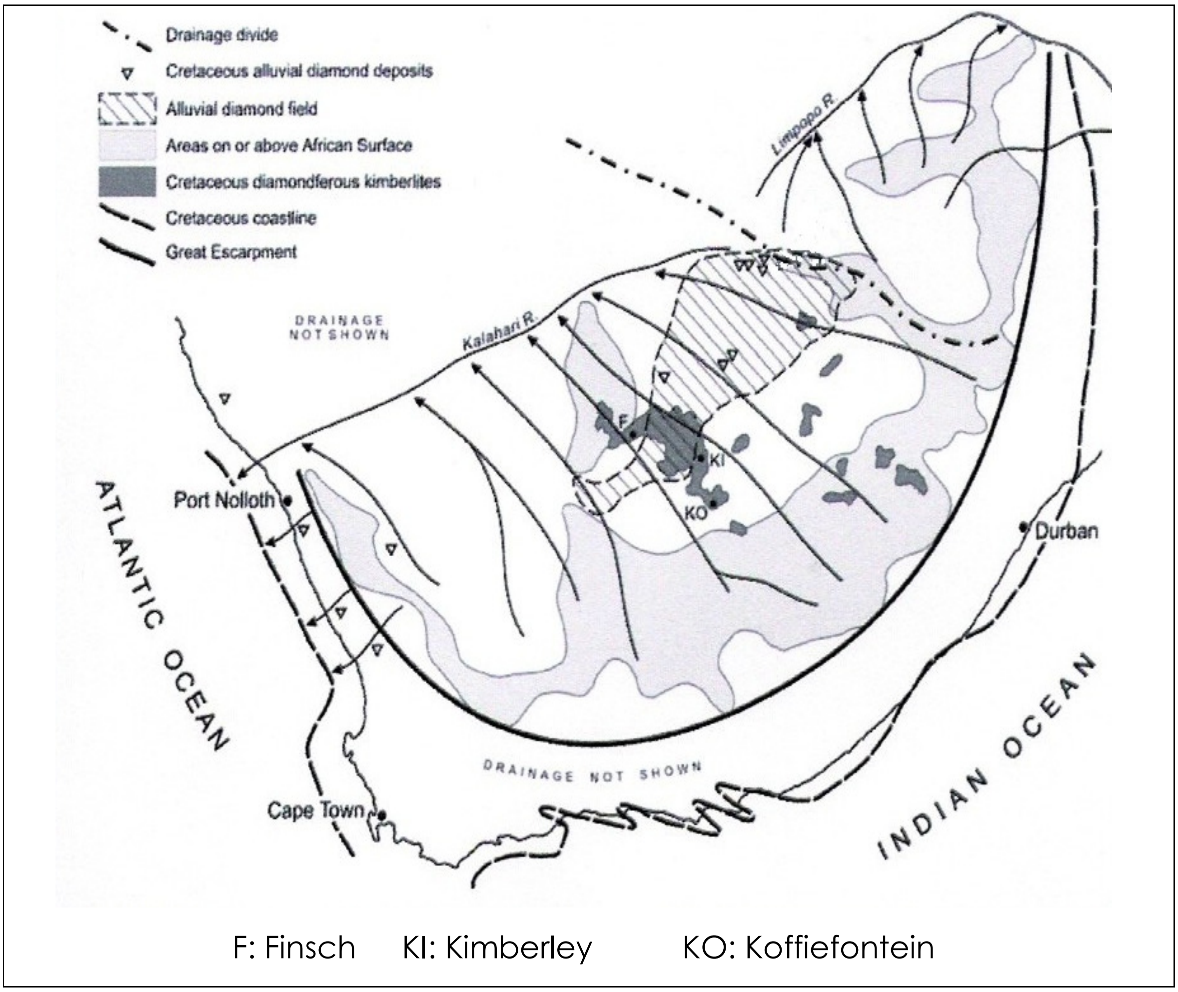


Figure 5.7 Major palaeo-northwesterly drainages (Moore and Moore, 2004).

If the major north-westerly movement of diamonds from the Kimberley-Barkly West field into the present day Northwest Province is correct, one would expect the alluvial diamond populations at any given one of these localities to indicate a diverse origin, but with an IR and surface feature signature reminiscent of those of the kimberlites in the above mentioned field. The diamond populations of this study, included two discrete alluvial localities about 30 km east-west from each other north of Ventersdorp, two alluvial localities on the Lower Vaal River, and the Samada kimberlite. Three of the Ventersdorp diamonds reveal a high incidence of both green and brown spots, reminiscent of the diamonds found in the auriferous-uraniferous conglomerates of the Witwatersrand Supergroup (Robinson, 1979), while the rest reveal morphological features and characteristics that cannot be linked to any known primary source located in the Kimberley area. The IR (NAD) characteristics of the Ventersdorp occurrences also do not compare well with those from Jagersfontein, Koffiefontein, Roberts Victor/Kimberley, while numerous overlapping sub-fields with kimberlites to the NW, N and NE *viz.* Orapa, Jwaneng, Venetia, Klipspringer, Premier and Helam do feature on the Ventersdorp diagrams. It is therefore concluded on the basis of surface features and IR characteristics, that the Kimberley-Griqualand-West and western Free State kimberlites made no significant – if any – contribution to the alluvial diamond populations north of Kimberley.

A remarkable similarity between the NAD's and surface feature characteristics of the two Vaal River deposits, Christiana and Sydney-on-Vaal, and that of the Samada or Kaal Valley kimberlite near Saaiplaats in the northern Free State Province was noticed. In addition, Samada is the only southern African kimberlite apart from Letseng in Lesotho, where the diamond population reveals a significant amount of platelet destruction caused by post-crystallization plastic deformation associated with a catastrophic heat event. The significance of the presence of irregular diamonds in the Samada population is important with respect to provenance studies for alluvial diamond populations, since the Platelet Preservation Index (PPI) offers a qualitative method of establishing a definite link between a portion of an alluvial population and Samada and/or Letseng.

This feature is a rare phenomenon among the alluvial diamond populations studied, but not so in the two Vaal River populations where it suggests a definite link with Samada.

In Section 4.1.2 it has been shown that plastic deformation is the reason for brown and pink colouration in diamond, and the platelet destruction observed on the Samada NAD and referred to above, finds support in the presence of brown and pink diamonds in this population.

Figure 5.8 Selection of coloured diamonds from Samada. Scale gradations in millimetres.

This indicated link between Samada and the Vaal River populations at Christiana and Sydney-on-Vaal lends support to the former existence of a localized north-westerly drainage, corresponding to the eastern part of the model proposed by Moore and Moore (2004 and Figure 5.7), but of limited extent and apparently not reaching beyond the Vaal River, in the light of the differences between these Vaal River populations and those identified near Ventersdorp.

It must however be conceded that there are a number of diamondiferous kimberlites not too far from Samada, for which no diamonds were available for this study, namely Star, Voorspoed and Lace, but according to F. Viljoen (pers. comm. 2008) irregular diamonds are rare among their populations.

5.3 Conclusions on diamond distribution

The postulated south-flowing fluvial system feeding the Gamoep River was probably not the only fluvial system to transport diamonds in a south- to south-westerly direction in post-Karoo times. The source(s) of the abundant alluvial diamond deposits of the Lichtenburg-Schweizer Reneke-Wolmaransstad-Bloemhof region have not been identified yet and is likely to comprise a research project on its own. Partridge and Maud (2000) see the diamondiferous Lichtenburg gravels as part of the palaeo-drainage network that transported diamonds "from sources north of the present continental divide". Furthermore, the postulated Gamoep River would not have been the only recipient of diamondiferous material *via* the former north-to-south drainages. The more westerly of these drainages would have fed the palaeo-Vaal River which according to De Wit (2004) must have been in existence during the early post-Gondwana period. Microscopic surface feature studies done on diamond populations from the Randfontein-Lichtenburg area (this study) indicate a major contribution from kimberlites with pre-Karoo emplacement ages. The fact that such kimberlites currently known are all located to the north and northeast of these deposits, confirms the conclusion of a generally north-south transport direction for these gravel deposits, arrived at by Stratten (1979), following a study of sedimentary clasts.

This study did not identify any remnant of a fluvial system that could have been involved in diamond transportation between the Ventersdorp area and the north-eastern parts of the postulated Gamoep River catchment area near Odendaalsrus. It is however true that the indicated period during which this postulated transportation took place falls inside a portion of the geochronology of southern Africa (end of Karoo volcanism to the Eocene) that is marked by the virtually complete absence of onshore remnants of deposits or drainages. We do know that severe denudation of the subcontinent took place during that period, but the record of the fluvial systems active immediately before and those that partook in that denudation is lacking.

It is suggested that at least part of the above-mentioned diamond populations were transported from the northwest, north and northeast by Dwyka glacials and hitherto unknown fluvial systems, from different source regions. Bootsman (1998) suggested that the predecessors of the Harts, Morokweng and Molopo Rivers were all southward-flowing and predated the formation of the Kalahari Basin. The headwater tributaries of the proto-Harts reached into southern Botswana. Mayer (1973) showed that the proto-Harts initially followed a course south of Lichtenburg. It was subsequently captured by a tributary of the Vaal River which developed along an exhumed pre-Karoo valley east of the Ghaap Plateau, the Harts River.

Following uplift along the Griqualand-Transvaal Axis, Du Toit (1933) saw the division of the proto-Harts into a north-westerly flowing arm (the Mahura Muthla) and a southerly flowing arm (the Harts). An analysis of the clast assemblage of the sediments preserved in palaeo-meanders of the Mahura Muthla River convinced Partridge and Maud (2000) that this river had an initial flow from northwest to southeast.

McCarthy (1983) presented evidence for a major southward-flowing river (which he called the Trans-Tswana River), with its headwaters "extending well into south-central Africa". He correlated the demise of the Trans-Tswana River with the commencement of the infilling of the Kalahari Basin.

The evidence submitted in the preceding paragraphs supports the author's suggestions about the former existence of north-south flowing rivers that would have been active in the generally southward transportation of diamonds from Botswana and the northern parts of South Africa.

Reference was made to the postulated Kalahari River, which was said to have drained southern Namibia and Botswana and linked up with the proto-Molopo River, entering the Atlantic close to the latitude of the modern Orange River (Behr, 1989; De Wit, 1993). The results of this study show that this palaeo-drainage either never existed, or developed after significant quantities of Botswana diamonds were transported to the headwaters of the palaeo-Gamoep River. The Gamoep would have been instrumental in transporting these, together with diamonds collected *en route* to the southwestern parts of the country. After beheading of the upper reaches of the Gamoep by the advancing Orange River upstream from Douglas, Botswana diamonds became part of the diamond population transported by the Miocene Orange River.

The evidence from the offshore Olifants River depo-centre and the diamond populations from the vicinity of the Olifants River mouth, the similarities reported between those populations and that at Kwaggaskop, the disparities between these populations and those of the Sak River, and the similarities between the Sak River population and that of Bosluispan, argue against the proposed transportation of vast quantities of diamonds *via* a former major Karoo River. These diamond populations do support the hypothesis of a palaeo-Gamoep River, which drained an area containing diamonds derived from a diverse group of kimberlites with emplacement ages ranging between Late Cretaceous and more than 1299 Ma ago.

The possible contribution of pre-Karoo drainage systems to the northeast-to-southwest dispersal of diamonds liberated from pre-Karoo kimberlites cannot be ignored. It is only logical to assume that diamonds liberated from those kimberlites over a period of a few hundred million years would have found their way into nearby valleys and streams to be transported for unknown distances. The fact that the movement of the Dwyka glaciers was in a generally south- to south-westerly direction, indicates a palaeo-slope that would have given rise to a drainage pattern in that general direction.

Southern Africa boasts numerous examples of Dwyka valleys that exploited pre-existing valley features, apart from those created by Dwyka glaciers themselves (Du Toit, 1910; Helgren, 1979; Visser, 1985, 1987). This aspect of the geomorphology of the subcontinent supports the postulated transportation of some diamonds liberated from pre-Karoo kimberlites by the Dwyka glaciers and ice sheets.

As for the field evidence submitted by Malherbe *et al.* (1986) and De Wit (1993) in respect of their two postulated major palaeo-drainages in the Karoo, it is possible that these authors in general refer to the erosional remnants of the same palaeo-drainage – with the exception of the Sout River deposits - adding different interpretations to its timing and final course, and thus to its possible role in diamond distribution.

CHAPTER 6. DISCUSSION

Ever since the discovery of diamonds along the south-western coast of Africa, their source regions and the way by which they were transported after liberation from their hosts to the coast have fuelled speculations and postulations.

While general consensus had been reached on the fact that these diamonds were derived from sources in the hinterland of southern Africa and not from offshore kimberlites as suggested by some earlier workers, two aspects remained unresolved: the specific provenance regions for individual alluvial diamond deposits and the evolutionary history of the fluvial and other system(s) responsible for the transportation of the diamonds from their ultra basic host(s) to the coast. One of the aims of this study, as set out in Chapter 1, was to identify specific sources in the hinterland of southern Africa as most likely provenance localities for specific alluvial occurrences. As the study proceeded it soon became apparent that the question regarding the source regions is intricately interwoven with the geochronology of the subcontinent and especially with the evolution of the fluvial and other processes that shaped the land surface. In summary, we find that the distribution or dispersal of diamonds in South Africa occurred during three major periods of time as illustrated in Table 2.1and listed below.

6.1 The Archaean period

Very little is known about diamond distribution during this period, other than that diamonds of gem quality occurred as a clastic heavy mineral component in Witwatersrand conglomerates located in the Klerksdorp and East Rand basins. (Minter and Loen, 1991). We have no idea about the age or exact locality of the kimberlites that acted as transport hosts from the mantle to the surface for these diamonds.

Richardson *et al.* (1984) found that peridotitic diamonds formed in the mantle underlying the Kaapvaal Craton ~ 3.3 Ga ago, and De Wit *et al.*, (1992) showed that the Kaapvaal Craton formed and stabilised between ~3.7 and 2.7 Ga ago (Table 2.1). We therefore know that there were diamonds available in the mantle, and the indications are that the right cratonic environment existed for ascending kimberlite magma to bring those diamonds to the surface so that they could be included in the gravels that ultimately became the Witwatersrand (WWR) conglomerates. Probably due to the considerable time that elapsed since then, coupled with the subcontinent's tectonic and metamorphic history, those Archaean-aged kimberlites did not survive.

As shown in 5.1, the sedimentary features, clasts and other minerals found in the WWR conglomerates point to provenance areas to the southwest, west, north-west and north and since Africa did not experience a major re-orientation during the Gondwana break-up, we can assume that these directions most probably indicate the locations of these unknown kimberlites.

6.2 The ~1.65 Ga to ~ 30 Ma period

Between ~1.65 Ga and 430 Ma a number of diamondiferous kimberlites were emplaced in southern Africa. All of these are located in the north-eastern part of the subcontinent, with the Premier-National group located around Cullinan and Rayton forming the southernmost of these. Should pre-Karoo diamondiferous kimberlites underneath the Karoo cover, *e.g.* in the Free State Province, be discovered in future, it will still not detract from the arguments presented here but rather support this model.

After emplacement of this group of kimberlites, a hiatus of between 1.338 Ga and 118 Ma went by during which these older kimberlites were attacked by atmospheric weathering agents and diamonds were liberated from their decomposing hosts. With the advent of the Dwyka glaciation, these liberated diamonds were entrapped, like the rest of the surface debris, in the ice sheets that covered southern Africa. As the ice sheets moved south and south-westward, the diamonds were transported to the south-western parts of the subcontinent as part of the glacial till (refer to Figures 6.1 and 6.2). Here they were embedded and buried with the rest of the tillite until they were once again liberated from a transport host, this time through the exhumation and weathering of the basal Karoo rocks since the Cretaceous.

Diamonds liberated from the Karoo sediments found their way under the influence of gravity to lower areas and thus became part of the sediment load of the post-Karoo drainage system, which in a similar fashion may also have sourced diamonds from:

i. weathered Proterozoic conglomerates,
ii. exhumed Jurassic kimberlites like Helam (Swartruggens) and
iii. Cretaceous kimberlites.

Rivers draining into the Atlantic from the escarpment in western Namaqualand were responsible for a local increase in average diamond stone size and diamond concentration in the shallow marine environment at their mouths. The increased grade is due to the added input of diamonds, and the increase in average stone size is due to a lag effect as the smaller stones tend to be moved away more readily than larger stones, under the influence of the long-shore drift enhanced by the Benguela current and prevailing southwesterly winds. This aspect has been demonstrated graphically by Sutherland (1982, Figure 2.20).

The diamondiferous nature of the river draining from the Kamiesberg eastward to Bosluispan has also been mentioned, as well as the numerous diamond deposits along the valleys of the major rivers between the Olifants and Buffels Rivers. Most of these rivers have no link with the on-craton kimberlite fields in the hinterland, and their diamondiferous nature can only be ascribed to proximal secondary sources like the Dwyka glacials and/or older conglomerates.

A higher incidence of pre-Karoo diamonds is found in the area between Concession 7A and Doringbaai, supporting the view that these diamonds were transported by glaciers moving in a south-westerly to southerly direction. The population found in the lower reaches of the Sout River and in/near the Olifants River estuary is distinctly different from the populations further north of the Olifants River mouth, including the raised beach deposit at Graauw Duinen. It is demonstrated by the IR and crystallographic characteristics of diamonds that Graauw Duinen received an input *via* smaller rivers draining the western Bushmanland plateau from the erosion remnants of the Gamoep River, carrying diamonds from the northeast of the country, as well as from the Griqualand-West/Free State field and Lesotho.

6.3 The period ~430 Ma to the present

The emplacement of the diamondiferous kimberlites at Dokolwayo (200 ± 5 Ma, Allsopp and Roddick, 1984) and Dullstroom (165 Ma, Skinner, 1989) probably did not influence the diamond population(s) transported by the Vaal-Orange fluvial system. The diamonds and other kimberlitic indicator minerals from Dokolwayo have been traced beyond doubt to the Upper Karoo sedimentary deposits at Ehlane, 30 km southeast of Dokolwayo (Hawthorne *et al.*, 1979; Turner and Minter, 1985), probably reflecting the kimberlite's location on the eastern limb of the Lebombo Monocline (Van der Westhuizen, 1988). At the time when the Dokolwayo and Dullstroom kimberlites started to deliver their erosion products into the environment the eastern escarpment in that particular region was probably already sufficiently developed to dictate an eastward dispersal for those diamonds as shown by their presence in the fluvial deposits at Ehlane.

Diamonds liberated from the Cretaceous Botswana kimberlites during subsequent denudation of the land surface were also transported in a southerly direction before being moved out to the southwestern parts of the subcontinent and Atlantic Ocean. It is conceded that the Botswana kimberlites are not extensively eroded, but the resemblance between portions of their NAD fields and those of some West Coast deposits, supported by kimberlite emplacement ages arrived at by Phillips and Harris (2008) for diamonds from one such corresponding West Coast deposit, cannot be ignored.

Between about 147 Ma and 83 Ma diamondiferous kimberlites were emplaced intermittently in the interior of southern Africa. It would appear as if the diamonds liberated from the Swartruggens kimberlites (~147-156 Ma, McKenna, 2001) had been moved in a generally southerly direction, as is the case with diamonds liberated from the Botswana kimberlites. With the exhumation of the basal Karoo rocks in the Northwest Province, diamonds initially liberated from the pre-Karoo kimberlites to the northeast were now liberated from decomposing Dwyka in that region, joining the Swartruggens and Botswana diamonds in south-bound drainages. The karstic Lichtenburg and Ventersdorp alluvial diamond fields are probably erosion remnants of this drainage as implied in Section 5.3.

The diamond populations found today along the Middle and Lower Orange River valley were derived from Cretaceous kimberlites of the Kimberley-Barkly West field, the western and southwestern Free State, Lesotho and Botswana. Diamonds derived from kimberlites with pre-Karoo emplacement ages are rare in the Orange River populations.

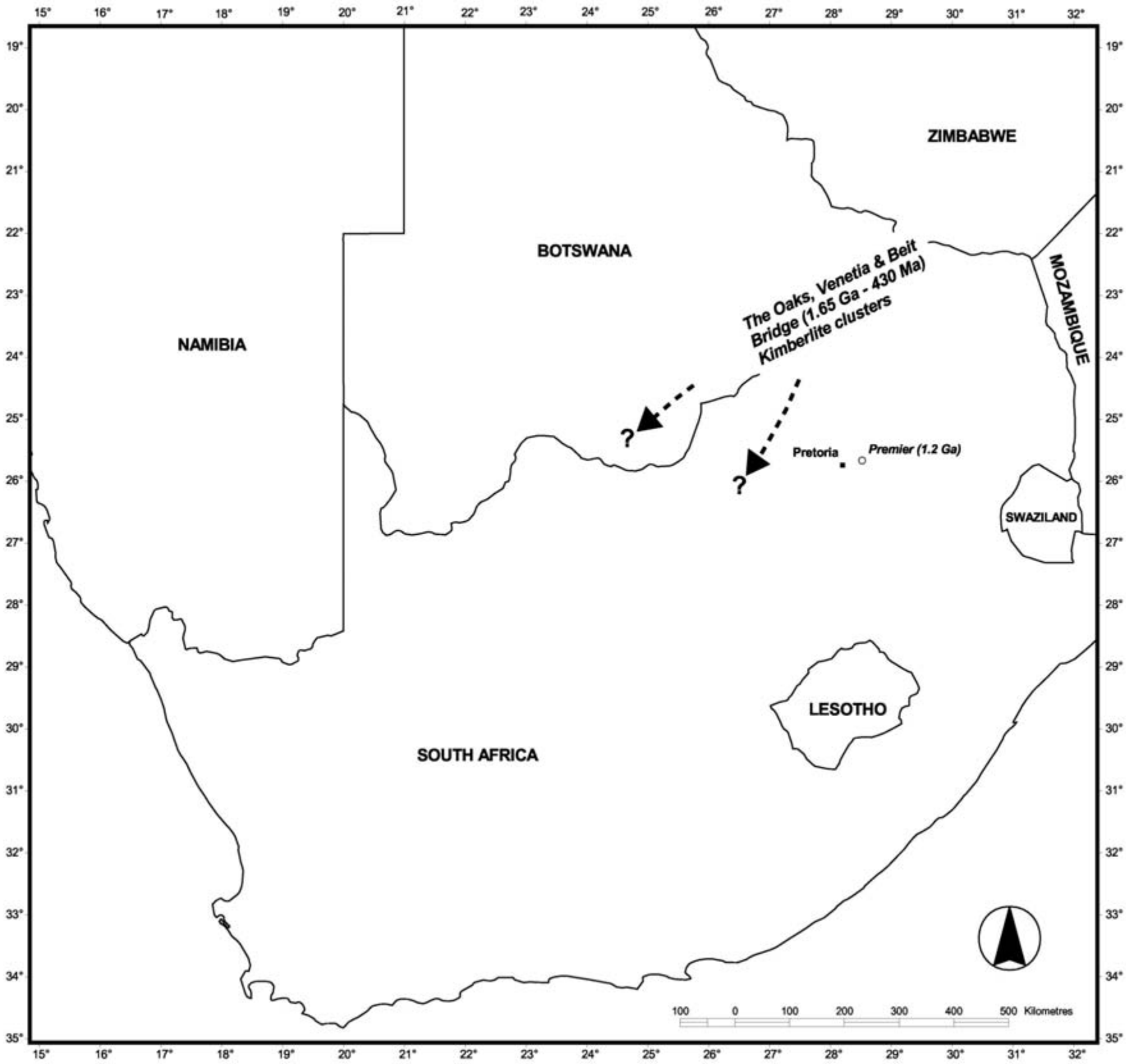


Figure 6.1: Location of the known pre-Karoo diamondiferous kimberlites on cratonic highland, southern Africa. The question-marked arrows with broken lines indicate the postulated general direction of pre-Karoo drainages, based on the subsequent ice vectors (Figure 6.2) from glaciers preferentially following existing valleys.

This simplified diagram represents the scenario prior to the development of alluvial diamond deposits derived from these kimberlites. It high-lights the principle that lies at the heart of the dispersal of diamonds from pre-Karoo kimberlites in southern Africa, namely the location of these kimberlites on a cratonic highland with a surface gradient that favoured the movement of water and ice towards the west and southwest.

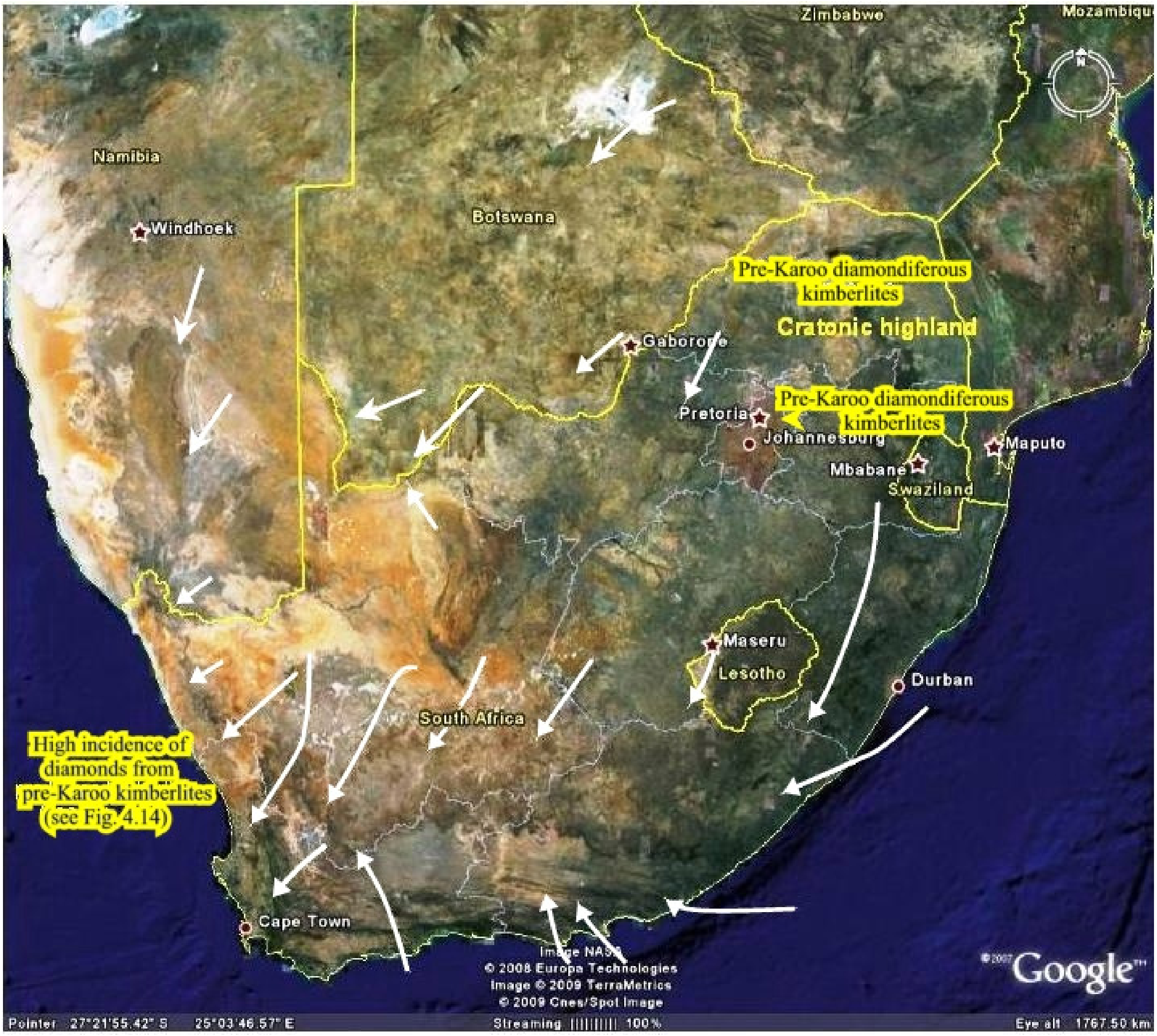


Figure 6.2 Known pre-Karoo diamondiferous kimberlite localities in southern Africa in relation to the Dwyka Ice Vectors of Moore and Moore (2004), and the location of those marine diamond deposits hosting anomalously high (up to 30% vs. between zero and 4% from the other alluvial deposits studied) concentrations of diamonds liberated from pre-Karoo kimberlites.

6.4 Economic implications emanating from this study

This study was successful in the discovery of a buried palaeo-valley of the Orange River on the farms Sterkstroom and Grootdrink between Upington and Groblershoop. From the sedimentary sequence, clast lithologies and elevation in respect of the present Orange River 3 km to the west, a Miocene age is assumed for this occurrence. The bedrock elevation (37 to 40 metres above present river bed) equates it to the Middle Terrace at Saxendrif between Douglas and Prieska, but resting on Precambrian bedrock conducive to the formation of trap sites, compared to the smooth shale bedrock of the Miocene Mid-Orange.

At the time of writing, a bulk sampling programme to determine the economic viability of the occurrence is in progress. The first diamonds have been recovered, but details have not been published yet. This is the first recorded diamondiferous Miocene Orange River deposit for the area between the Hopetown-Prieska sector and Renosterkop/Augrabies.

The importance of the former Gamoep River (Malherbe *et al.,*1986) is confirmed by the results of this study. The indicated course of this drainage, as shown in Figure 5.4, should be regarded as a macro-target area for alluvial diamonds. In the past this feature received very little attention, since it was dwarfed by the Karoo River hypothesis. Unfortunately it is situated on near-horizontal Karoo sediments for most of the way, but a desktop study using satellite imagery and magnetic data to locate possible trap sites caused by cross-cutting dolerite dykes, may identify areas of interest.

In Section 2.2.6, where the geology of the Skeleton Coast is discussed, the possible entrapment of diamonds in fault-related depressions acting as trap sites and/or palaeo-channels that ultimately gave rise to the formation of salt pans, was discussed. The surface feature study done on a parcel of

Skeleton Coast diamonds confirmed that (thus far unidentified) pre-Karoo sources in the hinterland offer the most likely provenance region(s) for these diamonds, and these salt pans are ideally placed to have acted as trap sites for diamonds moved seaward from primary sources and/or intermediate secondary deposits.

The raised marine terrace on the farm Annexe Blaauwklip 433 between Doringbaai and Lambertsbaai should be investigated for its diamond potential. The sedimentary clast composition reveals great similarity with that at Graauw Duinen. At Graauw Duinen very high diamond grades were reported, but the small average stone size makes Graauw Duinen vulnerable to exchange rate fluctuations. The location of Annexe Blaauwklip (nearly 30 kilometres south of the Olifants River estuary) makes the Olifants River an unlikely conduit for this distinct sedimentary clast population, but favours transportation by former west-bound drainages from the escarp. This proposal finds support in the local topography at Annexe Blaauwklip, where surface elevations seem to indicate a buried valley feature. If this proposed model is borne out by drilling and bulk sampling, it could be that Annexe Blaauwklip is shown to be located closer to the region where this postulated extinct drainage entered the Atlantic Ocean, in which case any diamond population present could be expected to have a larger average stone size than that of the Graauw Duinen deposit.

The very strong link identified between the Vaal River diamond populations and the Samada kimberlite, makes the area between Samada and the Vaal River an important macro-target area. This region also coincides with the head-waters of the palaeo-Gamoep River, and should be studied for erosion remnants of both the Gamoep River and a localized arm of the postulated northwest-bound drainage system proposed by Moore and Moore (2004).

The convergence of Dwyka ice vectors (Fig. 6.2) in the southwestern Cape identifies the major rivers draining that part of the Cape Fold Belt (*e.g.* Brede and Gouritz) as possible conduits of ancient diamondiferous sediments.

7. CONCLUSIONS (refer to figure 7.1)

i. Southern Africa intermittently experienced the emplacement of diamondiferous kimberlites over a prolonged period of time – from the Archaean to 86 Ma BP.

ii. Diamonds contained in these kimberlites were liberated from their primary hosts, became part of the surface debris and eventually migrated to lower topographic levels like valleys.

iii. In the Archaean, ~3.3 Ga (Table 2.1) diamonds from hitherto unknown kimberlites were washed by streams flowing into the Witwatersrand Basin as part of the heavy mineral suite of the gravel bodies that ultimately became the auriferous conglomerates of the Witwatersrand.

iv. The known diamondiferous kimberlites of pre-Karoo age are all located in the north-eastern part of South Africa, while the palaeo-drainages and the general flow of the Dwyka glaciers followed a northeast to southwest direction, facilitating a generally south-westerly dispersal of diamonds released from those kimberlites. This explains the discrete, highly aggregated diamond population found at Kwaggaskop in the valley of the Sout River as well as at Concessions 12A-De Punt, 12A-Deep and 13A, located on either side of the Olifants River estuary.

v. The exhumation of the pre-Karoo landscape went hand in hand with the following:

- Incision by post-Karoo drainages through the Karoo cover allowed their superimposition into the Precambrian basement;
- the reactivation of some pre-Karoo glacial valleys like the Harts River;
- the fluvial dispersal of diamonds liberated from:
  - decomposing glacial sediments,
  - Jurassic kimberlites (*e.g.* Helam and Klipspringer) and related fluvial deposits, and
  - the weathering of Cretaceous kimberlites.

vi. On the basis of Infrared characteristics and surface features, four distinct groups are recognized among the investigated diamond populations of the west coast:

- the highly aggregated group around the Olifants River estuary, showing a paucity of diamonds with nitrogen aggregation state of < 25-30%;

- the group without green and brown spots from the Hondeklipbaai Land Operations which are reminiscent of the diamonds from the nearby palaeo-channels at Koingnaas;

- the southern group from the marine production points, with between 17.5 and 30% containing brown spots, and

- the northern group from the marine production points, with only between 1.8 and 4.4% brown-spotted diamonds.

vii. The evidence from both the diamond (this study) and zircon (Rozendaal *et al.*, 2002) populations from the Hondeklipbaai area shows that the deposits of the Hondeklipbaai land operations are distinct from those of the shallow marine area barely 2 km to the west. The complete absence of green and brown spots on these diamonds also sets them apart from all the other alluvial deposits studied.

viii. The catchment areas of the Orange and Buffels Rivers in general had access to the same diamondiferous debris, but the Buffels River also received an input from a different source. This took place *via* the palaeo-Gamoep-Koa River connection prior to the stream capture by the Vaal-Orange system that beheaded the Gamoep River. In addition a contribution from the Cretaceous Botswana kimberlites is suggested in the light of significant similarities in NAD characteristics with the diamond populations of Marine Concessions 7A to 3B. This could have been afforded *via* the postulated Kalahari River (Behr 1989; De Wit, 1993) but more likely *via* the palaeo-Gamoep River. This indicated link with the Botswana kimberlites also found support in $^{40}Ar/^{39}Ar$ analyses reported by Phillips and Harris (2008).

ix. The areas south of Concession 7a for which diamonds were available for this study received a much higher diamond input from pre-Karoo kimberlites, with derivation from primary sources in diverse cratonic and mantle settings indicated by variable nitrogen aggregation states.

x. Overlapping NAD fields and the presence of rare cuboid, amber-yellow diamonds identified the Helam kimberlite near Swartruggens as a provenance for a portion of the Graauw Duinen population.

xi. The Graauw Duinen diamond population also shows a negative correlation between total nitrogen content and nitrogen aggregation state. A similar pattern has only been observed in the

NAD's of Roberts Victor and Jagersfontein. This could identify these two kimberlites as possible provenance areas for a significant portion of the Graauw Duinen population.

xii. The presence of a number of irregular diamonds identified at Graauw Duinen strongly suggests a link with Letseng and/or Samada. The most likely transport route for diamonds liberated from Lesotho kimberlites would have been the Orange River. It is therefore concluded that the palaeo-Gamoep river was instrumental in the transportation of irregular diamonds liberated from the Samada kimberlite. Samada is located in close proximity to the indicated headwaters of the palaeo-Gamoep River.

xiii. South-flowing palaeo-drainages also supplied alluvial diamonds to the North-West Province, from where these diamonds were dispersed further south to the catchment area of the palaeo-Gamoep River while large quantities were retained in karstic trap sites of the Lichtenburg-Ventersdorp area. A considerable amount was also trapped in and along palaeo-drainages of the Schweizer Reneke-Bloemhof-Christiana area.

xiv. The palaeo-Gamoep River was instrumental in the transportation of diamonds from diverse age and origin, to western Bushmanland and Namaqualand. A combination of the sediment load of the palaeo-Gamoep River and decomposing Dwyka Tillite, facilitated the dispersal of a mixed population of diamonds from pre- and post-Karoo kimberlites to western Bushmanland and especially the western escarpment, from where numerous west-flowing rivers transported them to the Atlantic.

xv. The results of zircon analyses reflected the Vaal-Orange River system's role in the denudation of the sub-continent, with the youngest zircons found in the oldest Orange River Cenozoic sediments, and the older zircons appearing only in the Miocene when incision of the Orange River had proceeded deep enough to expose Archaean rocks. This observation is underscored by the presence of the oldest zircon among the entire data base of this study (2.9 Ga) in the youngest sediments of the Lower Orange, namely the modern river.

xvi. The work done on the sedimentary clasts showed that the palaeo-Orange River, one of the main conduits of alluvial diamonds in the past, intermittently experienced high energy conditions during most of the Cenozoic. Bedrock depressions were scoured out and brittle components like flawed diamonds destroyed, resulting in an upgrading of the average quality of the surviving diamond population. The effect of the micro-topography of the bedrock in the deposition and concentration of larger clasts and heavy minerals has also been demonstrated by the particle size distribution of the sedimentary clasts. Many clasts were shown to be locally derived.

xvii. The diamond population of the Skeleton Coast, northern Namibia, has no link with the Oranjemund-Lüderitz deposits, but were derived from proximal sources with a pronounced pre-Karoo kimberlite emplacement character.

xviii. The geochemistry of the garnets studied, combined with the study of sedimentary clast lithologies confirmed the Namaqua and Richtersveld igneous and metamorphic provinces as source regions for the Lower Orange River gravel samples. In addition the sedimentary clasts also revealed the presence of derivatives of the Drakensberg basalts, Karoo metasediments and the BIF of Griqualand West.

xix. Unravelling the origin of the Proterozoic aged Marange diamond deposits in south-eastern Zimbabwe remains a challenge. The observation of co-existing diamond and red granite could indicate assimilation of a diamondiferous kimberlite by ascending granitic magma or metamorphic intergrowths during deep burial of diamondiferous sediments.

xx. The following processes played a role in the distribution of diamonds liberated from South African kimberlites:

- Pre-Karoo drainages, now mostly obliterated by erosion/denudation.
- Dwyka ice sheets and glaciers.
- Post-Karoo drainages, of which the Vaal-Orange System is the most important, and
- Marine processes that concentrated diamonds washed into the sea in lucrative beach deposits and bedrock trap sites.

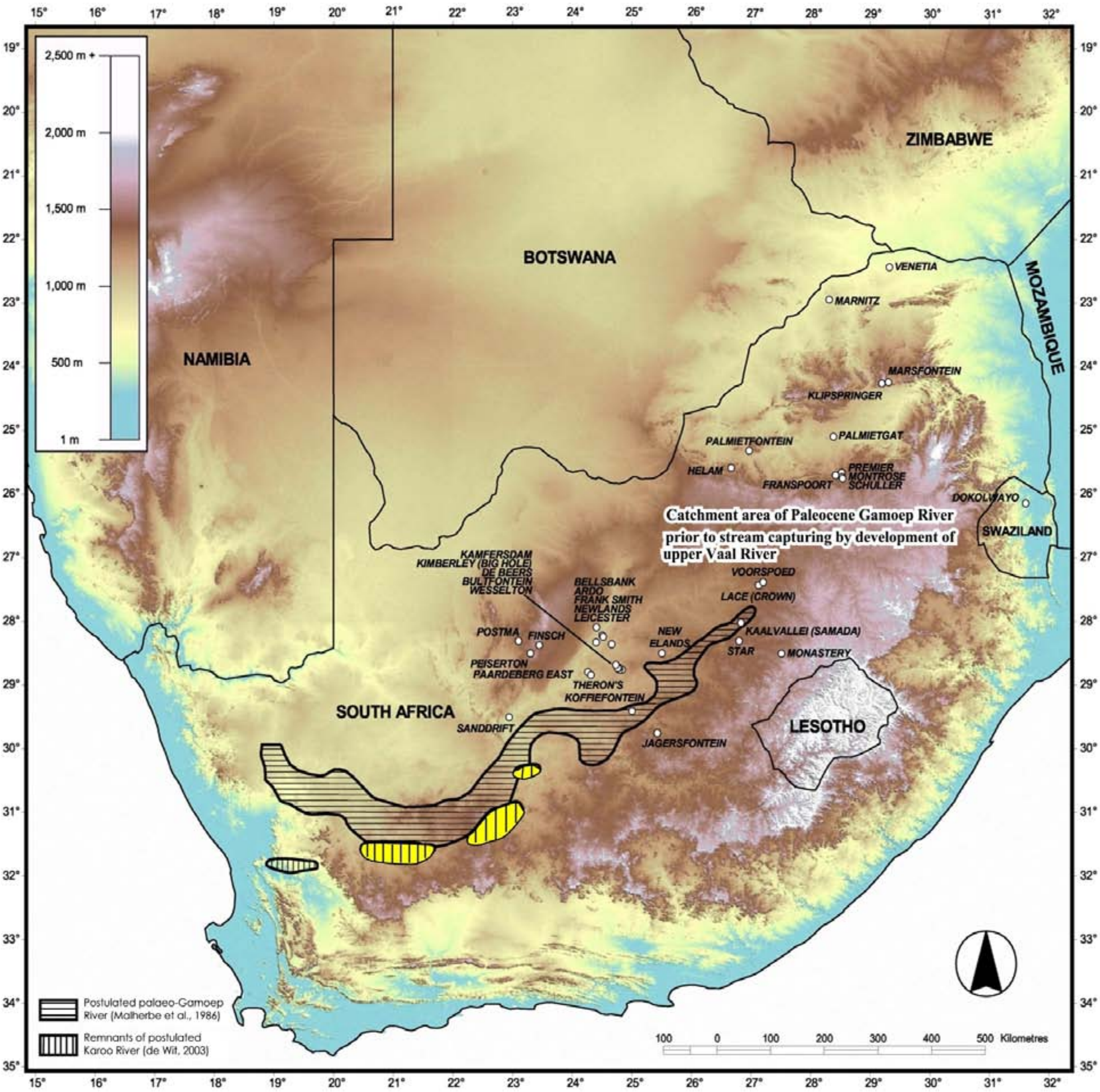


Figure 7.1 Digital elevation map of southern Africa with the location of postulated palaeo-drainages (overlapping areas of Malherbe *et al.* (1986) and De Wit (1993) high-lighted in yellow) and diamondiferous kimberlites relevant to this study.

8. APPENDICES

8.1 Sedimentology

The sedimentological investigation was done because it was thought that the lithology of sedimentary clasts in the palaeo-fluvial diamondiferous deposits would be indicative of their provenance and features such as roundness, sphericity and size distribution, of transport distances.

8.1.1 Bulk sampling and treatment of gravel

Bulk samples of at least 100kg each were collected from sedimentary packages representing different stages of deposition from different localities along the Middle and Lower Orange River.

The localities and their affiliation with proto- or meso-deposits are detailed in Table 8.1 and include the Middle Orange River at the Saxendrif/Brakfontein Mine between Douglas and Prieska, Renosterkop 15 km upstream from the Augrabies Falls, the farm Daberas 8 about 20 km downstream from the Augrabies Falls and numerous localities in the Richtersveld from Grasdrif to Swartwater. A small number of samples, identified as such in the size frequency charts, weighed less than 100kg as the result of limited gravel exposures.

Sampling positions were finally dictated by accessibility. The samples were extracted from units with a uniform fabric, endeavouring to exclude lenses or layers indicative of a bar head or tail which would have resulted in a biased size frequency. A 1m x 1m sample site was selected, demarcated and numbered by using red spray paint, photographed and a representative cut made within this outline. Falling material was collected on a canvas sheet, and shovelled into tuff bags (Figure 8.1 below).

TABLE 8.1 GRAVEL SAMPLE LOCALITIES

SAMPLE No.	LOCALITY	mamsl	DETAILS	NATURE
1	Baken	46	Koeskop upper gravel	Gravel sample
2	Baken	37	KS 15 S2 downstream of aplite dyke	Gravel sample
3	Baken	37	KS9-1A3 basal horizon, above aplite	Gravel sample
4	Baken	53	Upper Proto gravel, PK46	Gravel sample
5	Baken	51	Basal Proto gravel, PK46	Gravel sample
6	Baken, Skilpadsand Terrace	75	Basal Pre-Proto, pre-scour	Gravel sample
7	Baken, Skilpadsand Terrace	77	Upper Pre-Proto, pre-scour	Gravel sample
8	Baken	46	Upper Proto gravel in SWR 10	Gravel sample
9	Baken	44	Basal Proto gravel in SWR 10 W1	Gravel sample
10	Baken, PK13 W2		Basal Proto gravel	Gravel sample
11	Baken	68	Terrace 2, Pre-Proto	Gravel sample
12	Baken	71	Bas. Pre-Proto in Trench 8, Terrace 1	Gravel sample
13	Baken	75	Upper Pre-Proto, Trench 6, Terrace 1	Gravel sample
14	Xheis	54	Basal Proto gravel	Gravel sample
15	Sanddrif Terrace		Meso	Gravel sample
18	Bloeddrif	44	Meso in eastern face of XAR1	Gravel sample
19	Bloeddrif		B2 N2, toe of ramp, Proto	Gravel sample
20	Bloeddrif		Basal Meso gravel, Airport Terrace	Gravel sample
21-28	Saxendrif/Brakfontein		Proto gravel	Gravel sample
29	Grasdrif	116		Gravel sample
30	Grasdrif		Basal gravel in "B" Terrace	Gravel sample
31	Grasdrif Weaving's Hole 2	112		Gravel sample
32	Grasdrif: Up.Terrace, north			Gravel sample
33	Baken	84	± 100 m. from top of ramp	Fine grd. sed.
34	Bloeddrif	31	Pre-Proto in ramp of XAR 1	Gravel sample
35	Bloeddrif	29	Pre-Proto gravel in ramp of XAR 1	Gravel sample
36	Bloeddrif		Meso 2 in XAR 5	Gravel sample
37	Bloeddrif	20	Meso 3 in XAR 6	Gravel sample
38	Nxodap	34	Basal gravel in depression in NXO 2	Gravel sample
39	Nxodap	44	Upper gravel in NXO 2	Gravel sample
40	Nxodap	38	Toe of ramp, northern face, NXO 3	Gravel sample
41	Nxodap	37	Basal gravel in northern face,	Gravel sample
42	Nxodap	43	Upper gravel, NXO 7	Gravel sample
43	Jakkalsberg SW	62	Basal Proto	Gravel sample
44	Jakkalsberg SW #1	58	Proto	Gravel sample
48	Jak'sberg SW (Reservoir)	68	Proto	Gravel sample
49	Jakkalsberg E	28	Meso	Gravel sample
50	Reuning	48	Western entrance, FH 2	Gravel sample
51	Reuning	60	SE side of Glory Hole	Gravel sample
52	Reuning	52	Airport Terrace Trench 2, Up. Meso	Gravel sample
53	Reuning	51	Airport Terrace Trench 2, Mid. Meso,	Gravel sample
54	Reuning	48	Airport Terrace Trench 2, Low. Meso	Gravel sample
55	AACE	72	Proto	Gravel sample
56	AACE	47	Meso	Gravel sample
58	Bloeddrif		Airport Terrace Basal gravel, scour,	Gravel sample
59	Daberas		Left bank upstream from Bloeddrif	<32mm sample
60	Renosterkop	685	Proto in neck	Gravel sample
61a b c	Daberas 8,		Downstream from Augrabies	Gravel samples
62	Renosterkop	677	Old excavations on plain	Gravel sample
63	Augrabies	618	Clasts from dry "middle terrace" river bed immediately above falls	
63a	Tanqua Karoo		Zircons from Drill core: Ecca Group turbidite fans	
64	Laingsburg			
65	Laingsburg			
66	Laingsburg			

After collection the samples were transported to a mechanical screening facility built for this purpose, and screened into <2mm; >2 – 4mm; >4 – 8mm; >8 – 16mm; >16 – 32mm; >32 – 64mm; >64 – 128mm and >128mm fractions. The <2mm material was further screened into <65µ, 65 - <135µ and >135µ fractions at the Geology Department, Stellenbosch University. From the 65 - <135µ fractions garnet and zircon grains were selected for geochemical analyses.

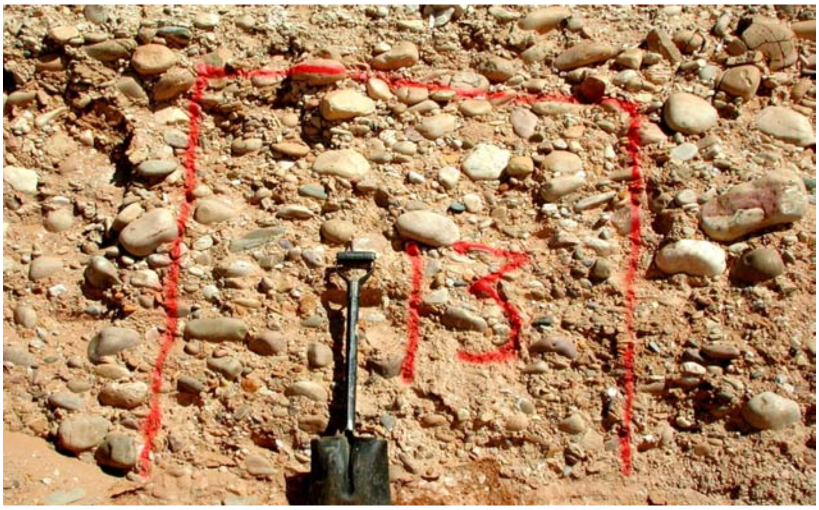


Figure 8.1 Research gravel sample locality marked prior to sample extraction.

Figure 8.2 Loading of tuff bag with gravel sample

Figure 8.3 Screening of gravel samples

Grain morphology and size analysis

It is conceded that differently sized particles found in the same sedimentary unit may not have been deposited simultaneously, as pointed out by Bluck (1982). Thus, the samples used in this study could very well be mixtures of grain populations from different depositional events, but yet may be seen as representing a portion of the sedimentary load from a certain geological period during which a number of floods took place.

For each sample the individual size fractions were weighed and size frequency tables compiled.

Apart from the size frequency analyses, roundness estimates were also done on the clasts. Pettijohn (1957) drew attention to the fact that *roundness* has to do with the sharpness of the edges and corners of a clastic fragment, and that it is independent of shape. In this study the roundness estimate of clasts was preferred to *e.g.* sphericity, since the latter tends to be influenced by primary shapes. In addition, cognisance had to be taken of the fact that some clasts possess sphericity and roundness unrelated to fluvial transport, as illustrated in Figure 3.1.

Lithological identification and roundness estimates were done on clasts larger than 2mm. In the case of the clasts larger than 64mm, each clast was used. Initially the size fractions <64mm >2mm were each split into four smaller parcels, from which 25 clasts - thus totalling 100 per sample - were randomly selected. This was done after test runs showed that only negligible variations in the major percentages occurred after 75 randomly selected clasts were dealt with. In a significant number of samples, the percentages reflecting the major lithological components were firmly established after only 30 clasts were identified, and the work was adjusted accordingly.

Roundness estimates were done according to Powers (1953), as reproduced in Leeder (1982). The author adapted the schedule slightly with respect to the values ascribed to the lowest and highest roundness estimates, *viz.* a value of 0.10 was added for particles that would be regarded as mere fragments instead of grouping them with the "very angular" category, while the three "rounded" categories were given slightly higher values in the light of actual field observations. (For the sake of comparison, the original values used by Powers (*op. cit.*) are shown in red).

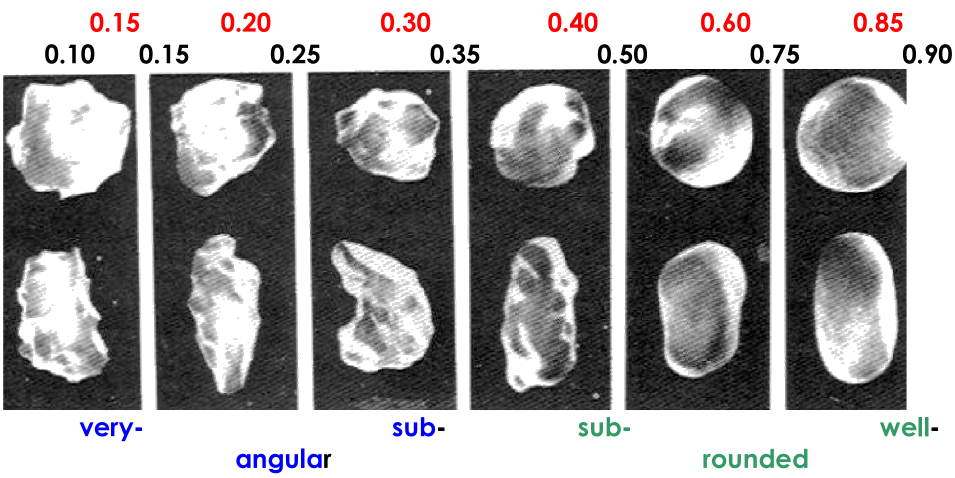


Figure 8.4 Photographic image of standards used for the visual estimation of roundness (Powers, 1953).

Subsequently, a synthesis of the results showed that the study of the sedimentary clasts and the successful discovery of a Miocene Orange River valley – as envisaged in Section 1.3, Aims and Objectives of this study - though interesting in their own right, could contribute very little to the main aim of the thesis, especially since at the various production points from where the diamond samples were borrowed, no records are kept of the detailed sedimentary environment or particular mining blocks from where the diamonds were recovered.

For these reasons the sections relating to geology and geomorphology and the results of the statistical investigation of the sedimentary clasts have been pruned to contain only what is deemed necessary for the discussion and interpretation of the results of the diamond study. However, the complete data sets including images of gravel sample sites prior to sampling, clast composition, roundness estimates as well as particle size distribution graphs appear on the enclosed CD as item 8.1CD.

8.1.2 Sedimentary clasts – Discussion of results

Roundness estimates

Using a combination of particle size, roundness and lithology, a number of important conclusions could be drawn. The proto-gravel data for the sector between AACE and Swartwater was used, since it comprises a more complete data set along a fairly continuous stretch of the Lower Orange River, to compose graphic illustrations of the progressive rounding on clasts over a control section of the river. For a meaningful comparison only litho types that are present throughout this interval, *viz.* porphyries, granite/gneiss and quartzite were used, and the roundness per lithotype and size fraction averaged to arrive at the "Roundness Estimate" figure used in these graphs. The distances shown on the horizontal scale of each graph correspond to the sample localities listed in Table 8.2.

The results of this exercise are illustrated in Figures 8.5 – 8.8 and discussed in Section 8.1.3, while the full data set is depicted in the "Clast lithology and roundness per size fraction" tables in Section 8.1.2CD.

In the following figures the term "porphyries" refers to undifferentiated igneous rocks containing conspicuous phenocrysts in a fine-grained or aphanitic groundmass (Parker, 1989).

TABLE 8.2 LOCALITIES USED IN STUDY OF DOWNSTREAM ROUNDING OF SEDIMENTARY CLASTS

DISTANCE (km)	SAMPLE NUMBER	LOCALITY
0	55	AACE
4	51	Reuning Central
10	48	Jakkalsberg-Central
11	43	Jakkalsberg-SW
12 – 25	No Cenozoic samples available to be studied	
26	35 & 36	Xarries (Bloeddrif)
27-42	No Cenozoic samples available to be studied	
43	14	Xheis
47	1	Koeskop
48	2 & 3	Up- and downstream from large aplite dyke, Koeskop
51	4 & 5	Upper and basal gravel, PK46, Baken Mine
54	9	Basal gravel, mining block SWR 10 W1, Baken Mine

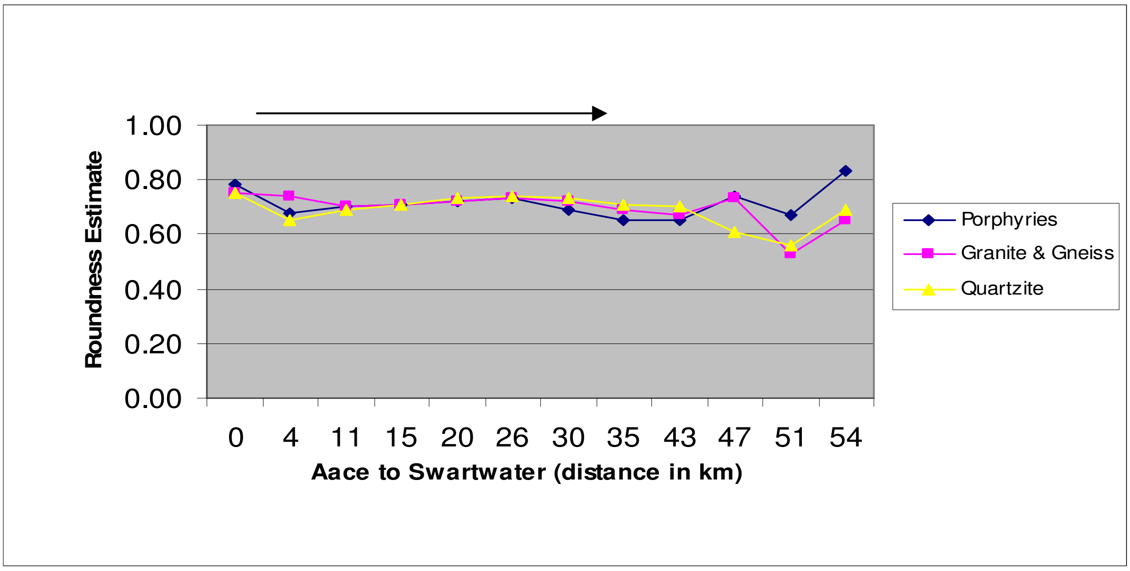


Figure 8.5 Downstream (left to right) rounding of clasts of porphyry, granite-gneiss and quartzite in the size fraction 64 - 128 mm at different sample localities from AACE to Swartwater, with interpolation of data points where no samples were available, as listed in Table 8.2.

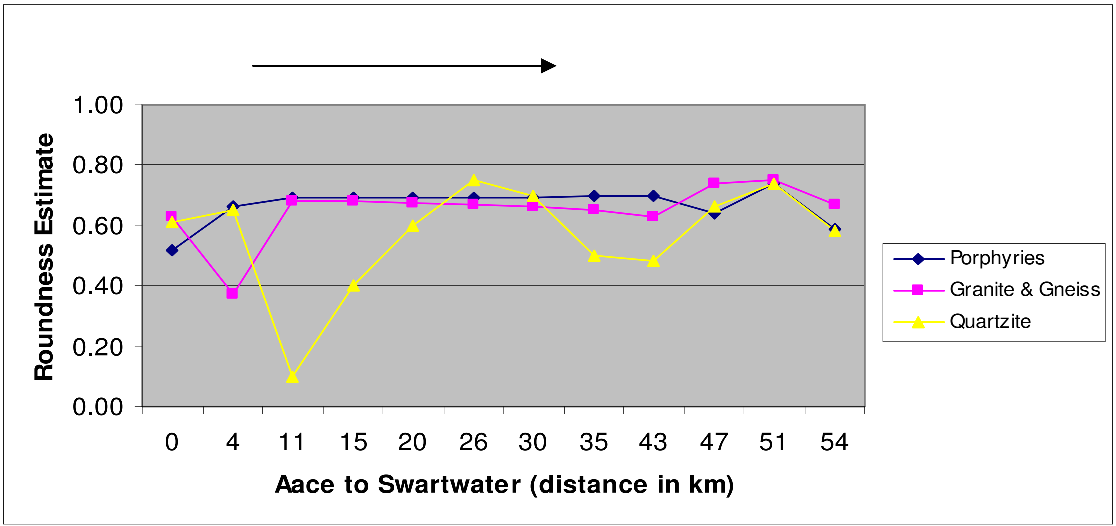


Figure 8.6 Downstream rounding of clasts of porphyry, granite-gneiss and quartzite in the size fraction 32 - 64mm at different sample localities from AACE to Swartwater, with interpolation of data points where no samples were available, as listed in Table 8.2.

The similarity between the two graphs above is remarkable. It would indicate that rounding in this particular stretch of the river was very similar for the lithologies mentioned above, and also between these two size fractions. The intermittent decrease in the roundness of the quartzite is thought to be the result of:

- The more brittle nature of quartzite compared to the two igneous types, and
- the occasional input of freshly broken quartzite clasts/fragments from the surrounding hills.

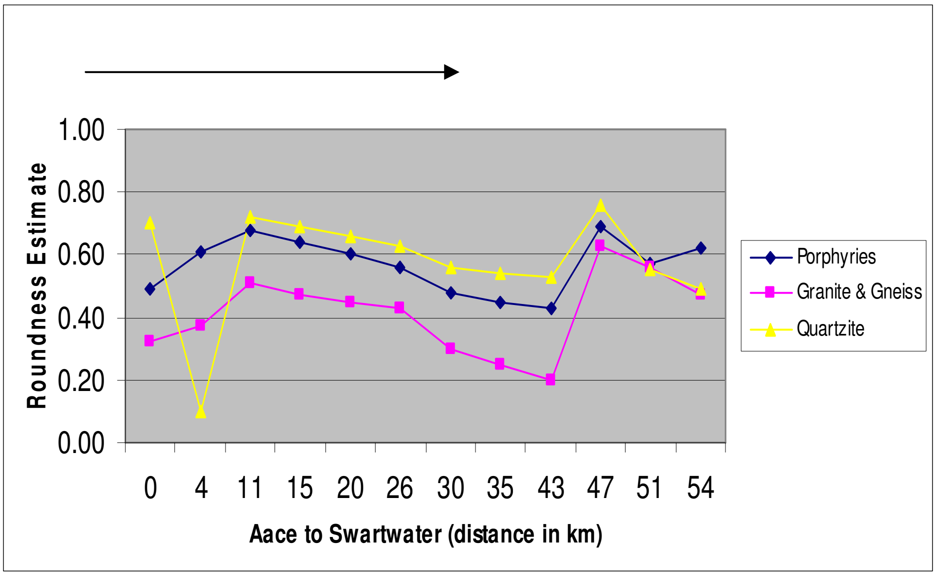


Figure 8.7 Downstream rounding of clasts of porphyry, granite-gneiss and quartzite in the size fraction 16 - 32mm at different sample localities from AACE to Swartwater, with interpolation of data points where no samples were available, as listed in Table 8.2.

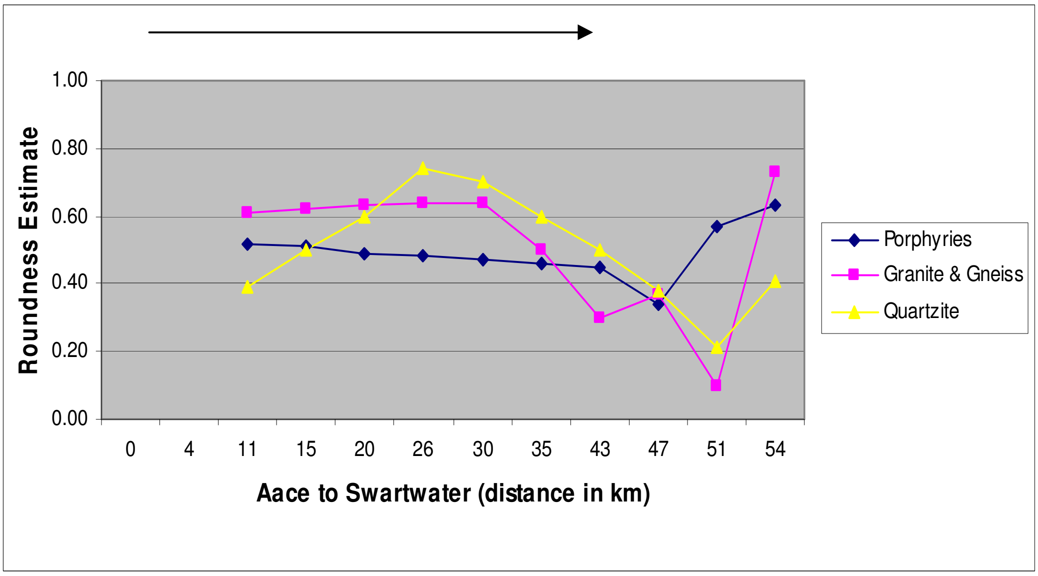


Figure 8.8 Downstream rounding of clasts of porphyry, granite-gneiss and quartzite in the size fraction 8 - 16mm at different sample localities from AACE to Swartwater, with interpolation of data points where no samples were available, as listed in Table 8.2.

The similarity between the two graphs for the 16-32 and 8-16 mm size fractions is equally remarkable, once again with the quartzite trend showing greater fluctuations as discussed above.

Three aspects germane to the graphs in Figures 8.5 – 8.8 call for attention.

1. The general trend observed on the first two (the coarser clasts) is that of fairly consistent roundness of approximately 70%, but occasionally something must have happened which had a pronounced negative effect on the roundness of all three litho-types, while quartzite, being more brittle than the other two litho-types, was more readily shattered. The fact that the trend lines of the porphyries show a very good correlation with particularly those of the granite/gneiss clasts, suggests that the above observation reflects the result of catastrophic events in the stream itself. The occasional less rounded character of the porphyry clasts is not due to the input of poorly rounded, locally derived clasts by tributaries, because along this stretch of the river none of these porphyries are known to crop out. Significant input of Rosyntjieberg and Nama quartzite clasts along tributaries did occur, but because their transportation into the Orange River took place as part of the sediment load of the tributaries, they already possessed some degree of roundness at their arrival in the Orange.

2. The downstream variations on the < 32 mm graphs are more pronounced than in the case of the > 32 mm fractions. The reason for this aspect most probably goes hand in hand with that of point 3.

3. The generally lower average roundness estimates recorded on the < 32 mm fractions illustrates that diminishing clast size in a high-energy fluvial system like the palaeo-Orange, is a function of breakage rather than of abrasion. This is in agreement with similar observations in Scotland and South Wales by Bluck (1969).

The results of the study as depicted in Figures 8.5 – 8.8 are also in agreement with those of a similar study along the Lower Orange River by Jacob (2005) on both the palaeo-deposits along the right bank as well as gravel samples from the modern river bed.

It must however be conceded that some variations in the observed roundness of clasts, may be attributed to the sample position with respect to gravel bar architecture of the river, which in most cases could not be established because the sites accessible for bulk sampling comprised erosion remnants of a palaeo-stream, making the reconstruction of the fluvial architecture risky .

Grain size distribution: palaeo-Orange River

Hancox (2003) pointed out that although a number of studies (Slingerland, 1984; Best and Brayshaw, 1985; Reid and Frostick, 1985) dealt with the mechanisms by which heavy minerals are concentrated in stream channels, our understanding of such accumulations is still incomplete. The work of Jacob *et al.* (1999) on fluvial deposits along the Lower Orange River suggested that the presence of suitable trap sites could be an important contributing factor in the concentration of heavy minerals in a fluvial system.

From the work of Krumbein (1942), Pettijohn (1957), Bluck (1982) and Hattingh and Illenberger (1995) we know that shape and size of sedimentary particles are important parameters in the energy levels required to transport them.

Apart from the tendency of clasts of particular shapes to settle out sooner than others, the velocity of the stream determines whether or not it will possess enough momentum to move certain particles. Since momentum is the product of mass and velocity, water with a high content of suspended or dissolved material offers a more effective transport medium than pure, clear water.

If we theoretically accept the influence of bed shear stress and particle shape to be equal for all particles concerned, it will be the difference between the size and SG of different particles, and the combination of velocity and density of the stream (Leeder, 1982; Foust *et al., 1962*) that should determine the stream's variable ability to move particles of different sizes and/or lithologies. Thus any drop in the energy level will render the system less effective as a transport medium. This will result in a tendency for those particles that require more energy to be moved (like heavy minerals), to settle out first. This principle lies at the heart of many field observations made during this study, where it has been observed that the influence of bedrock irregularities affected the stream velocity to the extent that such an irregularity constituted a trap site for particles with a relatively high SG and/or larger particles. While localized trap sites constitute attractive targets for diamond production, they host biased clast populations and in this study this aspect was borne in mind during the interpretation of the clast analyses.

The results of the particle size analyses are summarized here, while the full set of raw data appears on the CD in 8.1.1 and 8.1.2.

The meso 1, meso 2 and meso 3 deposits referred to, correlate with the meso upper, intermediate and lower deposits respectively of Jacob (2005).

Pre-proto deposits: Figures 8.9 and 8.10 depict histograms of the particle size distribution of two pre-scour, pre-proto deposits.

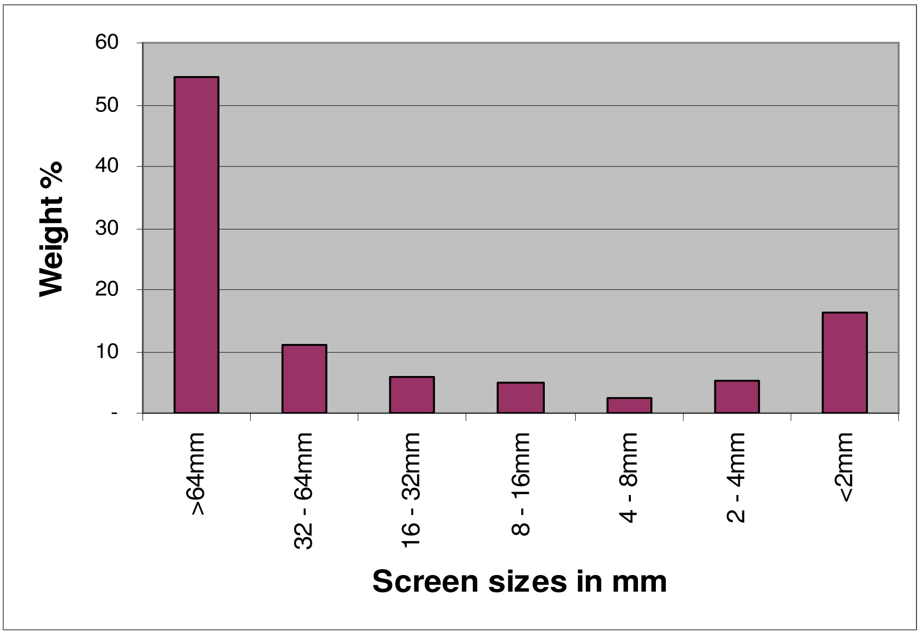


Figure 8.9 Particle size distribution of pre-scour, pre-proto deposits, Skilpadsand Terrace, Baken Mine.

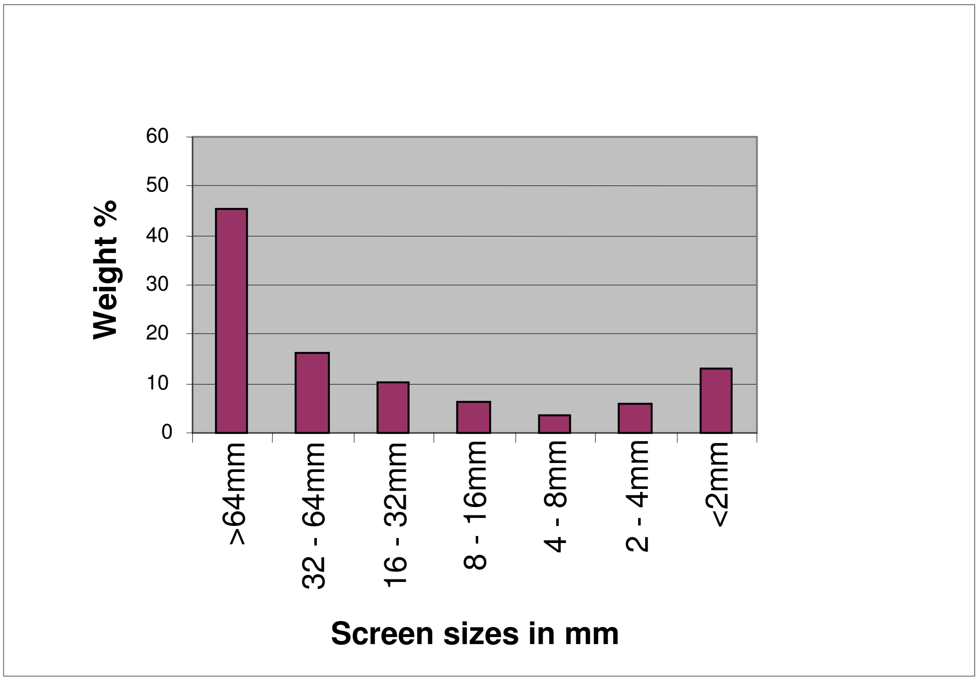


Figure 8.10 Particle size distribution of pre-scour, pre-proto deposits, Swartwater Terraces 1 and 2 combined.

There is a marked difference in the >64mm component in Figures 8.9 and 8.10 compared to those shown in Figures 8.11 and 8.12. While all four these occurrences are of pre-proto age, the Skilpadsand and Swartwater Terraces - Figures 8.9 and 8.10 – were deposited during the early part of the pre-proto era, prior to the incision of the Baken palaeo-channel and other bedrock scours discussed in 2.2.3. If it is accepted that this incision was also responsible for the development of the bedrock scours at Nxodap and Xarries where the other two pre-proto samples were collected – Figures 8.11 and 8.12 – then these deposits are slightly younger than the Swartwater Terraces. In other words, both the Skilpadsand-Swartwater and Nxodap-Xarries pre-proto deposits represent aggradational periods in the evolution of the palaeo-Orange River, separated more or less by the time during which the scouring took place. The pronounced difference in the >64mm component between the pre-scour and post-scour deposits could be attributed to the fact that the Nxodap and Xarries pre-proto deposits occur within fairly confined bedrock scours that acted as trap sites for the larger clasts.

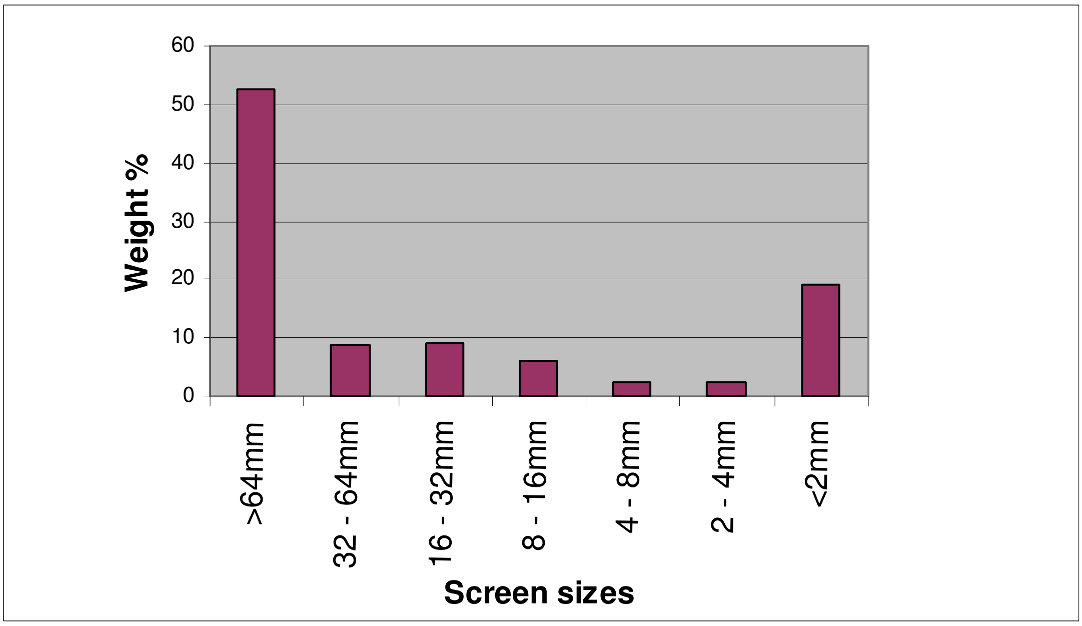


Figure 8.11 Particle size distribution of pre-proto deposit at Nxodap

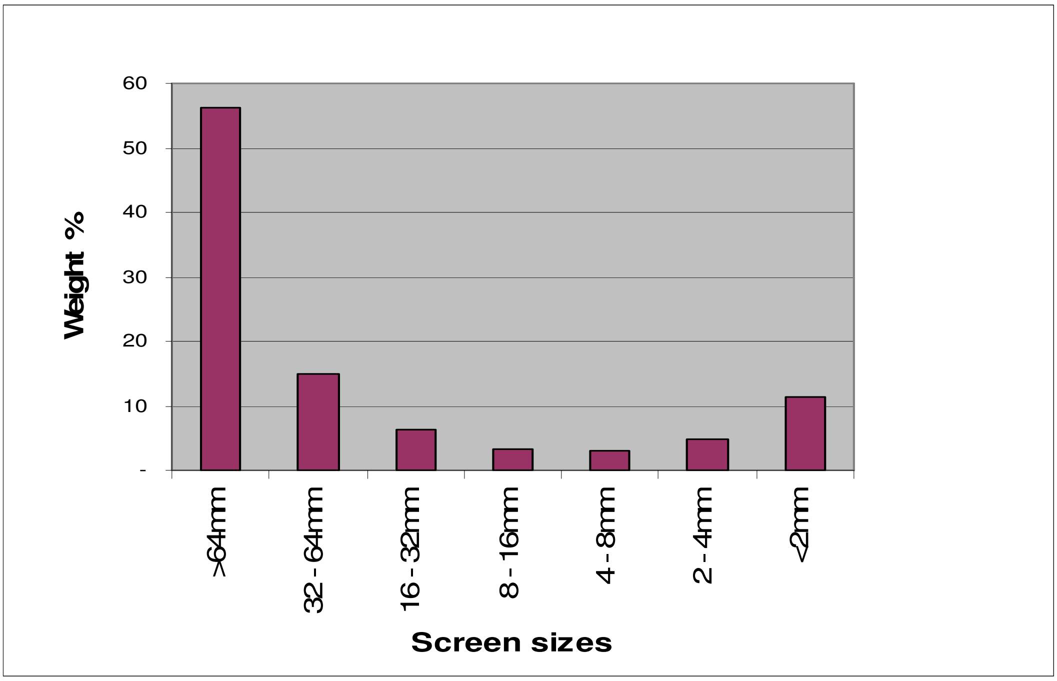
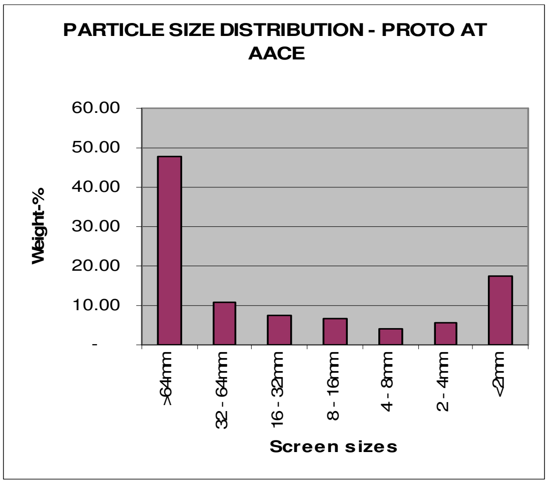
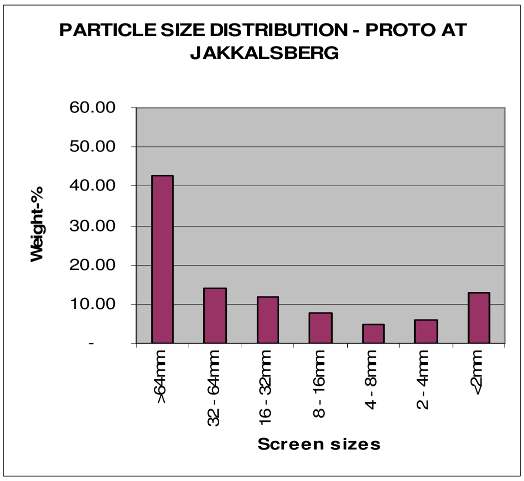


Figure 8.12 Particle size distribution of pre-proto deposit at Xarries, Bloeddrif.

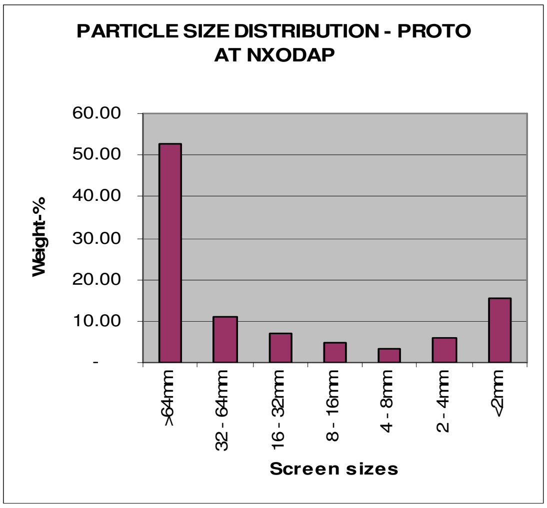
Figures 8.11 and 8.12 were discussed in the previous paragraph.

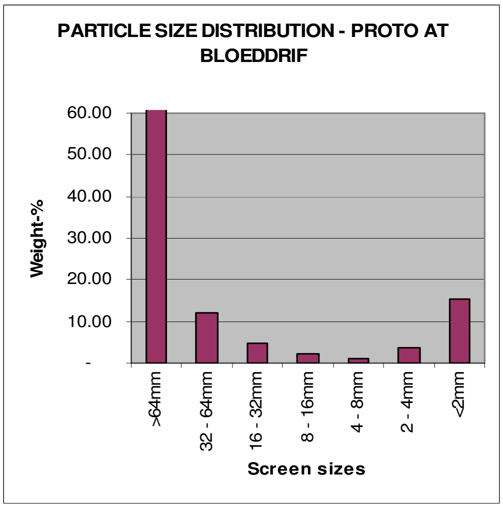
Proto-Orange River deposits: The results of the particle size distribution graphs for all the proto deposits are discussed as a group below Figure 8.18.



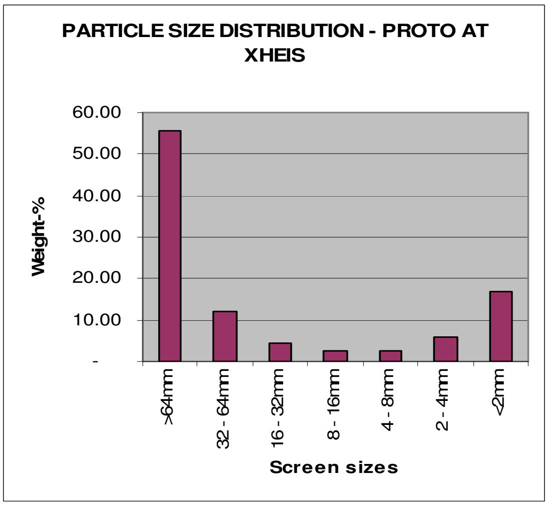


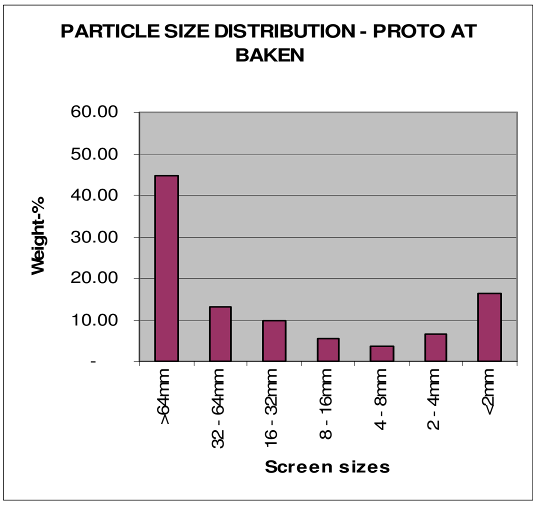
Figures 8.13 and 8.14 Particle size distribution: proto deposits at AACE and Jakkalsberg





Figures 8.15 & 8.16 Particle size distribution: proto deposits, Nxodap & Bloeddrif.

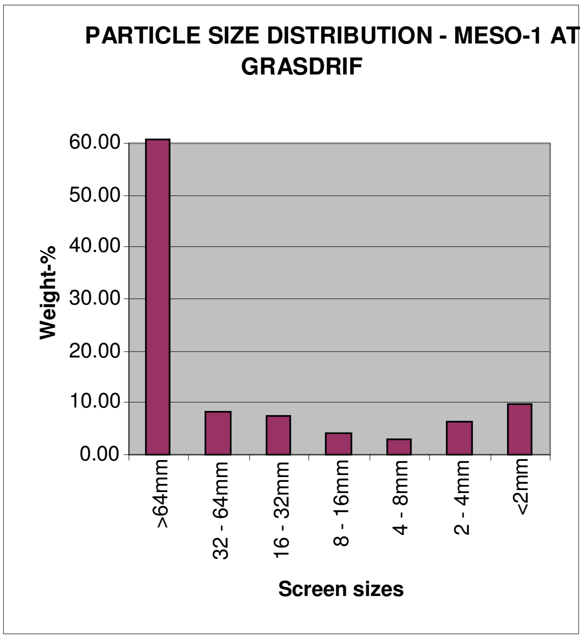


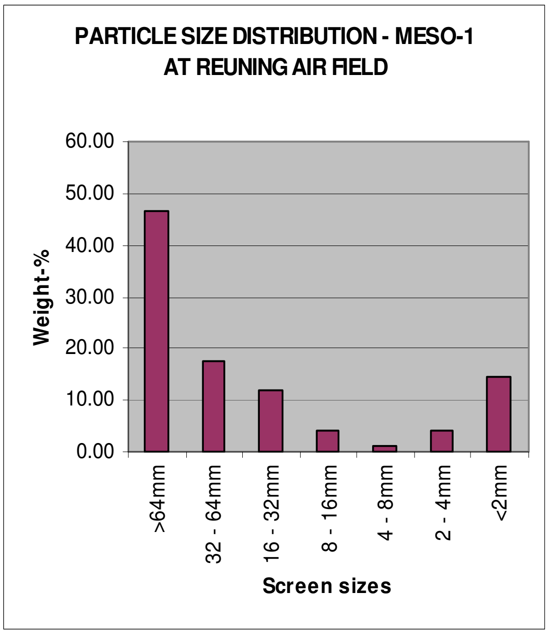


Figures 8.17 and 8.18 Particle size distribution: proto deposits at Xheis and Baken.

Figures 8.13 to 8.18 refer to the proto deposits from AACE to Swartwater/Baken. This sector is situated within the aggradational, fining upward wedge of proto-Orange River sediments starting at Noordoewer/Vioolsdrif and reaching its maximum preserved thickness at Baken. Studying the >64mm component of the clast populations a gradual decrease in the percentage of >64mm particles is indicated from AACE to Jakkalsberg. An increase is noted at Nxodap and Bloeddrif, from where a gradual decrease, typical of a downstream-fining population is evident through Xheis to Baken. It is suggested that the apparent interruption in this trend as noted at Nxodap and Bloeddrif should be ascribed to the effect of bedrock scours and obstacles on stream velocity, as discussed above.

Meso-1 deposits from Grasdrif to Bloeddrif: Comments and interpretation on the particle size distribution graphs of all the meso deposits as a group follow in section 8.1.4.





Figures 8.19 and 8.20 Particle size distribution: Meso-1 deposits at Grasdrif and Reuning Air field terrace

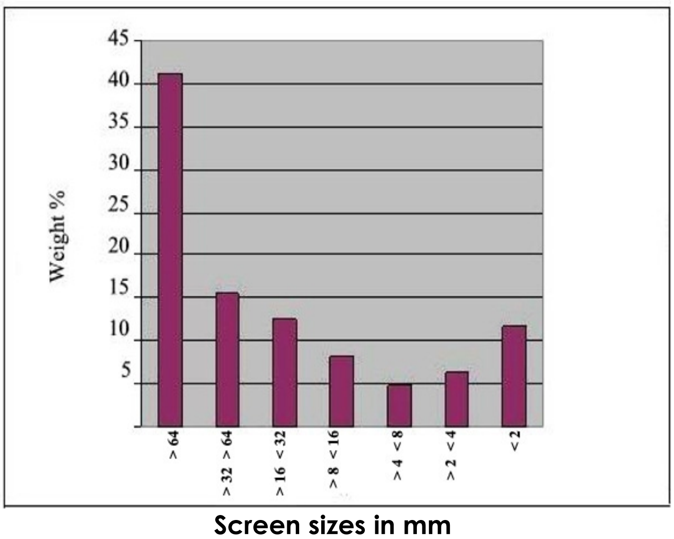
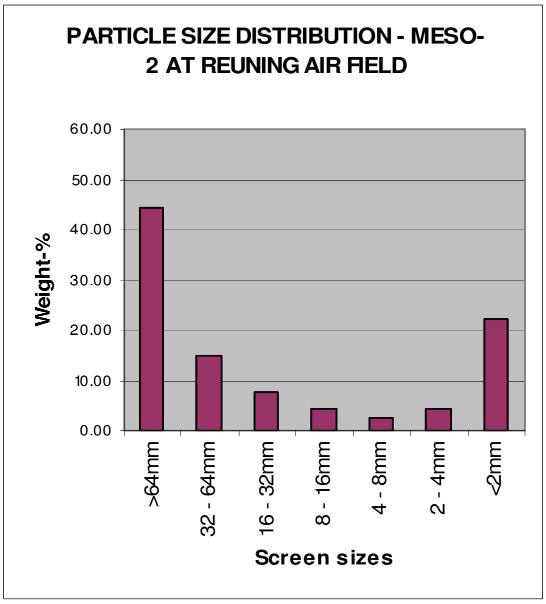
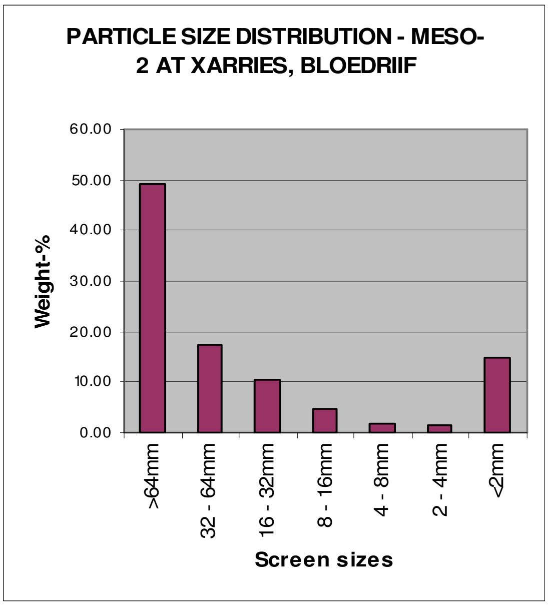


Figure 8.21 Particle size distribution: Meso-1 at Xarries, Bloeddrif.
A consistent downstream-decrease in >64mm particles is evident in these sample populations as illustrated in Figures 8.19 - 8.21.

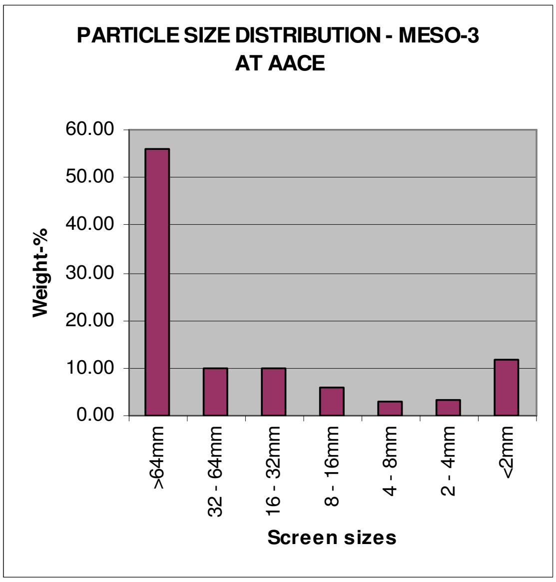
Meso-2 Deposits: Reuning and Xarries, Bloeddrif

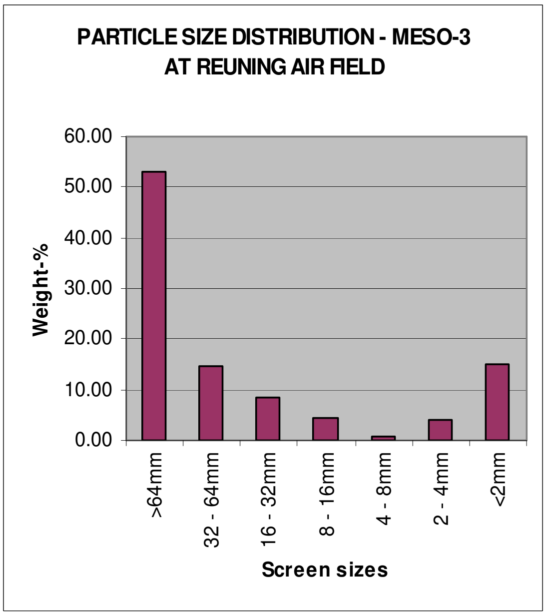




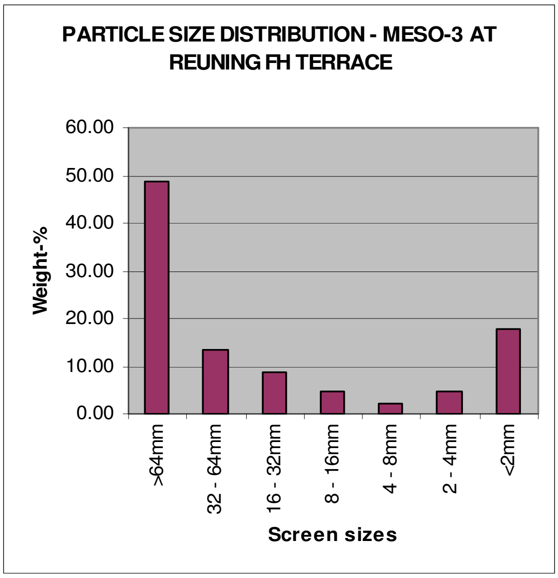
Figures 8.22 and 8.23 The Reuning Air Field Terrace and Xarries are the only two occurrences where meso-2 deposits (Figure 2.10) could be identified with certainty.

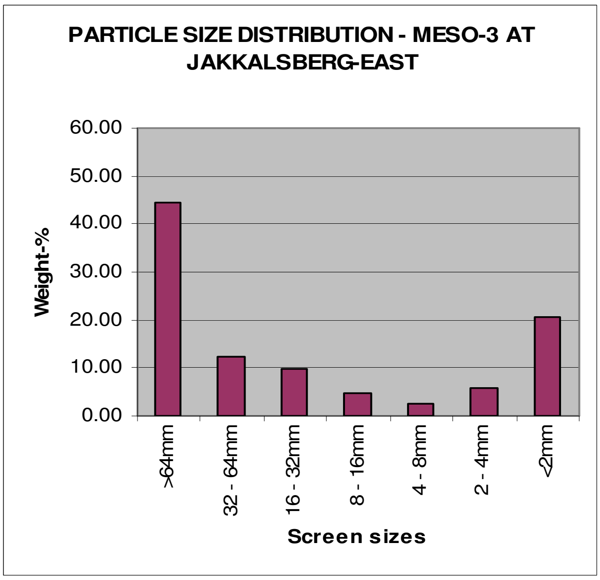
Meso-3 Deposits from AACE to Xarries, Bloeddrif





Figures 8.24 and 8.25 See discussion after Figure 8.28.





Figures 8.26 and 8.27 Comment after Figure 8.28; summary in Section 8.1.3.

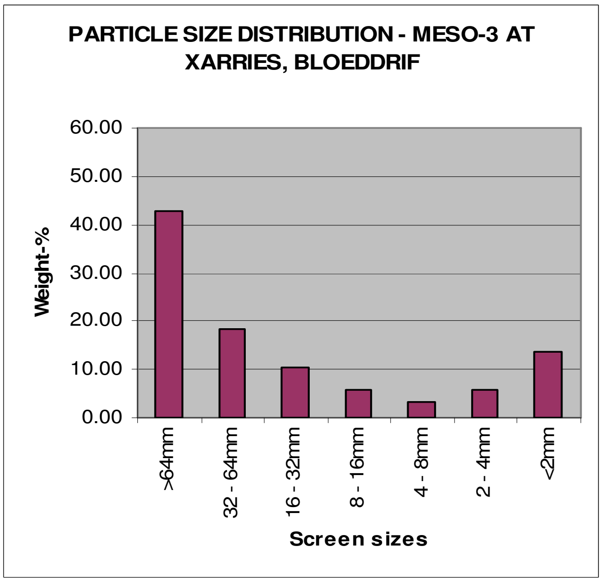


Figure 8.28 Particle size distribution in meso-3 at Xarries, Bloeddrif.

Comment: Figures 8.24 to 8.28 (summarized in Table 8.3) show that the meso 3 deposits from AACE to Xarries also reveal a consistent downstream-fining trend in the >64mm component, as is the case in the meso-1 deposits between Grasdrif and Bloeddrif. This reflects normal fluvial sorting in the absence of bedrock features like scours and protuberances, underscored by the fact that meso sediments were invariably deposited on older Orange River sediments, and seldom on bedrock.

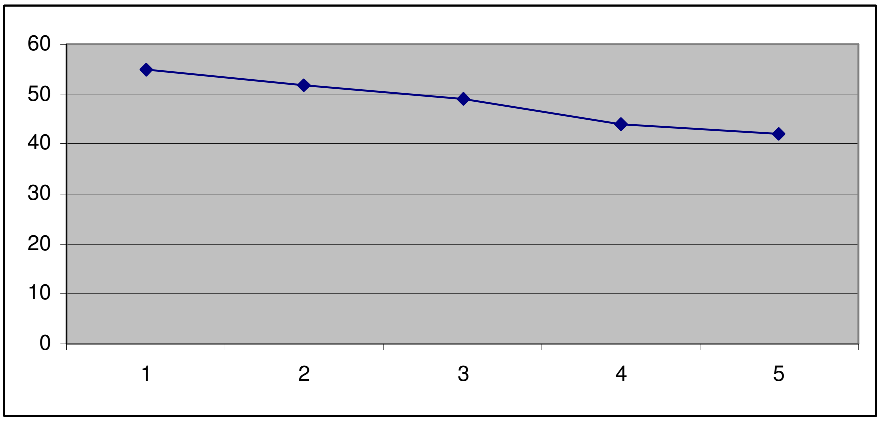
8.1.3 Summary Discussion

A study of the particle size distribution graphs reveals the following:

The more linear as opposed to erratic downstream-fining trend in the >64mm component of the meso deposits in general, as illustrated in Table 8.3 for the meso 1 deposits, is possibly related to the fact that these deposits where sampled, were found to be resting mostly on older Cenozoic sediments and were therefore to a lesser extent influenced by bedrock irregularities as was the case with the pre-proto and proto deposits.

TABLE 8.3 DOWNSTREAM VARIATION IN THE >64mm SIZE FRACTION OF MESO 1 CLASTS FROM AACE TO XARRIES, BLOEDDRIF

Locality	***>64mm material as % of total weight of sample***
1. AACE	*55*
2. Reuning Airfield	*52*
3. Reuning FHT	*49*
4. Jakkalsberg-East	*44*
5. Xarries	*42*



In Section 8.1.2 the theory explaining the relationship between the energy level of a fluvial system and its ability to transport larger particles has been discussed. In this study it was found that the >64mm clasts comprise a large percentage by weight of each sample population, with depositional ages varying from Late Oligocene/Early Miocene to Plio-Pleistocene. Except for those localities where the presence of bedrock scours could have influenced the particle size distribution, this observation would imply intermittent high energy conditions from time to time during most of the Cenozoic, except for the more arid period between the deposition of the Arrisdrif Gravel Formation and the onset of the Pliocene for which no palaeo-Orange River sediments were available to be studied.

The results of the study on roundness indices combined with the particle size distribution study confirmed the tendency for the sedimentary clasts to diminish in size with increasing distance from the source, but mainly as a result of fluvial sorting and breakage, and not so much because of abrasion. It also revealed intermittent local deviations from the trend described above, which are attributed to the presence of scours where increased turbulence would have had a detrimental effect on roundness of sedimentary clasts. Quartzite being more brittle than porphyries and the granitic types, was preferentially broken down under these conditions, hence the more erratic nature of the quartzite trend line on Figures 8.4 to 8.8. It is also conceded that some variation in clast roundness and size could be influenced by the sample location with respect to gravel bar architecture.

8.2. FTIR Work and Diamond Surface Features (Refer to Sections 4.1.5 to 4.1.8)

The analytical procedures involved in FTIR analyses as well as the analytical data are available from the enclosed CD under section **8.2.1**.

8.2.2 FTIR characteristics of known kimberlitic diamond populations, and acquired data (this study) used in provenance identification

A diamond population that resided in a relatively cool environment within the earth's mantle will generate plots that tend to be grouped along the left-hand side of the NAD, with a vertical spread reflecting differences in total nitrogen content. Plots of diamonds with higher aggregation states will tend to be clustered on the right-hand side of the diagram, indicating one or more of the following:

- Longer mantle residence time.
- Higher ambient temperatures.
- A history of deformation that enhanced aggregation (Evans, 1992; Davies *et al.,* 1999).

In Figures 8.29 to 8.42 FTIR results from a number of known kimberlitic diamond populations are illustrated and briefly discussed. All the diagrams of these populations were composed from data extracted from the literature, **except for the Helam and Samada Mines which formed part of the present study**. Data acquired for Helam and Samada are presented and discussed here together with those of the other primary sources, with a view to broadening the data base for kimberlitic diamond populations. This provides an essential part of the background against which the illustrations and discussions of similar results from the secondary deposits studied by the author can be compared.

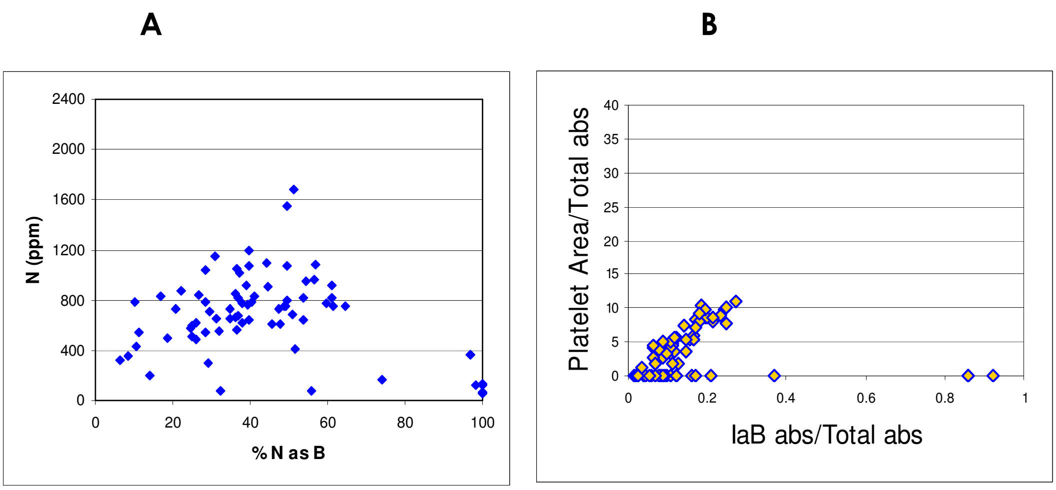


Figure 8.29 Left (A): NAD and Right (B): ratio of platelet strength vs. absorbance of B defects ("Platelet Preservation index") at 1282 cm^{-1} for diamonds from Samada. Data from this study.

On the NAD this population seems to comprise a dominant group with medium to high total nitrogen contents showing a positive correlation between total N and aggregation state, but with the aggregation state not proceeding beyond the 65% mark. A subordinate group (11.84% of the total) boasting total nitrogen of 400 ppm or less reveals aggregation states between 15% and 100%. The presence of two distinct groups could indicate two populations of diamond in the mantle, sampled by one kimberlite, or it could imply two kimberlite pulses, which would find support in the results of a mapping programme by the author (Van Der Westhuizen, 1987), which identified at least two different kimberlite intrusions in the open pit at Samada.

The platelet preservation diagram (8.29B) shows that 7.89% of this sample population are irregular diamonds, indicative of a post-crystallization catastrophic heat event associated with plastic deformation. These diamonds all show zero values for their platelet areas which would indicate that either platelets never formed, or that any platelet present was completely destroyed. Considering the high nitrogen aggregation state revealed by 11.84% of the sample population, it is suggested that platelets did form but were subsequently destroyed. There are no "intermediate" plots on the diagram, of diamonds having had their platelets partially destroyed – only the regular diamonds plotting along the 45 degree trend, and another group plotting along the zero line in respect of platelet area. This observation is seen as further evidence for the presence of two distinct diamond populations that were stored at different depths where different ambient temperatures prevailed (hence the difference in aggregation states), and that the population residing at greater depths, also suffered the plastic deformation that led to the total destruction of their platelets. The only other kimberlite from which data was extracted from the literature for this study and where similar observations were made, is Letseng.

McKenna (*in:* Bowen *et al.,* 2004) studied 100 small diamonds from Letseng-la-Terai (Letseng) in Lesotho. A total of 93 yielded reliable infrared spectra of which 12% was shown to be free of any substitutional impurities and are classified as Type II diamonds. In this regard it should be noted that Letseng is famous for the frequent recovery of >100 ct Type II diamonds of gem quality.

The following aspects are also noted from the results of McKenna (*op.cit.)*:

- As far as the nitrogen aggregation state of the population goes, a bi-modal character seems to be indicated: in most of the diamonds between 55% and 70% of the nitrogen is present as "B" aggregates, with a rather dispersed group that occupies the 15% to 45% area.
- Some 7% of the diamonds studied are classified as "irregular", indicating platelet destruction caused by plastic deformation during a catastrophic heat event.

Nixon and Boyd (1973c) reported on the presence of sheared mantle xenoliths found in the kimberlites of northern Lesotho, and ascribed it to plastic deformation that affected the deeper parts of the upper mantle prior to kimberlite emplacement. The presence of a substantial percentage of irregular diamonds in the Letseng sample population as reported by McKenna (2004) with some apparently having had their platelets completely destroyed, could be seen as further evidence for the work by Nixon and Boyd (*op. cit.)*.

A **B**

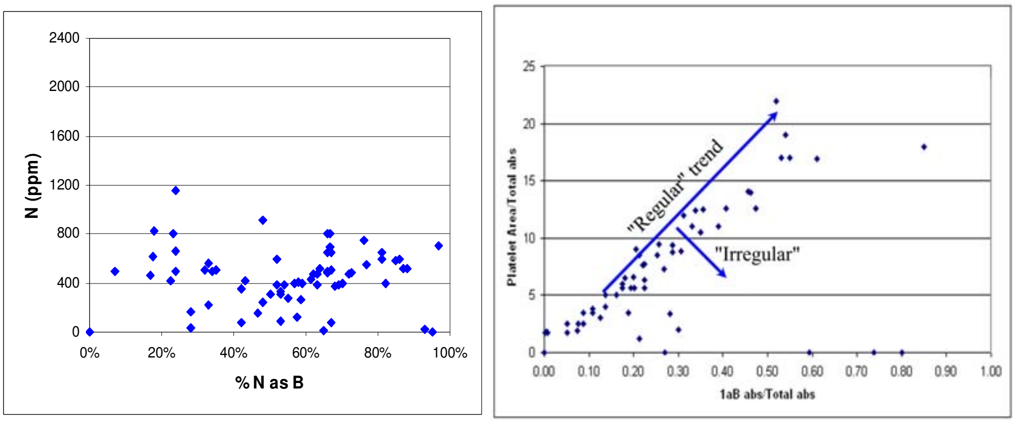


Figure 8.30 (A): NAD and (B): ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Letseng (McKenna, *in:* Bowen *et al.,* 2004).

Very interesting (and unique for southern Africa) NAD characterises the diamond population at Venetia.

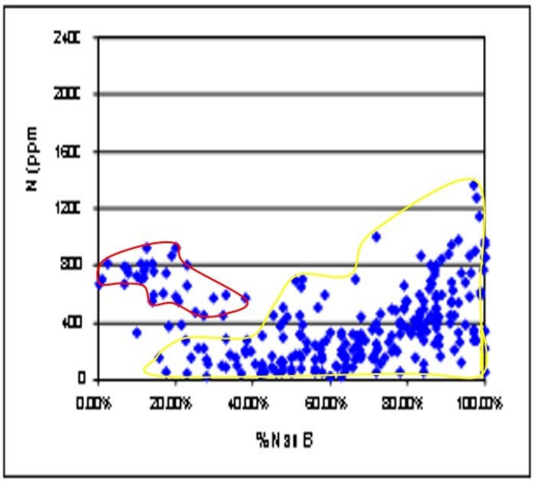


Figure 8.31 NAD for Venetia. Composed from data in Viljoen (2002).

Figure 8.31 shows the nitrogen aggregation characteristics of eclogitic, peridotitic and websteritic diamond populations from Venetia studied by Viljoen (2002), describing two distinct fields. The first group, describing a field in the left half of the diagram and demarcated in red, reflects a diamond population with medium to high nitrogen contents and where the nitrogen is poorly aggregated. In the light of the classification scheme explained in Section 4.1.6 these diamonds belong mainly to Type IaA. The other group, demarcated in yellow, reveals a similar range in nitrogen concentrations, but the aggregation state of nitrogen molecules varies from moderate to very high, even up to 100%; the majority of this group is classified as Type IaB. This latter group does not comply with the norm for diamonds derived from kimberlites on the Kaapvaal Craton (where diamonds revealing an aggregation state of more than 75% comprise a low percentage of the population), and Viljoen (2002) ascribes this high degree of nitrogen aggregation to diamond crystallization and subsequent mantle residence at ambient mantle temperatures higher than for most other kimberlites on the Kaapvaal craton.

The conditions that gave rise to the presence of the poorly aggregated group remain unknown, but the most likely explanation for the presence of two groups is considered to be populations of diamonds residing in different temperature horizons of the mantle. In the original paper Viljoen (2002) showed that most of the Type IaA diamonds are of an eclogitic paragenesis, while most of the highly aggregated group are peridotitic. According to Viljoen (2002) only negligible platelet destruction is revealed by the Venetia diamond populations.

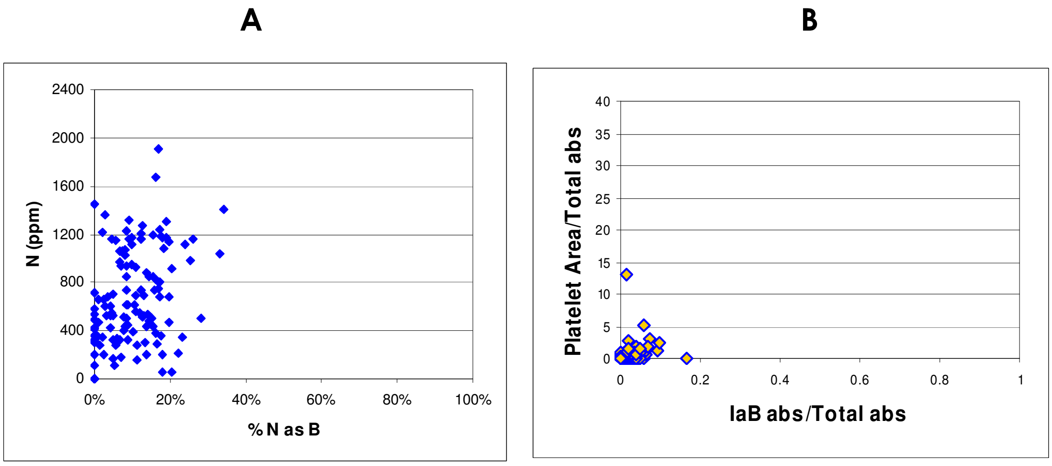


Figure 8.32 Left (A): NAD. Right (B): ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Helam, Swartruggens (this study).

Helam diamonds show a low aggregation state and no distinctive linear trend is discernible (Fig. 8.32). Only a single diamond reveals a zero value for its platelet area and could be termed "irregular".

From this work and that by McKenna (2001) it can be concluded that the diamonds indicate residence temperatures of 1090 – 1100°C for a mantle residence time of 2.75 Ga (residence time = age of diamonds less emplacement age of kimberlite) and sub-populations of diamond represent episodic crystallization within disparate mantle environments, spanning very long periods of time.

The relatively restricted temperature range suggested by McKenna (2001) is supported by the results of this study (Figure 8.32) where it can be seen that the entire diamond population analyzed exhibits a poorly aggregated state which suggests relatively low residence temperatures. This is in keeping with the large proportion of cubes in place of octahedral diamond growth forms evident at Swartruggens (Harris *et al.,* 1979; Robinson *et al.,* 1989). McKenna's conclusions that the diamonds reflect episodic crystallization over very long time intervals, however, is not supported.

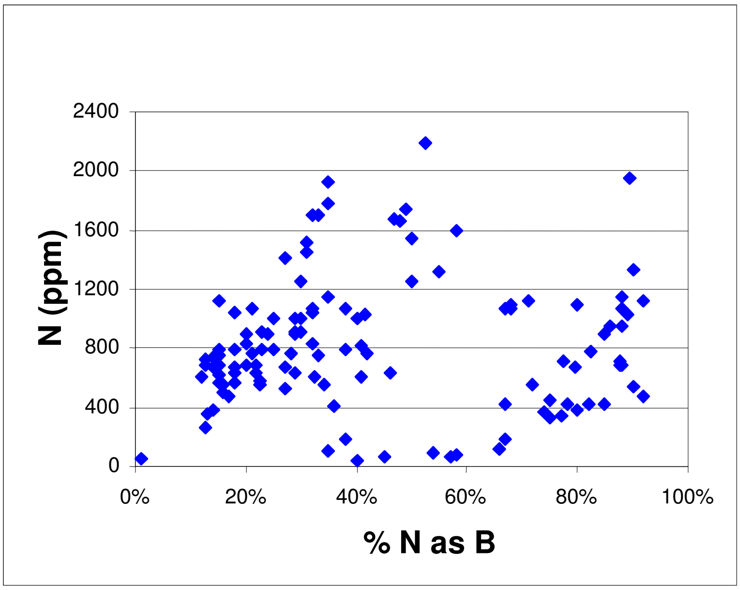


Figure 8.33 NAD, Klipspringer Main Fissure (Composed from Westerlund, 2000)

Klipspringer is located (Figure 1.5) closer to the EW centreline of the Kaapvaal Craton than to its margin, yet also hosts a diamond sub-population that indicates a degree of nitrogen aggregation that is anomalously high with respect to the norm for the Kaapvaal Craton. Westerlund and Gurney (2004) and Westerlund *et al.* (2004) referred to the two groupings as the Low-T and the High-T types. They concluded that the former is considerably younger than the latter that attained its enhanced aggregation state prior to the crystallization of the Low-T group as a result of longer mantle residence time and not because of higher temperature events.

Westerlund and Gurney (2004) suggested that plastic deformation (which would enhance nitrogen aggregation – Evans, 1992) associated with a tectono-thermal event responsible for the reactivation of the Thabazimbi-Murchison Lineament at 2.7 Ga, was responsible for the enhanced aggregation state of the High-T diamonds. Westerlund *et* al. (2004) proposed that the formation of the Low-T diamonds was activated by the same processes that caused the outflow of the Ventersdorp lavas (~2.7 Ga) further south.

Apart from the possibilities mentioned by Westerlund and Gurney (2004) and Westerlund *et al.*, (2004), in view of the close proximity of

Klipspringer to the north-eastern edge of the Bushveld Igneous Complex (~2.0 Ma), the latter could also be considered as a source of heat that caused the pronounced aggregation in the High-T group of diamonds from this locality, with the Low-T diamonds formed subsequently. However, mantle heating events as envisaged here are likely to be of short duration (maybe 1–2%) compared to diamond age. Supposing the occurrence of a hypothetical, relatively large heating spike of 200°C, it will only have the effect of increasing the time-averaged temperature by 2° to 4°C, which would not influence the nitrogen aggregation diagram significantly. Higher aggregation is thus far more likely to be the result of longer mantle residence time. This conclusion finds support in the fact that Westerlund (2000) reported that the Klipspringer diamonds revealed negligible platelet destruction, which would have been unlikely had they been subjected to a significant tectono-thermal event.

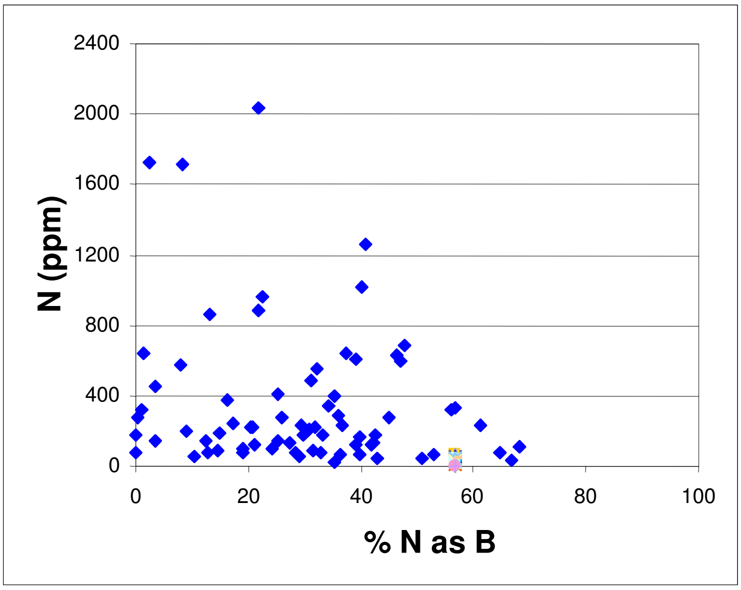


Figure 8.34 NAD, Roberts Victor. Composed from data in Deines *et al.*, 1987

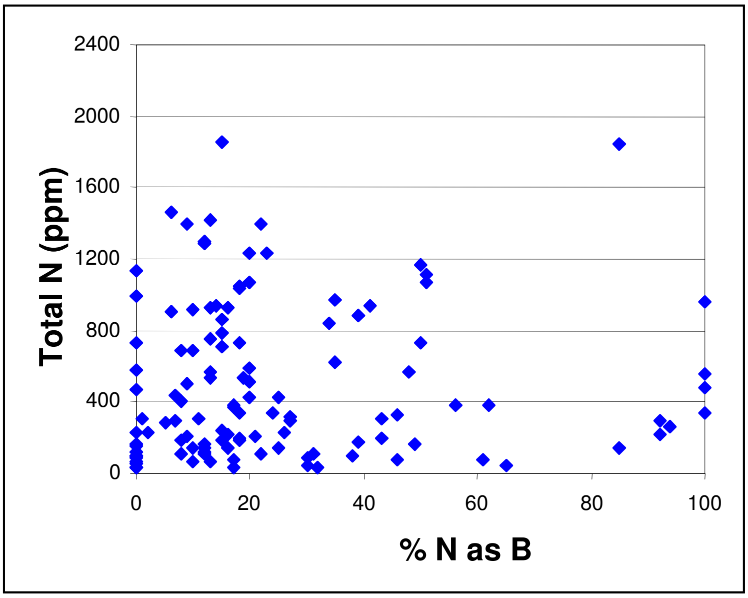


Figure 8.35 NAD, De Beers Pool (Du Toitspan, Bultfontein, Wesselton) (Composed from data in Cartigny, 1997)

The results of the FTIR analyses of the Roberts Victor and Kimberley diamonds depicted in Figures 8.34 and 8.35 describe a field that indicates low to moderate aggregation states, typical of diamond residence in a cool and stable lithospheric environment. Three eclogitic diamonds from the Kimberley population have a N-aggregation state of >85%, while three peridotitic diamonds from the same source have all their nitrogen in the B form. This is probably a reflection of the fact that peridotitic diamonds have a much longer mantle residence time than their younger eclogitic counterparts as suggested by Richardson *et al.* (1984, 1993). Except for a solitary eclogitic diamond from the De Beers Pool boasting a nitrogen aggregation state of >80% and a total N-content of >1800 ppm, both these diagrams reveal a pronounced negative correlation between total N-content and N-aggregation state.

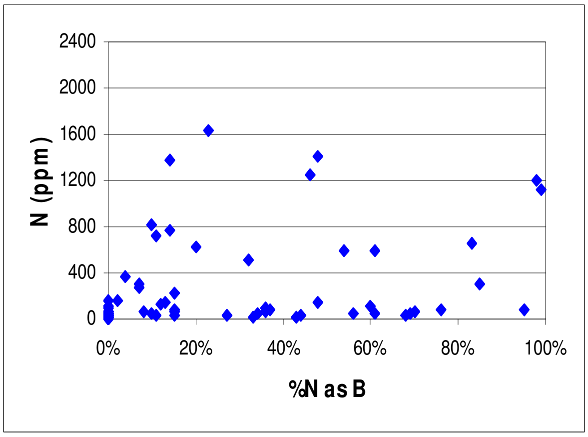


Figure 8.36 NAD, Finsch Mine (Composed from data in Deines *et al.,* 1989)

The most striking feature on this graph is the fact that 53% of the diamonds with measurable nitrogen, display total nitrogen of less than 200 ppm. Not evident on the graph but observed in the published data, is the fact that the sample population also contained 23 Type II diamonds, bringing the total <200 ppm nitrogen stones to 78%.

About 23% of diamonds with measurable nitrogen have more than 60% of their nitrogen in the B form, compared to about 5% at Roberts Victor. This observation is most likely a reflection of the fact that the Finch diamond population is essentially comprised of very old diamonds, *viz.* mainly 3.2 Ga of peridotitic paragenesis with some 1.58 Ga eclogitic diamonds, whereas Roberts Victor contains mainly younger eclogitic diamonds (Deines *et al.,* 1987; 1989) .

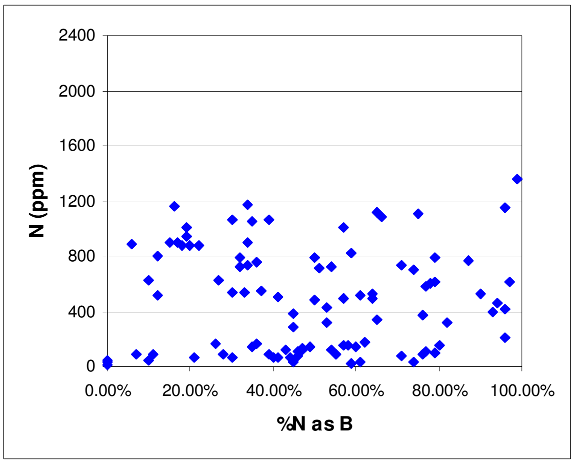


Figure 8.37 NAD, Premier Mine (Composed from data in Deines *et al.*,1989)

This diagram (Fig. 8.37) shows an equal distribution of diamonds with low and high aggregation state. This is probably a reflection of relative ages. Deines *et al.* (1989) showed that about 50% of the Premier diamond population have a peridotitic paragenesis comprising two age groups (3.2 Ga and 2.0 Ga respectively) while the other 50% seems to consist of eclogitic diamonds which formed only about 25 Ma prior to kimberlite emplacement (Richardson *et al.*, 1984).

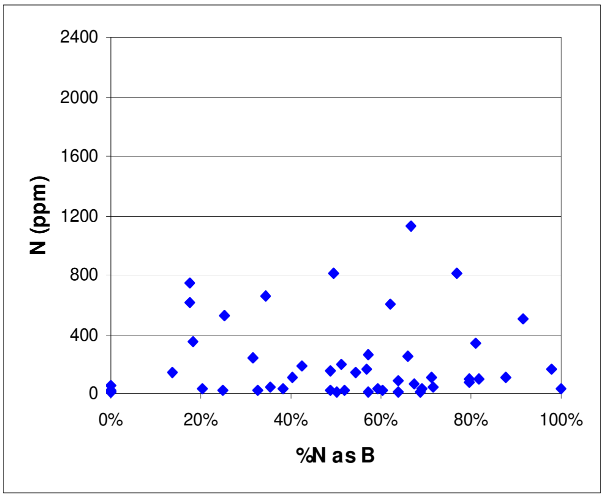


Figure 8.38 NAD, Koffiefontein (Composed from data in Deines *et al.*,1991)

The diagram reveals great similarity to that of Finsch discussed above. None of the diamonds have total nitrogen above 1200 ppm and of those with measurable nitrogen, 55% have ≥ 50% of their N in the B form. Type II diamonds comprise almost 18% of the total sample population.

Referring to Figure 1.4 it would appear that proximity to the southern margin of the Kaapvaal Craton could have been instrumental in the observed aggregation state which is higher than *e.g.* what we have seen at Roberts Victor. However, Koffiefontein also has widely disparate age groups in its diamond population (Pearson *et al.*, 1998) and older diamonds (longer residence time) can also be expected to reveal more advanced aggregation states.

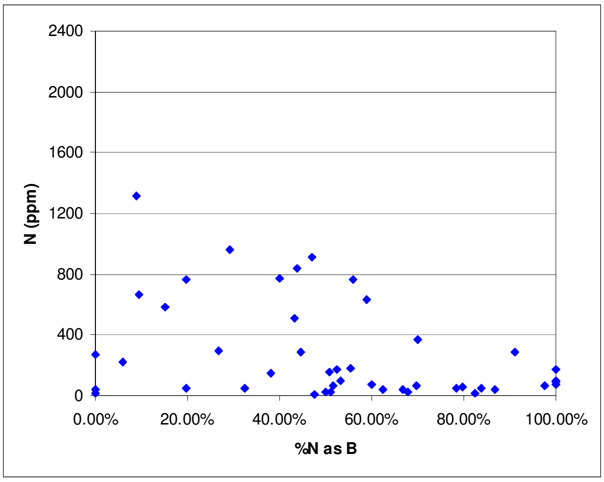


Figure 8.39 NAD, Jagersfontein (Composed from data in Deines *et al.,* 1991)

The Jagersfontein results are very similar to those obtained from Finsch and Koffiefontein. Jagersfontein is closely situated to Koffiefontein and closer to the southern edge of the Kaapvaal Craton. About 59% of the diamonds with measurable nitrogen have ≥ 50% of their N in the B form compared to 55% at Koffiefontein. Perhaps the most important aspect in this regard, however, is the presence of a significant population of ultra-deep (asthenospheric) diamonds that would have experienced much higher mantle temperatures during post-crystallization residence (Deines *et al.,* 1991; Shirey *et al.,* 2002).

A poor negative relationship between N content and aggregation state is evident.

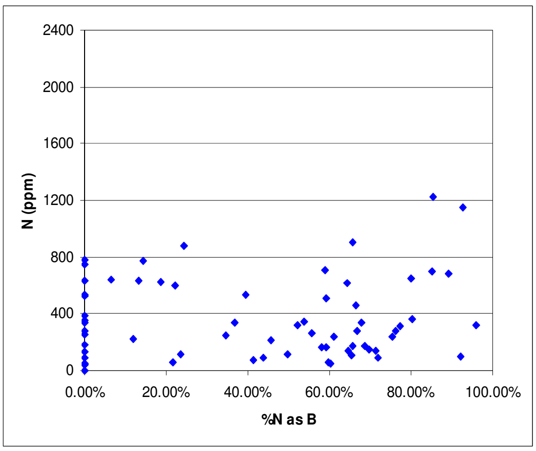


Figure 8.40 NAD, Jwaneng (Composed from data in Deines *et al.*,1997)

A bi-modal character is a feature of the Jwaneng diamond population. In one group, about 81% of the diamonds with measurable N have more than 50% of their N in the B form. The other group consists almost entirely of Type IaA, indicative of the early stages of N-aggregation. Of these (Deines *et al., op* cit.), 50% have an eclogitic paragenesis and 50% are peridotitic. This apparent deviation from the model that describes nitrogen aggregation essentially as a function of mantle residence time necessitates the realization that different residence periods in this case also involved different ambient temperatures.

Deines *et al.* (1997) concluded that the Jwaneng diamonds, as in most cases studied, formed over an extended time interval, maybe as long as 3 Ga (for the peridotitic diamonds) in several distinct chemical environments.

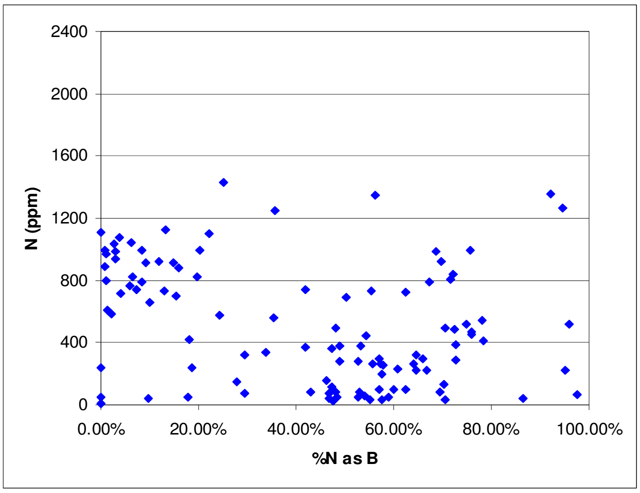


Figure 8.41 NAD, Orapa (Composed from data in Deines *et al.,* 1993)

The NAD's of Jwaneng and Orapa are very similar. The bi-modal character revealed by the Jwaneng sample population is also visible in the Orapa results, with one exception: the Low-T, poorly aggregated group does not consist almost exclusively of Type IaA diamonds and its total nitrogen content is clustered between about 750 to 950 ppm, compared to the 0 to 400 range that dominates the poorly aggregated group at Jwaneng. As with the Jwaneng population, the Orapa diamond population consists of at least two groups of eclogitic diamonds, some websteritic diamonds plus some with 3.2 Ga peridotitic paragenesis. The latter two types appear to have equilibrated at lower *P-T* conditions than the eclogitic types (Deines *et al.*, 1993), which is in agreement with the trend observed elsewhere by Gurney (1989).

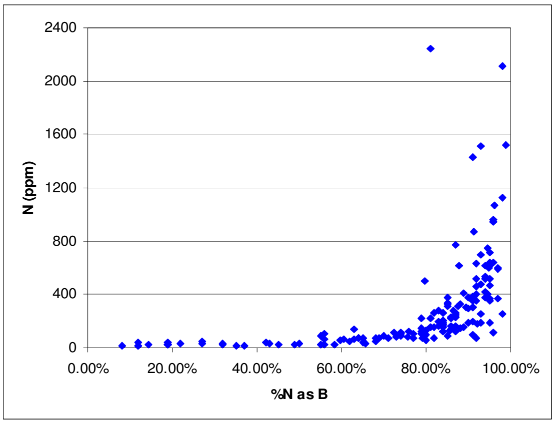


Figure 8.42 NAD, George Creek, Colorado (Comp. from data in Chinn, 1995)

The highly aggregated condition of the majority of the diamonds analyzed and the pronounced positive correlation between total nitrogen content and aggregation state typifies this diamond population. Deines *et al.* (1989, 1991, and 1993) stated that no such correlation was found in their studies of numerous kimberlitic diamond populations in southern Africa. George Creek is situated in a craton margin area, while Deines and co-workers studied the well-known Cretaceous kimberlites of southern Africa, located on the Kaapvaal Craton. One would have expected to see greater similarities with George Creek at Letseng, Jagersfontein, Koffiefontein and Finsch, all located not too distant from the craton margin. This is not the case, and the extent of aggregation observed at these localities, can be explained in terms of local conditions as discussed in the relevant sections.

8.2.3 FTIR data as provenance indicator

With the exception of the 114 diamonds from the Helam kimberlite mine and 107 from the Samada Mine that formed part of this study, and the data from Bultfontein, Du Toitspan and Wesselton, which were acquired from Cartigny (1997) all the data referred to in Section 8.2.2 were extracted from published literature as well as unpublished reports as cited. The rest of the diamonds used in this study were from the localities listed in Table 1.3 and in ensuing paragraphs, and analyzed by the author. The results from the thirteen (with Du Toitspan, Bultfontein and Wesselton having been grouped together as one source called "De Beers Pool") primary sources in southern Africa submitted (Deines *et al.,* 1989, 1991, 1993, 1997; McKenna, 2004; Viljoen, 2002; Westerlund, 2000; Cartigny, 1997) offer a diversity of diamond populations that will serve as a data base with which the results of the alluvial populations studied could be compared. The results could possibly allow the tracing of source to sink and associations with particular kimberlites. The heterogeneity is sufficient to facilitate discrimination in the fluvial-marine populations.

The possibility of depicting the FTIR results that appear on the NAD statistically rather than graphically was investigated. There are unavoidable errors within the (FTIR) method, not only to obtain the nitrogen aggregation state, but also in the mathematics of the deconvolution to arrive at total nitrogen content. The conversion factors to determine concentrations have errors of 10%. The activation energy for the Type A to Type B aggregation process also has quite significant errors associated with it. But even if we were successful in obtaining near-perfect results, we would still be mixing data from different diamonds that formed and resided in different T and P regimes in the mantle. "Putting these factors together means that statistics are not part of FTIR of diamond" (verbatim quote: Prof. J.W. Harris, Glasgow University, pers. comm. November 2009).

The Richtersveld group. This group comprises a combination of diamonds from the fluvial deposits mined at Baken and Bloeddrif along the Lower Orange River.

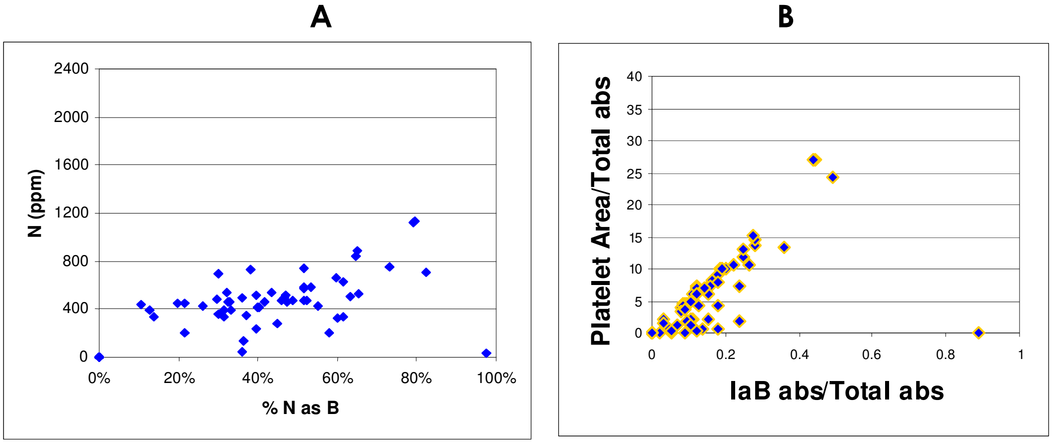


Figure 8.43. NAD left (A) and right (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from the "Richtersveld group". See discussion with the results from the Mid-Orange region below.

Diamonds selected from this locality:	76
Useful analyses obtained:	56
Type II stones identified:	2 (total N $\leq$ 40)
Irregular diamonds:	3 (5.4% of useful analyses)

Mid-Orange group. This group is comprised of the Saxendrif and Brakfontein mining areas exploiting fluvial deposits located along the Mid-Orange about 1000 km upstream from Baken and Bloeddrif.

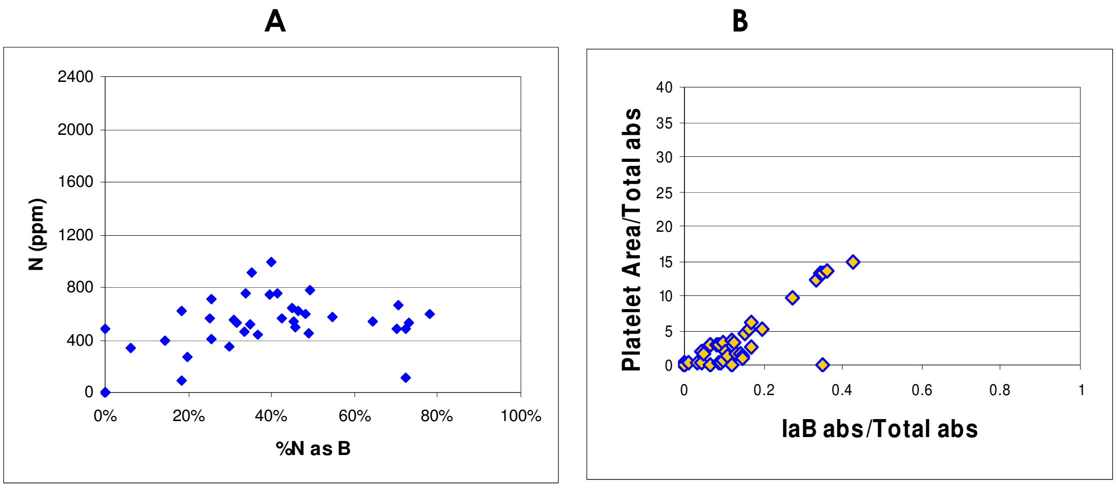


Figure 8.44 NAD left (A) and right (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects: diamonds from Saxendrif-Brakfontein ("The Mid-Orange")

Diamonds selected from this locality: 55
Useful analyses obtained: 36
Type II stones identified: 3 (total N = 0)
Irregular diamonds: 1 (2.8% of useful analyses)

TABLE 8.4 COMPARING NAD CHARACTERISTICS OF MID-ORANGE AND RICHTERSVELD GROUP DIAMOND POPULATIONS WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	Remarks
Venetia	Venetia's 2 main populations do not feature here; some of the scattered field in-between its two main groups overlap with the Richtersveld population, but not very convincing
Helam/Swartruggens	As a population quite distinct from the Orange River sample populations
Letseng	Reasonable correspondence in some areas, but both boasts compositions that are lacking on the other graph.
Klipspringer Main Fissure	There is limited overlap of individual data points, with Klipspringer's Low-T group, around 380 – 500 ppm, < 20% B aggregates, but the fields as such do not correspond
Kimberley Group (Rovic and De Beers Pool combined)	Overlap of numerous individual data points in the 300 – 800 ppm N, 20-60% B aggregate area, but fields do not correspond well
Samada	Remarkable resemblance with < 800ppm N field
Finsch	Very poor correspondence
Premier	Very scattered population; limited overlap
Koffiefontein	Reasonable correspondence with <400 ppm field
Jagersfontein	Reasonable correspondence, including some highly aggregated diamonds in the < 400 ppm range.
Jwaneng	Reasonable overlap in places, but not very convincing
Orapa	The fields are distinct, but limited overlap with a scattered component of the Orapa High-T group is discernible

In Table 8.4 and all similar ensuing tables, the colour of highlighting does not have any specific significance, but merely serves to enhance the visual distinction between poor and better correspondence).

The general characteristics of the Mid-Orange NAD and platelet preservation index correspond so well with that of the combined Richtersveld plot that mutual provenance regions seem most likely. Between 2.5% and 5% of these sample populations are termed irregular because of the amount of platelet degradation they underwent.

When the Richtersveld/Mid-Orange plots are compared to the kimberlite data base the best visual correlation is with Letseng, because most of the diamonds have nitrogen contents of between 400 and 800 ppm and aggregation states essentially concentrated between 20% and 80%.

The Richtersveld/Mid-Orange populations also reveal a resemblance with the <800ppm nitrogen field on the NAD for Samada. In addition Letseng and Samada are the only primary sources where irregular diamonds comprise significant percentages of the diamond sample populations. These similarities suggest that a large proportion of the diamonds in the Richtersveld and Mid-Orange groups are derived from sources similar to Letseng and Samada.

Approximately 2.9% of the De Beers Pool diamond population are Type 1aA diamonds, with total N varying between 400 and 800ppm. One such diamond was found in the Mid-Orange population, indicating a link between this primary source and the Orange River sample populations. Similar data points were also recorded for Jwaneng.

Diamonds with ≤ 400 ppm N and an aggregation state between zero and 70% are responsible for 31.5% and 22% respectively on the Richtersveld and Mid-Orange NA diagrams. Similar data points comprise 47.6% and 73.5% respectively in the sample populations of the De Beers Pool and Rovic, and 60% and 52.3% at Koffiefontein and Jagersfontein respectively. As stated before, exact correspondence between kimberlitic and alluvial diamond deposits should not be expected, since the alluvial deposit(s) comprise mixtures of diamonds from different primary sources. Therefore, even though the percentages mentioned above do not correspond exactly, the fields that their data plots describe illustrate similar diamond populations. Considering the geographic location of the Kimberley, Rovic, Koffiefontein and Jagersfontein kimberlites with respect to the Vaal-Orange drainage network, prevailing ideas that the Vaal-Orange system was a major conduit for the transportation of diamonds from the Kimberley region to the Atlantic coast are supported. The fact that the percentages mentioned above are lower in the Orange River diamond populations than in the primary sources referred to is seen as evidence that the Vaal-Orange drainage transported diamonds from other sources as well. In order to illustrate the above e conclusions graphically, the sample populations from Du Toitspan, Koffiefontein, Letseng and Samada were combined into a theoretical "Provenance Population" for the combined Mid-Orange and Richtersveld populations. The results are depicted in Figures 8.45A and 8.45B.

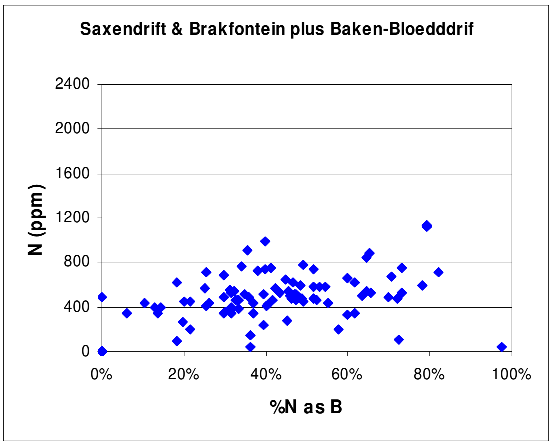


Figure 8.45A NAD for combined Orange River sample populations

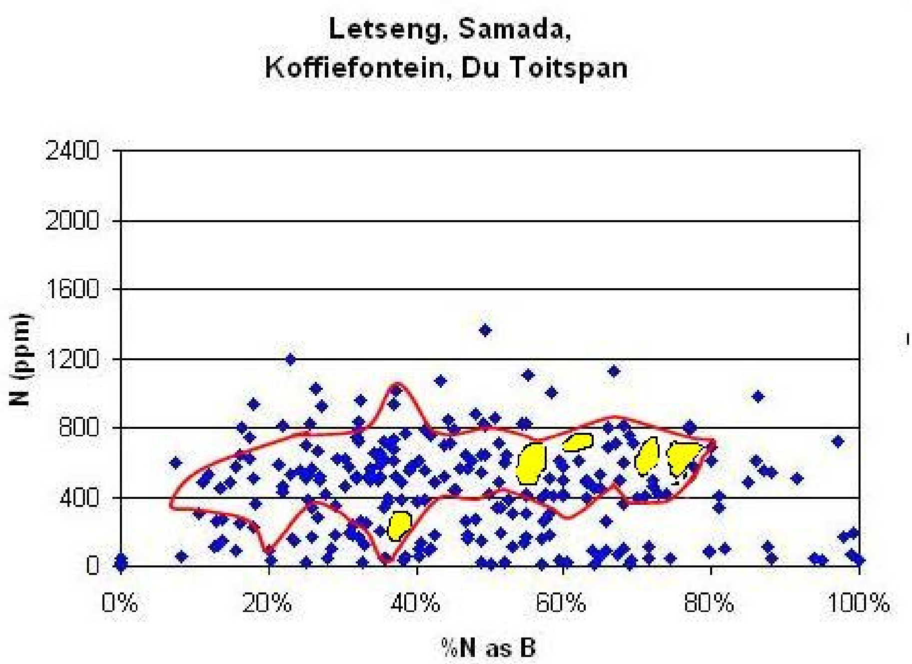


Figure 8.45B NAD for combined sample populations from Du Toitspan, Koffiefontein, Letseng and Samada. *The figure outlined in red represents the main field described by the plots in Figure 8.45A while the yellow patches highlight corresponding "blank" areas. It must be conceded that it is unlikely for diamonds from the various kimberlites listed here, to accumulate in one alluvial deposit in the same ratio as that of the sample populations used in this study. The correspondence is however demonstrated so well that the combined Orange River population can be accepted as being part of the theoretical provenance population used to construct Figure 8.45B.*

From Table 8.4, Figure 8.45 and the discussions above it is concluded that the Miocene Orange River deposits derived the majority of their diamond populations from the Cretaceous kimberlites of Letseng, Samada, Du Toitspan and Koffiefontein, with subordinate contributions from Rovic, Jagersfontein, Jwaneng and Orapa. This conclusion finds support in the fact that the surface feature studies summarized in Table 4.4 failed to recognize any diamonds from pre-Karoo kimberlites in these sample populations, except for a few stones with polished surfaces that are present at Baken Mine.

Yellow octahedrons (5 to +10 ct size range), are often reported from the Kimberley mines as well as from production sites along the Lower Orange River (pers. obs.). The Kimberley region is however not the only source of these large yellow diamonds in the Orange-Vaal catchment area, as illustrated in Figure 8.46.

Figure 8.46 Yellow 5ct diamond in kimberlite, Liqhobong, Lesotho (Birnie, 2005)

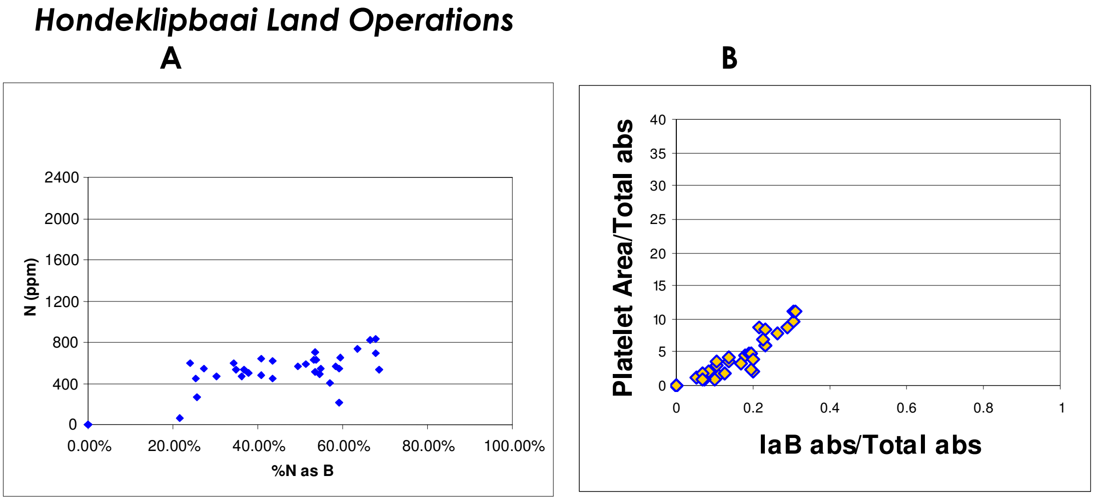


Figure 8.47: NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Hondeklipbaai Mine (Land Operations)

Diamonds selected from this locality:	40
Useful analyses obtained:	34
Type II stones identified:	0
Irregular stones w.r.t. platelet preservation:	0

Of the 40 diamonds selected from this mine, 34 useful analyses were obtained. On the NA diagram this population has two distinguishing features:

- The effective absence of diamonds with a nitrogen aggregation state of less than 20%. Among the known primary sources it is only the Klipspringer Main Fissure (Fig. 8.33) that lacks a <20% tail, however the remainder of the Klipspringer diagram correlates poorly with this occurrence.
- Of all the alluvial deposits studied, this sample population - and that at Holfontein in Gauteng - are the only ones revealing a total absence of diamonds with green or brown spots (discussed in 4.4.4.iv). The diamond population of the Samada kimberlite is unique in this regard among the known kimberlitic populations in southern Africa, but 6% of the Samada sample population reveals a nitrogen aggregation state of less than 20%.

The very narrow range described by the data points of this population on the NAD is similar to those of the fluvial deposits along the Orange River with which it also shares similar concentrations of most of the other surface features as summarized in Table 4.4.

Marine Concession 3B.

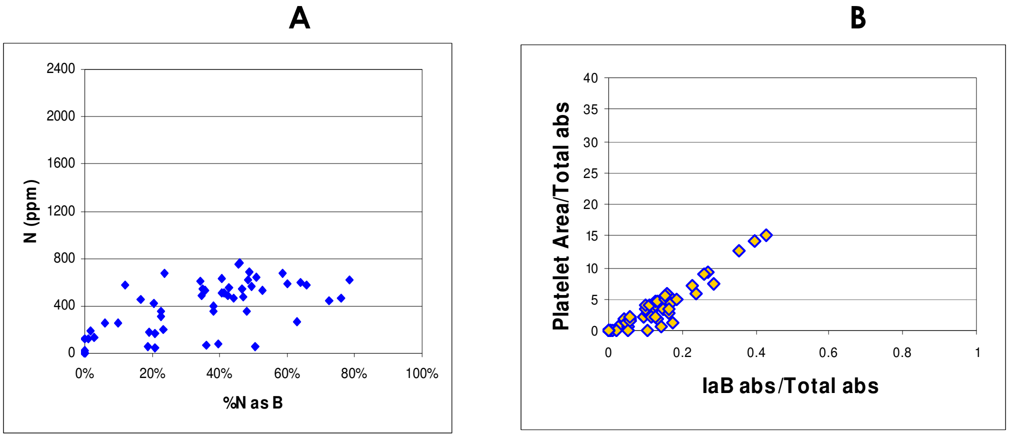


Figure 8.48 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from Marine Concession 3B

Diamonds selected from this locality:	54
Useful analyses obtained:	42
Type II stones identified:	2 (total N $\leq$ 39)
Irregular stones w.r.t. platelet preservation:	2 (4.8% of useful analyses)

This population is characterized by a significant number of diamonds with a low N content and low aggregation state which makes it distinct form the Orange River populations as such. Furthermore, 27.3% of the 3B diamond population show appreciable abrasion of crystal edges, compared to only 5% in the case of the Baken basal gravel, as depicted in Table 4.4. This aspect cannot be ascribed to exposure in a marine environment only. Compared to the low percentage of appreciably abraded diamonds at Baken referred to above, such diamonds comprise 31% of the population of the fluvial deposit of Buffelsbank along the Buffels River valley while they are completely absent from the marine deposits 12A Geelwal Karoo and 12A De Punt.

But for a few stones revealing polished surfaces found at Baken Mine, diamonds with an indicated pre-Karoo emplacement history (presence of brown spots) are absent from the Orange River populations, but comprise 9.1% of the 3B population.

It is concluded that the Orange River was not the only conduit active in the transportation of the diamond population of Marine Concession 3B from the hinterland to the Atlantic Ocean.

From the above discussions it is clear that the NAD of this population cannot mirror that of any single primary source, but the presence of a number of low-nitrogen, poorly aggregated diamonds are reminiscent of portions of the populations from the De Beers Pool, Rovic, Helam, Finsch, Jwaneng and to a lesser extent, Orapa. The presence of a few irregular diamonds would indicate a Samada/Letseng contribution as well.

Marine Concession 5A

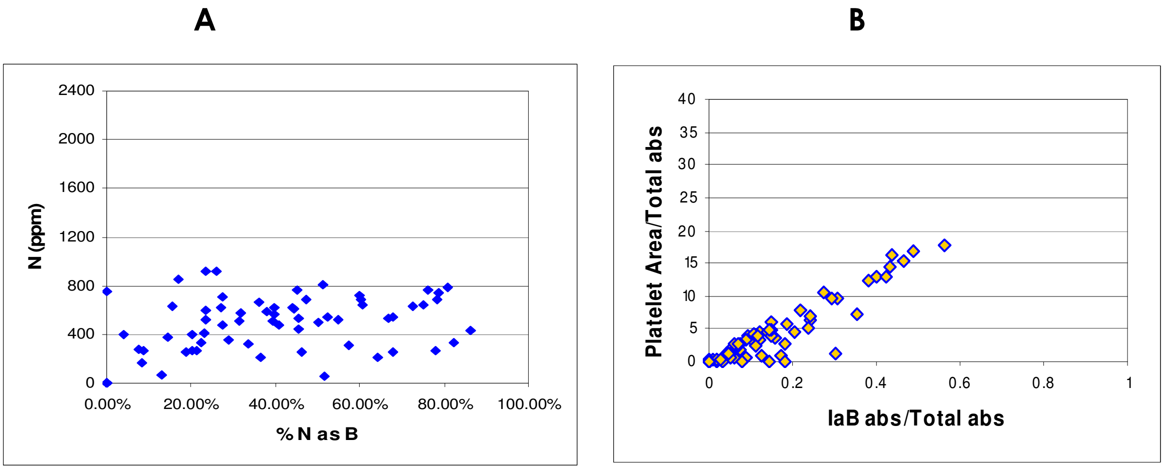


Figure 8.49 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from Marine Concession 5A, straddling the Buffels River estuary at Kleinzee.

Diamonds selected from this locality:	89
Useful analyses obtained:	66
Type II stones identified:	0
Irregular stones w.r.t. platelet preservation:	5 (7.6% of useful analyses).

This NAD distribution is again typified by the N content that does hardly exceeds 800ppm. It is in some respects reminiscent of the Richtersveld group (Figure 8.43), but with the introduction of a number of high-nitrogen, poorly aggregated, as well as a number of low-nitrogen, highly aggregated diamonds. Irregular diamonds are slightly more abundant (7.6%) compared to the 3B population. Diamonds with an indicated pre-Karoo emplacement age (presence of brown spots and polished surfaces) comprise 13.1% of the sample population, 44% higher than is the case at 3B.

Robinson (1979) reported on the presence of brown spotted diamonds at the Buffelsbank Mine in the Buffels River valley (locality 28 on Figure 1.3). At Bosluispan (locality 34 on Figure 1.3) brown spotted diamonds constitute 1.7% of the sample population, and irregular diamonds, 8.8%. Support for the probable link between the diamond populations of Bosluispan and Marine Concession 5A *via* the palaeo-Buffels River valley is also seen in the presence of brown and deformed diamonds, namely 32.8% at Bosluispan, 15% at Buffelsbank and 17.4% at Marine Concession 5A that straddles the Buffels River estuary.

The presence of diamonds with brown spots (totally absent from the Orange River populations) in concessions 5A, 3B, the Buffels River Valley and Bosluispan is also significant since it points to an additional source region to that of the Orange River deposits.

Irregular diamonds do not feature in the sample populations from Hondeklipbaai Land Operations and Surf Zone, and Marine Concession 7A. Thus the presence of irregular diamonds in Concessions 5A and 3B is anomalous for the West Coast deposits north of Concession 8A, confirming a significant input of diamonds *via* the Buffels River.

The surface feature study thus indicates multiple source regions for the diamond population of Marine Concession 5A. Comparing the NAD of 5A with those of the known kimberlitic populations in the hinterland, contributions from Samada, Letseng, Jwaneng and Orapa are indicated. The presence of irregular diamonds tend to support the link with Samada and Letseng, while the brown spotted diamonds could have been sourced from Dwyka remnants at Bosluispan and the Kamiesberge.

Hondeklipbaai Surf Zone.

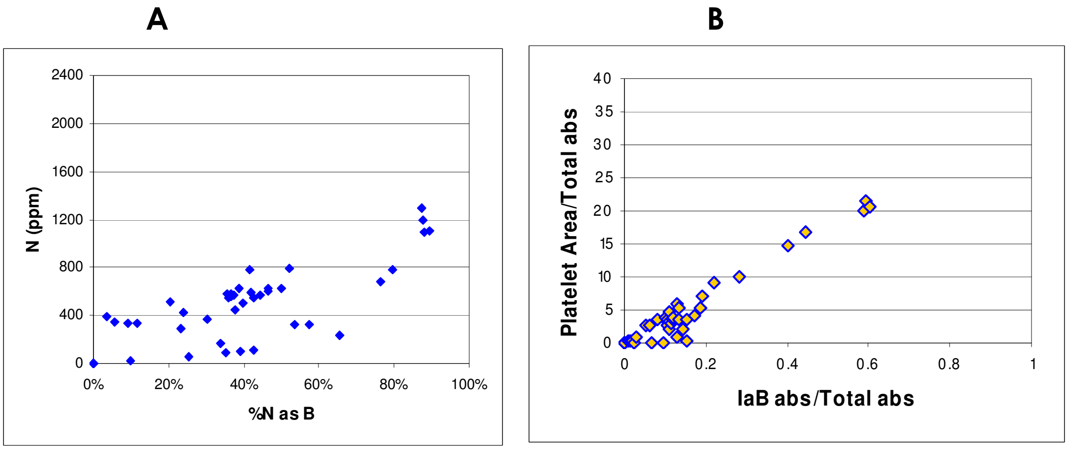


Figure 8.50 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm-1 of B defects (B) for diamonds from the Hondeklipbaai Surf Zone

Diamonds selected from this locality:	80
Useful analyses obtained:	34
Type II stones identified:	2 (total N ≤ 21)
Irregular stones w.r.t. platelet preservation:	0

This NAD compares more closely with those from the Richtersveld (Fig. 8.43) and Concessions 3B and 5A, than it does with that of the Hondeklipbaai Land Operations (Fig. 8.47) only 2 kilometres inland. Both the low-nitrogen, poorly aggregated tail and a high-nitrogen, highly aggregated head which are missing from the land operations' data set, are present here. It should be noted that both sample populations were recovered at the same recovery facility. This aspect suggests the presence of distinctly different diamond populations rather than metallurgical inadequacies.

The best analogues among the primary sources are from distal locations like Jwaneng, Orapa and to a lesser extent, Premier.

Marine Concession 7A.

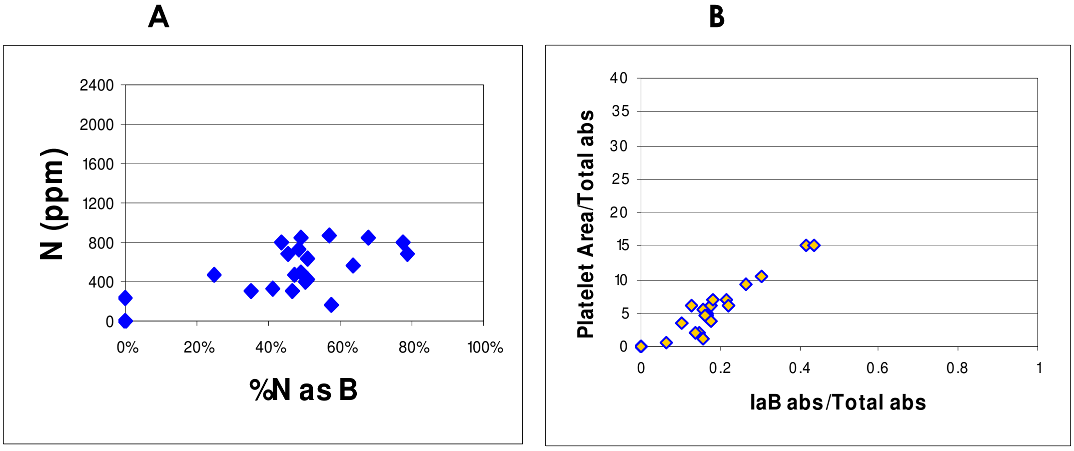


Figure 8.51 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from Marine Concession 7A

Diamonds selected from this locality:	41
Useful analyses obtained:	20
Type II stones identified:	1
Irregular stones w.r.t. platelet preservation:	0

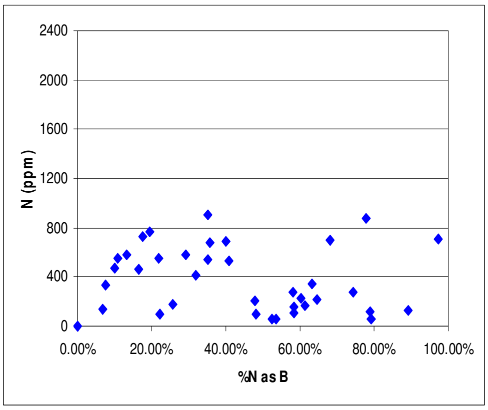
The NAD plot of this population once again reveals N content that hardly exceeds the 800ppm mark. With the exception of one Type Ib and one Type II stone (see relevant table on analytical results in 8.2 in the Appendix) this field also lacks a tail of <20% aggregation plots as is the case at Hondeklipbaai land operations. However, the presence of green and brown spots on some of the diamonds found in Concession 7A argues against a common source for all the diamonds in these two populations.

This diamond population was derived from Jwaneng, Orapa, Letseng and to a lesser extent, Koffiefontein and Jagersfontein. The most likely provenance regions for the diamonds linked to kimberlites with pre-Karoo emplacement features - comprising 9.7% (3.2% brown-spotted, 6.5% polished surfaces) of the population - are Venetia and Premier.

TABLE 8.5 COMPARING NAD CHARACTERISTICS OF MARINE CONCESSION 7A DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	Some resemblance with a portion of the scattered field observed between the High-T and Low-T groups at Venetia.
Helam/Swartruggens	No resemblance at all, but for a single unaggregated (Type Ib) stone in the 7A population
Letseng	Good correlation with the High-T group from Letseng.
Klipspringer Main Fissure	No correlation; 7A actually fits into the gap between Klipspringer's two discrete populations!
Kimberley (De Beers Pool)	A very small group overlaps with the 50% aggregation, 600-700 ppm N plots of the Kimberley group fields
Samada	Poor correlation
Finsch	A few isolated plots of the Finsch graph overlap with a diffuse 7A field between 45% and 80% aggregation coupled with a restricted range of 400 – 800 ppm N
Premier	The entire 7A field overlaps with the widely scattered Premier field but lacking Premier's low-N stones
Koffiefontein	Weak overlap with portion of scattered Koffiefontein field but lacking Koffiefontein's low-N stones
Jagersfontein	Weak overlap with portion of scattered Jagersfontein field but lacking Jagersfontein's low-N stones
Jwaneng	The Jwaneng population comprises a large group of Type Ib stones and another group with varying aggregation but more or less restricted to ≤ 800 ppm N; the 7A population has 1 Type Ib stone, with the rest of its population clustered between 40 and 80% aggregation and ≤ 800 ppm N, overlapping very well with that portion of the Jwaneng graph.
Orapa	In general, the 7A ≤800 ppm N field overlaps very well with that portion of the Orapa NAD

Marine Concession 11A



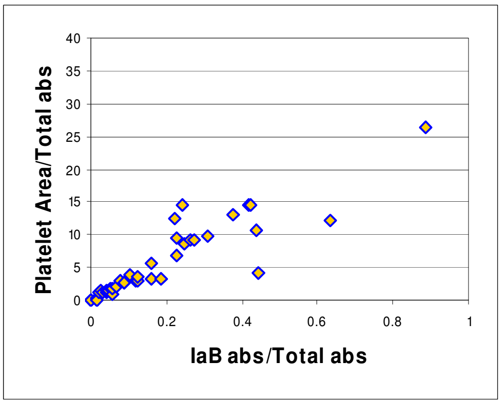


Figure 8.52 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from Marine Concession 11A.

Diamonds selected from this locality:	40
Useful analyses obtained:	36
Type II stones identified:	1 (total N = 0)
Irregular stones w.r.t. platelet preservation:	4 (11.1% of useful analyses)

Irregular diamonds make up 11.1% of the useful analyses obtained. Only Letseng and Samada among the kimberlitic populations available for this study boast significant percentages of irregular diamonds, and both these also reveal NAD similarities with the 11A population.

TABLE 8.6 COMPARING NAD CHARACTERISTICS OF MARINE CONCESSION 11A DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	Weak overlap of 11A's ≤900 ppm N with Venetia
Helam/Swartruggens	<20% aggregated stones overlap with Helam's Low-T field
Letseng	Good correlation with Letseng
Klipspringer Main Fissure	Some overlap of the Low-T groups
Kimberley group	Weak overlap with the <30% aggregation, <800 ppm N fields
Samada	Partial overlap with Samada's <40% aggregation field
Finsch	Some overlap, but not pronounced
Premier	Some overlapping
Koffiefontein	Reasonable correspondence
Jagersfontein	Overlapping of the low-N, highly aggregated groups
Jwaneng	Some reminiscence between the two High-T groups
Orapa	Some reminiscence between the two High-T groups

Of the diamonds in this population, 32.5% were derived from kimberlites with pre-Karoo emplacement ages (30% brown-spotted and an additional 2.5% with polished surfaces). Observed overlaps with the NAD fields of Premier and Venetia seem to account for the presence of these diamonds.

Among the Cretaceous kimberlites Letseng and Samada - on the basis of platelet preservation, supported by partly overlapping NAD fields - contributed at least 10% (11.1% of useful analyses) of the population.

Marine Concession 12A

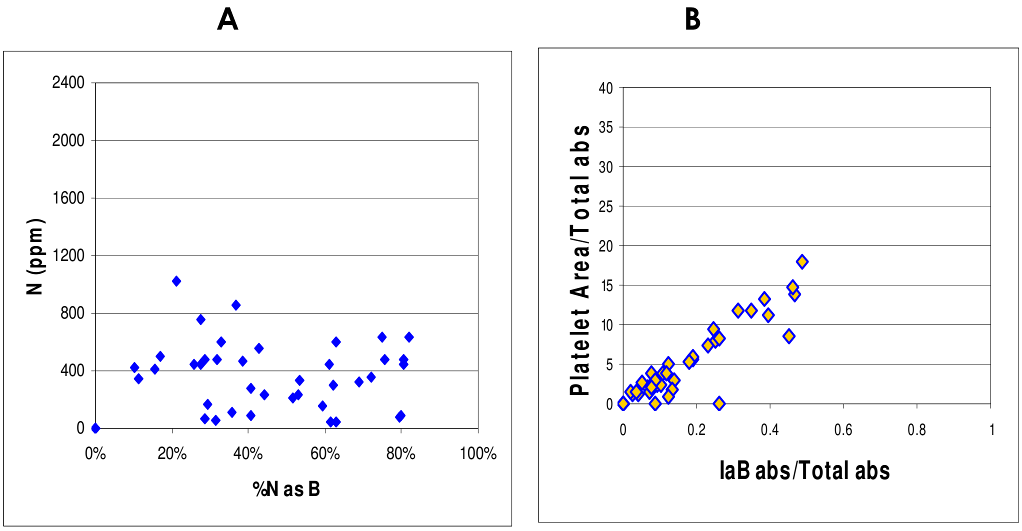


Figure 8.53 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from Marine Concession 12A

Diamonds selected from this locality:	55
Useful analyses obtained:	38
Type II stones identified:	2 (total N ≤ 48ppm)
Irregular stones w.r.t. platelet preservation:	4 (10.5% of useful analyses)

This NAD plot has the same general characteristics of that for 11A, as well as an almost identical percentage of irregular diamonds, indicating a probable correlation.

Logistic constraints precluded surface feature studies on this population, situated between 12A Deep and 12A Geelwal Karoo Surf Zone.

Marine Concession 12A Deep (Western part of concession)

A **B**

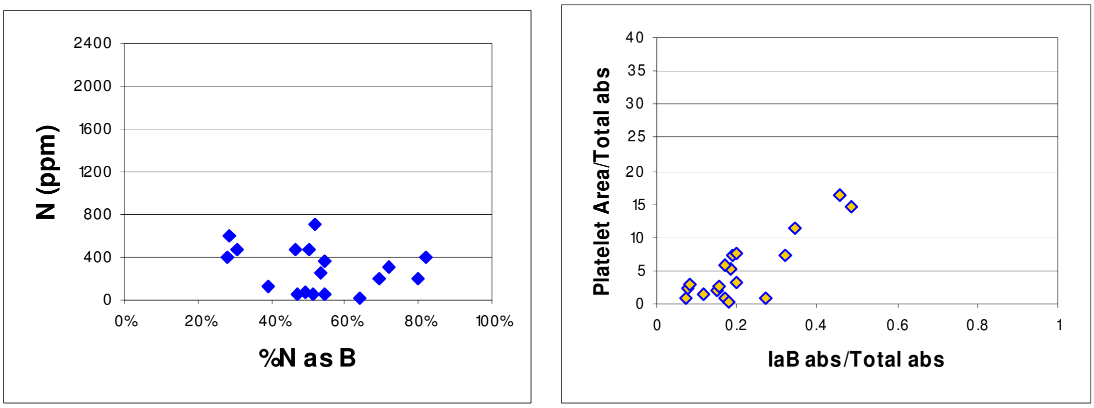


Figure 8.54 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from the deeper parts of Marine Concession 12A, generally known as 12A Deep.

Diamonds selected from this locality:	30
Useful analyses obtained:	18
Type II stones identified:	1 (5.6% of useful analyses)
Irregular stones w.r.t. platelet preservation:	2 (11.11% of useful analyses)

Diamonds with an indicated link with pre-Karoo emplaced kimberlites comprise 23.3% (16.6% brown-spotted and an additional 6.7% with polished surfaces) of the 12A Deep sample population studied. The percentage irregular diamonds present is almost identical to that in 12A and 11A.

TABLE 8.7 COMPARING NAD CHARACTERISTICS OF MARINE CONCESSION 12A DEEP DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	Weak overlap of 12A's ≤900 ppm N with Venetia
Helam/Swartruggens	<20% aggregated stones overlap with Helam's Low-T field
Letseng	Reasonable correlation with Letseng
Klipspringer Main Fissure	Some overlap of the Low-T groups
Kimberley (De Beers Pool)	Weak overlap with the <30% aggregation, <800 ppm N fields
Samada	Good correlation with Samada's <40% aggregation field
Finsch	Some overlap, but not outstanding
Premier	Some overlapping
Koffiefontein	Reasonable correlation, especially with low-N field
Jagersfontein	Overlapping of the low-N, highly aggregated groups
Jwaneng	Some reminiscence between the two High-T groups
Orapa	Some reminiscence between the two High-T groups

Portions of the NAD of the 12A Deep population reveal reasonable to good correlations with certain portions of the NA diagrams for both Letseng and Samada, an observation borne out by the presence of irregular diamonds. Weak to reasonable correlations with portions of NAD fields from all the other primary sources are noticed.

A diverse origin involving the primary sources mentioned above is concluded for the diamond populations of Marine Concessions 12A, 12A Deep and 11A with the presence of 10 irregular diamonds out of 92 useful analyses emphasizing the influence of Letseng and/or Samada.

Marine Concession 12A, Geelwal Karoo Surf Zone

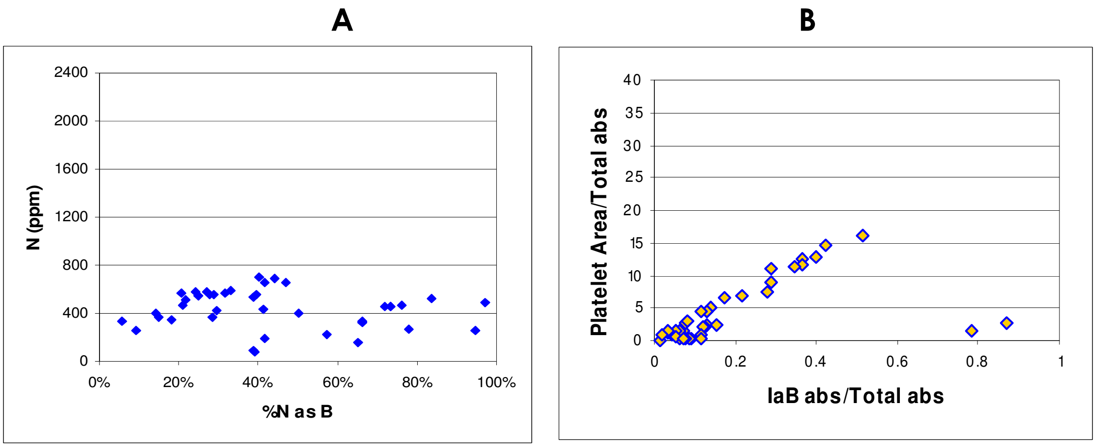


Figure 8.55 NAD (A) and ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects (B) for diamonds from Marine Concession 12A, Surf Zone at Geelwal Karoo

Diamonds selected from this locality:	40
Useful analyses obtained:	35
Type II stones identified:	0
Irregular stones w.r.t. platelet preservation:	2 (5.7% of useful analyses)

As is the case with the majority of these marine deposits, the 800ppm N concentration is not exceeded.

TABLE 8.8 COMPARING NAD CHARACTERISTICS OF CONCESSION 12A SURF ZONE (GEELWAL KAROO) DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	Some overlap with the scattered zone between the Low-T and High-T fields of Venetia
Helam/Swartruggens	No correlation
Letseng	Some overlap in the region demarcated by the 55-80% aggregation state and 300 – 450 ppm N.
Klipspringer Main Fissure	Some overlap at 70 – 80% aggregation and 400 ppm N.
Kimberley (De Beers Pool)	Minor overlap at 40-50% aggregation state, 400-700 ppm N and with the 10 – 25% aggregation, 350 – 500 ppm N field
Samada	Poor correspondence
Finsch	No correlation
Premier	Some overlap with Premier's high-T, 300-500 ppm N field
Koffiefontein	Poor correlation with sample population's 60 – 80% aggregated, 400 ppm N group.
Jagersfontein	Some overlapping plots coincide with weakly developed isothermal trends of Jagersfontein
Jwaneng	12A's Highly aggregated group around 300-500 ppm N overlaps with a portion of Jwaneng's High-T field.
Orapa	Poor correlation, but for a small overlapping group at about 80% aggregation and just over 400 ppm N

Diamonds with an indicated pre-Karoo emplacement age comprise 23.1% of the sample population studied. In Table 8.8 attention is drawn to correlations between portions of the Geelwal Karoo NAD and those of Venetia, Letseng, Klipspringer Main Fissure, Jagersfontein, the De Beers Pool at Kimberley and Premier. A diverse origin involving the primary sources mentioned above is also concluded for this diamond population.

In a discussion of the characteristics of these diamond populations, some overlap between surface features and FTIR results is inevitable. Both the "12A Deep" and Geelwal Karoo populations (located at comparable latitudes) show a conspicuous "ceiling" of 800ppm N. Both populations also feature a high percentage (46.7% and 15.4% respectively) of brown and deformed diamonds, which also form a significant part of all the alluvial populations studied, except those located in the North-West Province and the Skeleton Coast. In all the cases where deformed, brown diamonds were observed, low nitrogen contents also prevail, supporting the suggestion by Wilks (1958) that nitrogen in diamond tends to prohibit plastic deformation.

The diamond population of Marine Concession 12A Deep differs from those at 12A Geelwal Karoo (recovered from the surf zone) and 12A De Punt

Beach Mining (next section) in the presence of diamonds with appreciably abraded crystal edges. At 12A Deep such diamonds constitute 16.7% of the population studied, but are completely absent at 12A Geelwal Karoo and 12A De Punt (Beach Mining). In Section 4.1.4.viii and 4.1.5.1 it has been shown that appreciably abraded crystal edges can be a function of long transport distances, as well as of the energy level in the fluvial system, the nature of the bedrock and sedimentary load and the time spent in a more abrasive environment. The diamond population of 12A Deep is located between 20 and 30 metres deeper than the surf zone and modern day beaches, and would have been transported into the ocean at a time when the sea level was considerably lower. In addition, the area from where these diamonds were recovered comprises a high-energy environment riddled with bedrock channels and gullies containing sediments that indicate high energy depositional conditions (pers. comm. C Neethling, Manager, Trans Hex Marine Operations, 2009). The fact that the transportation and depositional history of this diamond subpopulation differed so dramatically from the conditions pertaining to the Geelwal Karoo and De Punt diamonds, explains their more abraded appearance.

Marine Concession 12A-De Punt Beach Mining

A B

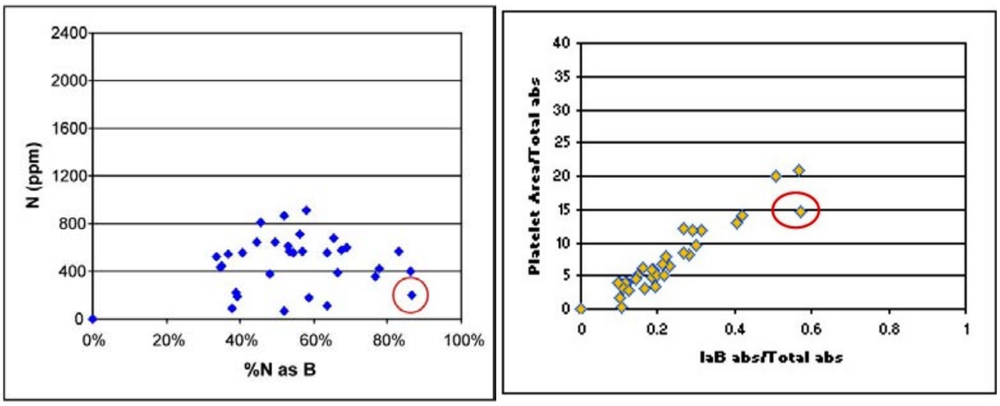


Figure 8.56: NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Marine Concession 12A, De Punt Beach Mining.

Diamonds selected from this locality:	60
Useful analyses obtained:	58
Type II stones identified:	1
Irregular stones w.r.t. platelet preservation:	1 (1.75% of useful analyses)

This sample population contains one irregular diamond. It happens to be the most highly aggregated in the sample population, as evident (circled red) in Figures 8.56A and 8.56B.

An outstanding feature of this NAD is the absence of diamonds with a nitrogen aggregation state of less than about 34%, while none of them achieved an aggregation state of >90%. The presence of one Type II diamond totally free of nitrogen indicates that the paucity of low-nitrogen stones is not necessarily the result of inadequate recovery processes. All the West Coast diamonds used in this study, with the exception of one group recovered on a grease belt at Graauw Duinen and which is clearly indicated as such, were recovered by X-ray technology. (The comparability of results obtained from diamond populations recovered by grease and X-ray technology respectively has been discussed in sections 1.5 and 4.1.7).

The NAD field of 12A De Punt Beach Mining, and to a large extent, 12A Deep, overlaps with the *H-T* fields of the diagrams for Orapa, Jwaneng, Premier, Letseng, Kimberley De Beers Pool and the >40% aggregation field of Samada. However, none of these primary sources shows the lack of stones that have <34% (27.9% in the case of 12A Deep) of their nitrogen in the B form. Nowhere has a reference been found that would indicate that diamonds with low aggregation state are more prone to be destroyed during fluvial or glacial transport than their higher-aggregated counterparts. Thus it is considered most unlikely that the absence of poorly aggregated diamonds from these sample populations is the result of selective survival. It is therefore concluded that:

- These diamonds were subjected to a post-crystallization heat event that caused moderate to high aggregation in all the diamonds in the sample populations, but was curtailed before a significant number of them reached an aggregation state or more than 60%, while none of them reached an aggregation state of >90%;
- They were liberated from none of the primary sources that feature in this study, or
- they were indeed derived from one or more of the primary sources mentioned above, but underwent a metamorphic event that produced the

brown spots; in such a case, Premier seems the only likely candidate due to its Precambrian age and the occurrence of brown-spotted diamonds. However, the absence of diamonds with less than 34% of their nitrogen in the B form from this population while, according to Deines *et al.* (1989*)* they abound at Premier, argues against this correlation.

It is suggested that the situation described above, could be explained in terms of the geological history of the Premier Mine. The oldest of three main kimberlite intrusions, generally referred to as the 'brown' kimberlite, is a volcaniclastic kimberlite breccia that has to a large extent been cored out by the younger intrusions and now occupies some 25% of the volume of the diatreme. At a depth of about 350 metres below surface, the kimberlites are cut by a horizontal gabbro sill some 75 metres thick. The kimberlite is altered by contact metamorphism up to 15 metres from the contact. All diamonds within 1 metre of the sill (and in places, up to 8 metres away) were destroyed (Bartlett, 1994; Wilson *et al.,* 2007).

Figure 4.3 shows that at a depth of 100 kilometres, the diamond/graphite transition still requires a temperature of about 900°C, with the required temperature increasing with increasing depth. It is unlikely that the current depth of 350 metres from the surface to the top of the gabbro sill in Premier Mine relates to more than 1 kilometre 1180 Ma BP, prior to exhumation of the deeper parts of the diatreme, and therefore the destruction of diamonds close to the sill could have taken place at temperatures too low, and at too short a duration, to cause significant nitrogen aggregation in the remaining population. It is however well known that the diamonds found in the oldest of the kimberlites, the "brown" kimberlite, are of a more superior quality than those associated with the two other phases (pers. comm., D.N. Robinson, 2008), proving the presence of at least two different diamond populations. It is suggested that Premier diamonds liberated from the brown kimberlite during pre-Karoo times were derived from the brown kimberlite and moved to the south-western parts of the sub-continent by Dwyka glacials. The research done by Deines *et al.* (1989) included diamonds from the deeper parts of the diatreme, including the two other kimberlite intrusions. It is suggested that the low-aggregation diamonds seen on the NAD produced by Deines *et al.*

(1989) and which distinguishes the Premier population at large from those of Marine Concession 12A (Beach Mining) where they are conspicuously absent, were not available for transportation to the West Coast at the advent of the Dwyka glaciation.

It is also possible that the diamondiferous basal marine conglomerate of the Table Mountain Group occurring northeast of Van Rhynsdorp (see Section 8.5: Baxter-Brown, 1963b) could have supplied diamonds with a pre-Karoo emplacement signature, to the Sout- and Olifants River catchment area.

Marine Concession 13A

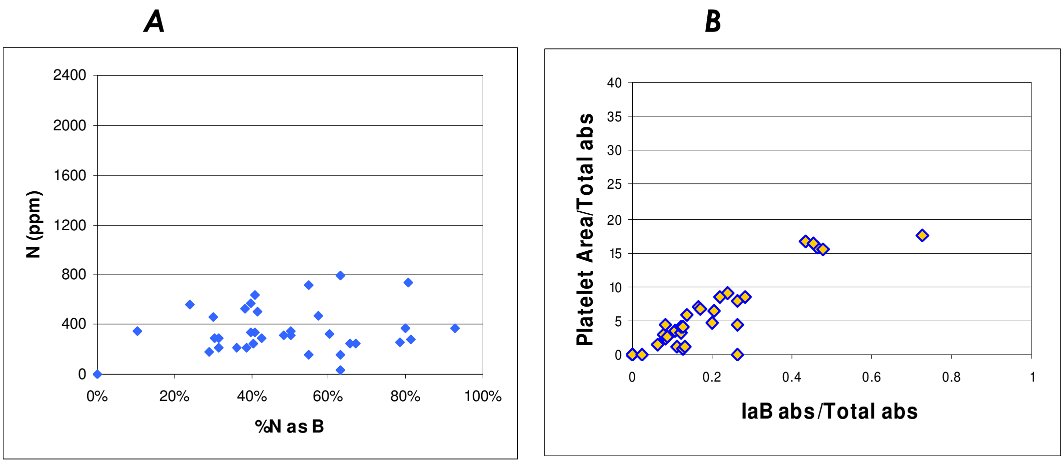


Figure 8.57 NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Marine Concession 13A.

Diamonds selected from this locality:	46
Useful analyses obtained:	35
Type II stones identified:	2
Irregular stones w.r.t. platelet preservation:	4 (11.43%)

Four irregular diamonds were identified in this population. Two of these form part of a group of 7 diamonds (20%) that have aggregation states between 10.3% and 31.6%. These lower – compared to the 12A De Punt Beach Mining population – aggregation states indicate input from another source compared to the neighbouring De Punt sample population where such stones are absent. This difference is not a metallurgical one, since both populations were recovered at the same facility. It is not a statistical phenomenon either, since the De Punt Beach sample population is larger (59) compared to the 35 of this population.

Almost due east of Marine Concession 13A (Figure 1.3), on the farm Annexe Blaauwklip 433 about 30 kilometres south of the Olifants River, occurs an erosion remnant of a marine raised beach deposit rich in similar sedimentary clasts that characterize the diamondiferous raised beach gravel (Figure 5.3 and Sections 2.2.5 and 4.1.8) at Graauw Duinen 20 kilometres north of the Olifants River mouth. It is concluded that the diamonds found in the 13A sample population, reached the Atlantic Ocean *via* a different route, a considerable distance south of the Olifants River. Diamonds with a pre-Karoo emplacement signature comprise 25% (22.5% brown-spotted plus 2.5% with polished surfaces) of the 13A population. Comparing these two NAD's and considering the evidence from the sedimentary clasts mentioned above, a mutual secondary source for portions of the 13A and Graauw Duinen deposits is concluded.

Graauw Duinen.

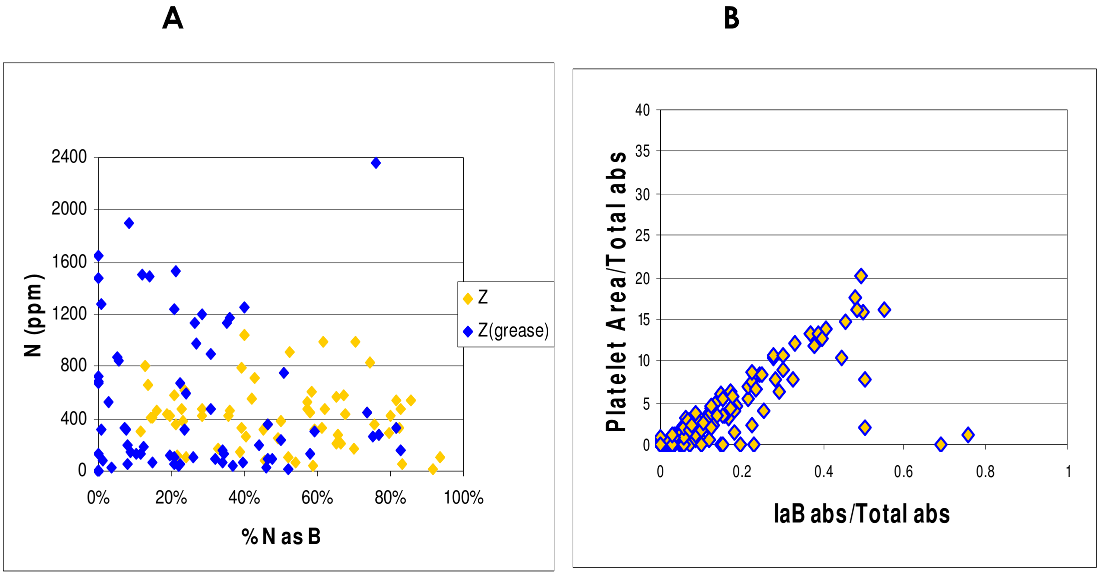


Figure 8.58: NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Graauw Duinen (raised marine beach).

Diamonds selected from this locality:	208
Useful analyses obtained:	179
Type II stones identified:	18 (10%)
Irregular stones w.r.t. platelet preservation:	6 (3.4%)

The metallurgical aspects regarding diamond recovery at Graauwduinen is comprehensively discussed in Section 4.1.8.

The nitrogen content and aggregation characteristics of this locality (blue and gold dots combined to represent one population) do not compare well with those of any of the other alluvial deposits in this study. Sub-populations boasting varying nitrogen contents up to 1600 ppm N are present, with two isolated single plots at 1900 and 2355 ppm N respectively. The latter represents the highest nitrogen content of all the diamond data used in the entire study.

The NAD also reveals a negative (ρ = 0.4) correlation between nitrogen content and aggregation state, with the highest state of aggregation corresponding to some of the lowest nitrogen values, similar to the results from Jagersfontein (Figure 8.39), Roberts Victor (Figure 8.34) and Samada (Figure 8.29). Deines *et al.* (1989, 1991, and 1993) stated that in their study of a number of kimberlitic diamond populations in southern Africa, they found no evidence of a positive correlation between nitrogen content and nitrogen aggregation state. The evidence from Graauw Duinen is perhaps the first from an alluvial deposit in support of these observations by Deines *et al.* (*op. cit*.), although this trend at Graauw Duinen could also be the result of diamond populations from different primary sources (and which by implication could have aggregated under totally different conditions) that now constitute one composite alluvial population. Subsequent to the work by Deines *et al.* referred to above, FTIR analyses (Venetia – Viljoen, 2002 and George Creek – Chinn, 1995) further demonstrated that primary deposits do occasionally reveal a positive correlation between nitrogen content and aggregation state. A number of primary sources referred to in this study (including the majority of those reported on by Deines *et al.* (1989, 1991, and 1993) show no specific trend at all. It is therefore concluded that different mantle conditions affecting diamond populations may result in positive, negative or non-correlation between nitrogen content and aggregation state.

In Table 8.9 below reference is made to the correspondence observed on the Graauw Duinen NAD and portions of the fields recorded for Samada, Letseng, Helam, Kimberley and Finch. In the discussion of FTIR characteristics of the primary sources in southern Africa (Section 8.2.3), mention was made of the fact that Letseng and Samada were the only primary localities where significant percentages of the diamond populations comprised irregular diamonds. It is therefore regarded as important that 3.4% of the total Graauw Duinen population consist of irregular diamonds, while it is completely absent from many of the alluvial deposits studied.

TABLE 8.9 COMPARING NAD CHARACTERISTICS OF GRAAUW DUINEN DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITE POPULATIONS

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	Weak correspondence with the scattered field between Venetia's Low-T and High-T fields
Helam/Swartruggens	The diamonds with an aggregation state ≤ 20% show very good correlation with the Helam field.
Letseng	The remainder of the population correlates very well with the entire graph of Letseng.
Klipspringer Main Fissure	Weak correlation with Klipspringer's High-T field
Kimberley (De Beers Pool)	Good correlation. The Kimberley Group, Samada and Klipspringer, are the only primary sources other than Helam with nitrogen values of >1600 ppm.
Samada	Good correlation with >7% aggregation state, <1200 ppm N
Finsch	Good overlap
Premier	Reasonable overlap with low-nitrogen area
Koffiefontein	Reasonable overlap in low-nitrogen area with aggregation state ≥12%
Jagersfontein	Reasonable overlap
Jwaneng	Reasonable overlap, especially i.r.o. unaggregated group
Orapa	Moderate to good correlation

As mentioned before, alluvial diamond deposits that received diamonds from different kimberlites are unlikely to yield a NAD that mirrors that of any particular primary source. Therefore, in the light of the observations listed in

Table 8.9, a NAD has been constructed by combining the different sample populations from a number of primary sources listed above.

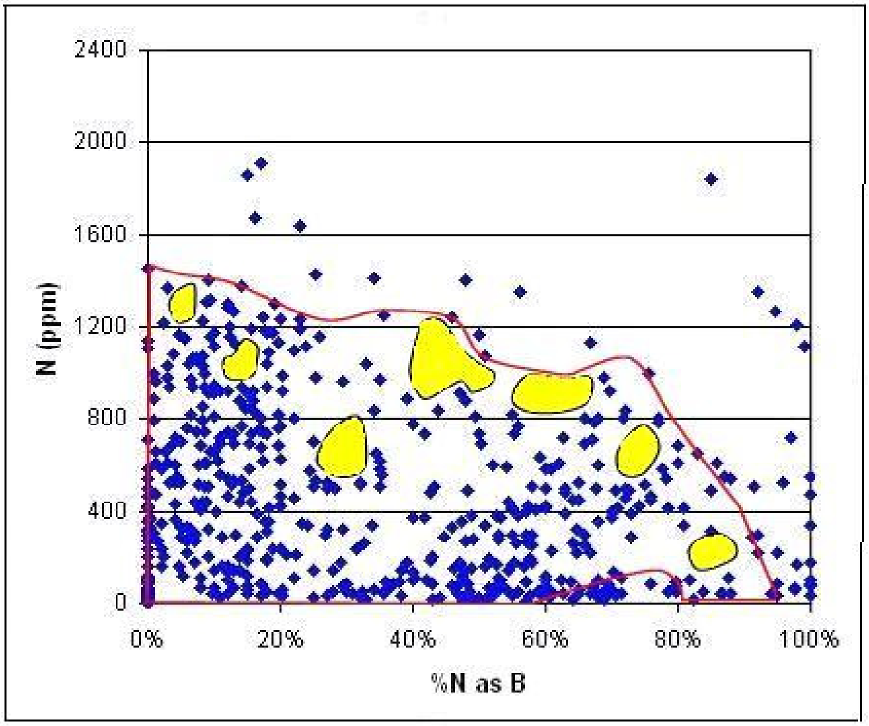


Figure 8.59 NAD constructed from data available from the De Beers Pool, Helam, Jagersfontein, Koffiefontein, Letseng, Orapa and Samada. *The figure outlined in red represent the main field described by the data plots on the Graauwduinen NAD (Figure 8.58A), while the yellow patches highlight corresponding "blank" spots on both NAD's. It must be conceded that this NAD comprises a theoretical provenance population, since the relevant contribution from the individual primary sources depended on the number of diamonds from each source that were available for inclusion in the study, a mixture that is unlikely to have been repeated in nature. The resemblance between the two groups is however so remarkable that significant contributions from the kimberlites used in this combined NAD seems to be confirmed.*

Furthermore the strong correlation between the poorly aggregated side of the NAD of this deposit and that of the Swartruggens/Helam kimberlite (Figure 8.32) is supported by the presence of amber-coloured cuboid diamonds at both localities. These amber-coloured cuboid diamonds have an abnormally high distribution at Helam (Robinson, 1979; Harris *et al*., 1979; McKenna, 2001 and results of this study – Figure 8.32) although they are occasionally found among the Kimberley diamond populations (pers. comm. F Viljoen, 2007). Among the alluvial deposits studied, they were only found at Graauwduinen, except for a single stone found at Marine Concession 7A.

Bosluispan

A B

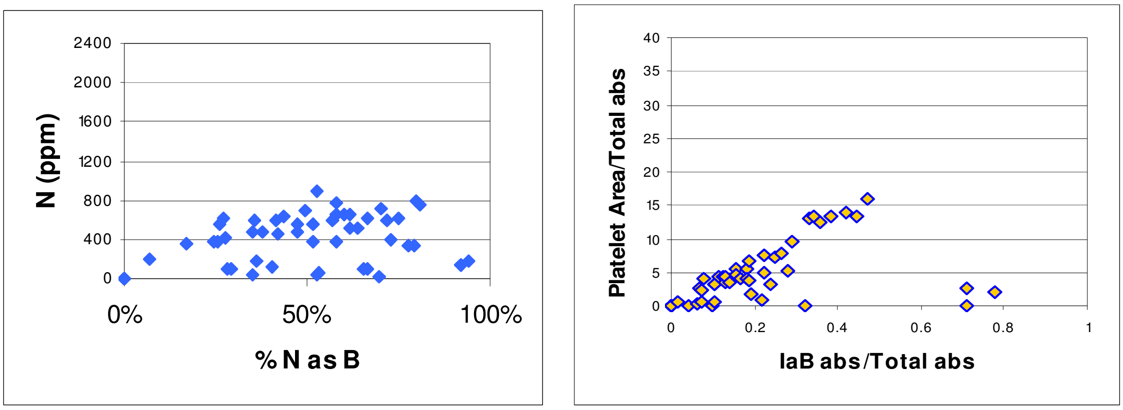


Figure 8.60: NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Bosluispan.

Diamonds available from this locality:	58
Useful analyses obtained:	52
Type II stones identified:	4 (7.7%)
Irregular stones w.r.t. platelet preservation:	5 (9.6%)

The Bosluispan NAD is characterized by the fact that all but one of its data points are clustered between 0 and 800 ppm N, with aggregation states between 22 and 80%, but for two poorly aggregated, and two highly aggregated plots. The four Type II diamonds predictably plot at the 0/0 position of the NAD. A small number (5.2%) of these stones contain brown spots or polished surfaces. The significance of diamonds with a pre-Karoo emplacement signature as well as that of 9.6% irregular diamonds in the sample population at this locality must be emphasized.

The irregular diamonds in this sample population, suggest a correlation with Letseng and Samada, the only primary sources where significant numbers of irregular diamonds were identified. This link with Cretaceous kimberlites finds support in the observations by De Wit (1993) concerning the occurrence of diamonds in the Sak River and Carnavonleegte south of Brandvlei and Van Wyksvlei resting on top of Karoo Supergroup sediments, and D.N. Robinson's (pers. comm., 2007) observations concerning the remarkable similarity between the Sak River and Bosluispan diamond populations.

One important difference between the diamond populations of the Sak River and that at Bosluispan, is the presence of a small percentage diamonds liberated from pre-Karoo kimberlites at Bosluispan (this study), which are completely absent from the Sak River population (pers. comm. D.N. Robinson, 2007), as can be expected from diamonds liberated from Cretaceous kimberlites, now contained in a sedimentary package resting on Karoo sediments. Bosluispan is however located topographically lower than the surrounding exhumed Dwyka Group glacial deposits, the obvious source for this small percentage of "pre-Karoo" diamonds.

TABLE 8.10 COMPARING NAD CHARACTERISTICS OF BOSLUISPAN DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	**NAD characteristics in relation to this alluvial deposit**
Venetia	Moderate overlap at ≤800 ppm N and 25-80% aggreg.
Helam/Swartruggens	Absolutely no correspondence
Letseng	Reasonable overlap with Letseng's High-T field, but without the pronounced isothermal trends
Klipspringer Main Fissure	Only overlapping i.r.o. <200 ppm N/30-70% aggregation
Kimberley (De Beers Pool)	Only isolated plots overlap with the Kimberley fields.
Samada	Fair correlation with <800ppm N field
Finsch	Only overlapping i.r.o. <200 ppm N/30-70% aggregation
Premier	Reasonable correspondence up to 800 ppm N
Koffiefontein	Some overlap, especially i.r.o. the paucity of <20% aggregation in both graphs and <200 ppm N stones with aggregation states between 30 and 70%
Jagersfontein	Very weak overlap
Jwaneng	Weak overlap with Jwaneng's H-T field
Orapa	Poor correlation

Klipgat, Ventersdorp

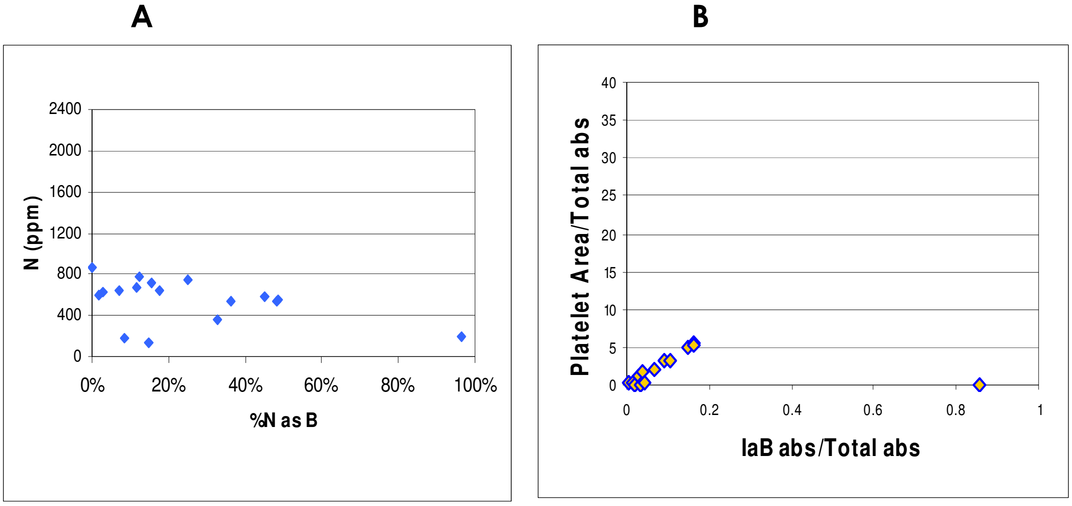


Figure 8.61 (A) NAD and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Klipgat, Ventersdorp.

Diamonds available from this locality: 24
Useful analyses obtained: 17
Type II stones identified: 0
Irregular stones w.r.t. platelet preservation: 1 (5.9%)

TABLE 8.11 COMPARING NAD CHARACTERISTICS OF KLIPGAT DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITES

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	No correlation
Helam/Swartruggens	Some overlap i.r.o. small field with 400 – 800 ppm N and ≤ 20% aggregation state
Letseng-la-Terai	No correlation
Klipspringer Main Fissure	No correlation but for a few isolated plots
Kimberley (De Beers Pool)	No correlation
Samada	Poor correlation
Finsch	No correlation
Premier	No correlation but for a few isolated plots
Koffiefontein	No correlation
Jagersfontein	No correlation
Jwaneng	Good correlation with array of poorly to >20% aggregated stones along 600 ppm N line
Orapa	Very weak overlap

Even though the available sample population from this locality is very small, the NAD generated from the analytical data overlaps very well with that from the nearby Nooitgedacht data (next section). In both instances the only correlations observed are with primary sources located to the north.

Nooitgedacht (alias Vetpan), Ventersdorp

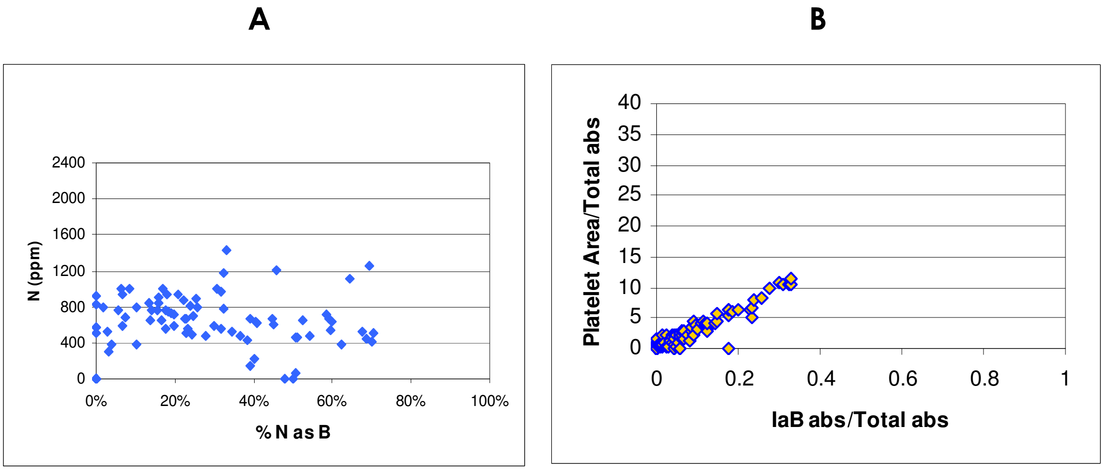


Figure 8.62 (A) NAD and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Nooitgedacht *alias* Vetpan, Ventersdorp

Diamonds available from this locality:	100
Useful analyses obtained:	81
Type II stones identified:	3
Irregular stones w.r.t. platelet preservation:	1 (2.4%)

TABLE 8.12 COMPARING NAD CHARACTERISTICS OF NOOITGEDACHT DIAMOND POPULATION WITH THOSE FROM KNOWN KIMBERLITE POPULATIONS

Primary Source	NAD characteristics in relation to this alluvial deposit
Venetia	Weak correlation with Venetia's scattered and low-N, moderately aggregated field
Helam/Swartruggens	Moderate correlation with Helam's ≤1000 ppm N field
Letseng-la-Terai	Weak overlap with Letseng's ≥400 ppm N field
Klipspringer Main Fissure	Very good correlation with Klipspringer's 400 – 900 ppm-N, 15 – 30% aggregation field
Kimberley (De Beers Pool)	Very little correlation
Samada	Very little correlation
Finsch	Very few overlap
Premier	Slight overlap with Premier's poorly aggregated,
Koffiefontein	No correlation
Jagersfontein	No correlation
Jwaneng	Reasonable overlap
Orapa	Reasonable overlap with Low-T field of Orapa

It is significant that the nitrogen aggregation diagrams of the diamond populations residing in karstic depressions at the above-mentioned two Ventersdorp localities only correspond with diamond populations of primary sources to the north and northeast. This is seen as evidence for the north-south to northeast-southwest transport of diamonds along a palaeo-gradient that dictated the direction of both fluvial systems and the movement of ice sheets and glaciers.

The small sample population from Klipgat does not contain any brown-spotted diamonds, and only one with polished surfaces. Its NAD also shows no correspondence with any known pre-Karoo kimberlite.

Sydney-on-Vaal, Barkly West

A **B**

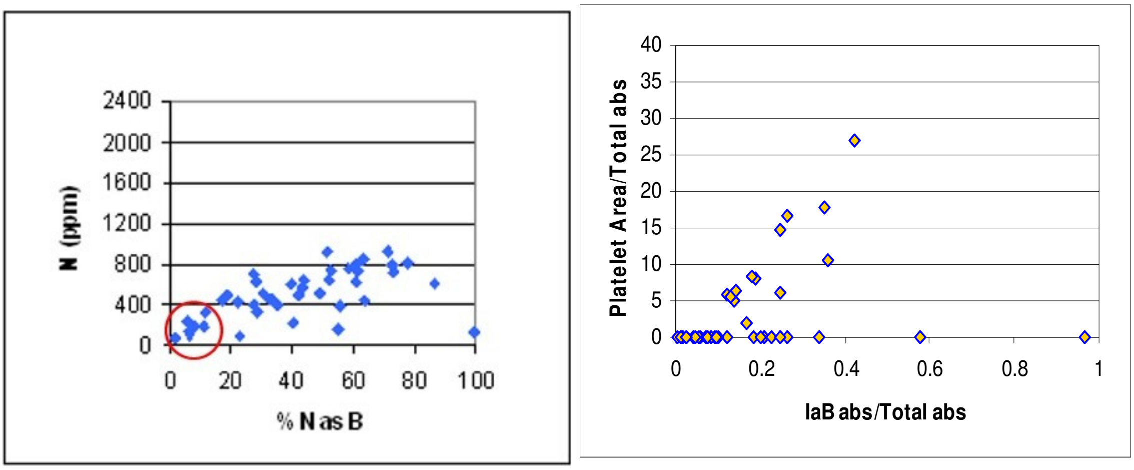


Figure 8.63 NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Sydney-on-Vaal

Diamonds available from this locality:	60
Useful analyses obtained:	42
Type II stones identified:	0
Irregular stones w.r.t. platelet preservation:	13 (31%)

Apart from a few of the <400 ppm plots that are scattered above the 22% aggregation mark (as in the case of Samada) the majority of this population reveals an almost linear, positive correlation between nitrogen content and aggregation state. A single source is visualized with a possibility of minor input involving another, low-nitrogen, low-aggregation state population (circled in red on Figure 8.63) which entered the Vaal River valley downstream from Christiana. Sydney-on-Vaal is located at the confluence of the Vaal and Harts Rivers, and such a subordinate population may have come either *via* the Harts River, or from one or more of the many small diamondiferous kimberlite occurrences known in the

Vaal River valley between Warrenton and Barkly West. No diamonds from these subordinate occurrences were available for this study.

However, NAD characteristics are not the only similarity that this sample population enjoys with the Samada kimberlite. The diagram illustrating the platelet preservation for the Sydney-on-Vaal population shows that 31% of these diamonds are irregular. Among the known kimberlitic diamond populations of southern Africa significant quantities of irregular diamonds are only known to occur at Letseng and Samada (F. Viljoen, pers. comm. 2007). Studying the primitive and modern drainage patterns that developed on top of the Jurassic Karoo cover near the headwaters of the Orange and Vaal Rivers (Figure 2.29 and 2.30), it seems highly unlikely for the erosion products of Letseng to have been transported by the Vaal River or any of its tributaries. A portion of the primitive drainages proposed by Moore and Moore (2004) does however offer a viable conduit for the transportation of erosion products of Samada in a northwesterly direction to the Vaal River valley.

Christiana

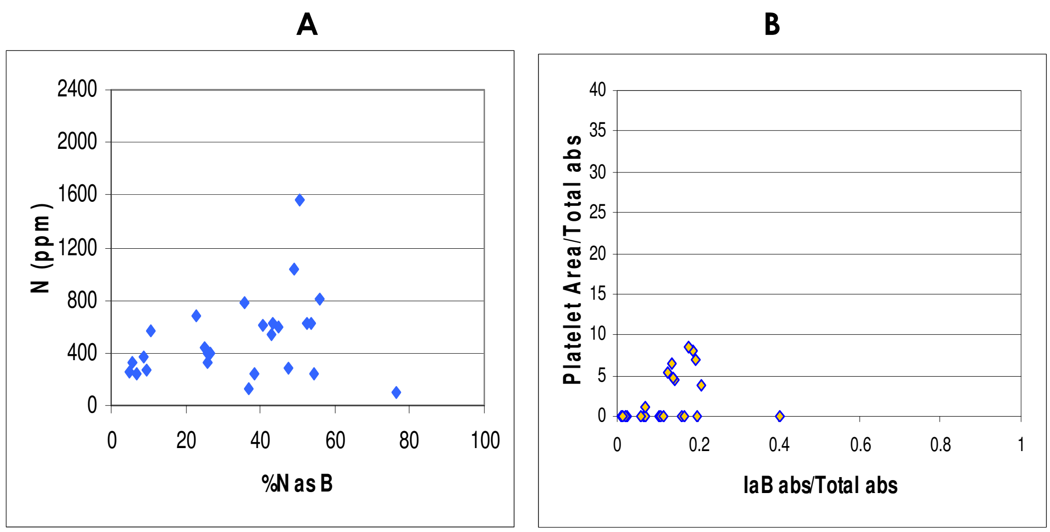


Figure 8.64 NAD (A) and (B) ratio of platelet strength vs. absorbance at 1282 cm^{-1} of B defects for diamonds from Christiana.

Diamonds available from this locality:	42
Useful analyses obtained:	26
Type II stones identified:	0
Irregular stones w.r.t. platelet preservation:	7 (26.9%)

A good correlation exists between the field described by the data points of this NAD and the <800 ppm N field of Samada. This population also includes a single analysis reaching 1600 ppm N; among the primary sources this has only been observed at Helam, Klipspringer Main Fissure, Kimberley (De Beers Pool) and Samada, while Graauw Duinen is the only other alluvial deposit in this study where such a high nitrogen content was observed. A reasonable resemblance with the NAD of Marine Concession 3B is also observed, with the latter lacking the >800ppm N plots present here. A less pronounced correlation with the Orange River populations exists.

In the previous section it has been shown that Samada is the most likely primary source for the bulk of the diamond population at Sydney-on-Vaal. In the case of the Christiana deposit the similarity with the Samada NAD is even more striking, with the subordinate low-nitrogen, low-aggregated group of Sydney-on-Vaal which is anomalous with respect to the Samada NAD, being absent. The platelet preservation index at Christiana also corresponds to the 7.9% irregular diamonds found at Samada.

The same arguments concerning the palaeo-drainage lines depicted in Figures 2.22 and 2.23 and Sydney-on-Vaal, holds for the Christiana deposit.

8.3. Garnet Investigation - on CD

8.3.1 Extraction

8.3.2 Analytical Procedures

8.3.3 Analyses

8.3.4 End Members calculated

8.3.5 End Members - Locock data sorted for graphic display

8.3.6 End Members – Locock, graphic display.

8.4. Zircon

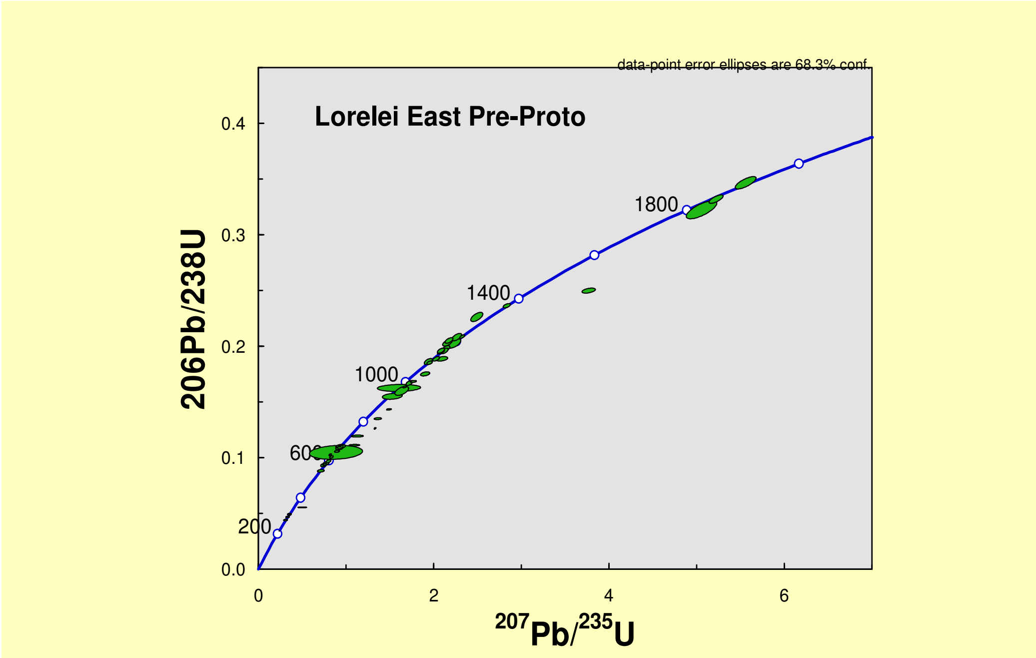
8.4.1 Sample collection and preparation - on CD
8.4.2 Notes on the analytical philosophy followed - on CD
8.4.3 Analytical procedures - on CD
8.4.4 Results – raw data, on CD
8.4.5 Processed data and discussions.

In the following paragraphs images pertaining to some of the analyses, with grains and sample spots marked, are followed by short lists of preferred ages for the grains thus identified and full tables of corrected data. Histograms showing the concentration of different age groups are followed by Concordia Diagrams of $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ values.

8.4.5.1 Lorelei

TABLE 8.13 RESULTS OF LORELEI ZIRCON ANALYSES

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
LOR-13.1	197.5	1.5	186	53	-6	197.5	1.5
LOR-42.1	259.1	2.2	242	91	-7	259.1	2.2
LOR-11.1	276.4	2.6	234	116	-18	276.4	2.6
LOR-8.1	291.3	3.9	311	70	6	291.3	3.9
LOR-23.1	292.6	3.1	221	57	-33	292.6	3.1
LOR-41.1	530.0	4.3	543	64	2	530.0	4.3
LOR-15.1	559.6	5.2	529	67	-6	559.6	5.2
LOR-24.1	563.0	4.3	559	37	-1	563.0	4.3
LOR-32.1	569.2	5.9	560	55	-2	569.2	5.9
LOR-36.1	580.5	5.2	598	38	3	580.5	5.2
LOR-18.1	604.7	4.8	609	33	1	604.7	4.8
LOR-30.1	616.6	3.3	527	24	-17	616.6	3.3
LOR-50.1	630.5	24.3	651	496	3	630.5	24.3
LOR-22.1	635.6	3.3	656	43	3	635.6	3.3
LOR-26.1	653.3	6.2	664	58	2	653.3	6.2
LOR-21.1	657.5	7.1	671	42	2	657.5	7.1
LOR-37.1	660.2	7.2	681	82	3	660.2	7.2
LOR-6.1	662.3	2.7	652	14	-2	662.3	2.7
LOR-19.1	668.1	2.8	975	74	31	668.1	2.8
LOR-2.1	921.0	10.7	970	100	5	970	100
LOR-49.1	962.7	11.7	975	212	1	975	212
LOR-5.1	968.0	4.0	1045	13	7	1045	13
LOR-3.1	947.4	15.2	1047	53	10	1047	53
LOR-14.1	988.8	7.9	1059	25	7	1059	25
LOR-16.1	1094.7	9.2	1083	25	-1	1083	25
LOR-27.1	995.8	4.1	1099	24	9	1099	24
LOR-48.1	1087.6	5.8	1112	21	2	1112	21
LOR-17.1	1149.0	7.7	1118	20	-3	1118	20
LOR-20.1	1197.7	8.7	1118	21	-7	1118	21
LOR-34.1	1186.8	10.8	1122	26	-6	1122	26
LOR-7.1	1144.2	7.7	1127	19	-2	1127	19
LOR-40.1	1108.0	7.7	1149	20	4	1149	20
LOR-46.1	1157.1	9.8	1160	25	0	1160	25
LOR-45.1	1148.2	8.6	1161	22	1	1161	22
LOR-10.1	1215.0	11.4	1169	26	-4	1169	26
LOR-35.1	1312.9	14.0	1189	29	-10	1189	29
LOR-33.1	1184.3	14.7	1199	36	1	1199	36
LOR-29.1	1108.1	7.6	1206	39	8	1206	39
LOR-1.1	1217.6	5.5	1218	12	0	1218	12
LOR-12.1	1365.4	6.8	1358	16	-1	1358	16
LOR-38.1	1804.8	26.2	1859	29	3	1859	29
LOR-43.1	1852.7	12.1	1862	13	0	1862	13
LOR-4.1	1923.5	17.4	1898	17	-1	1898	17



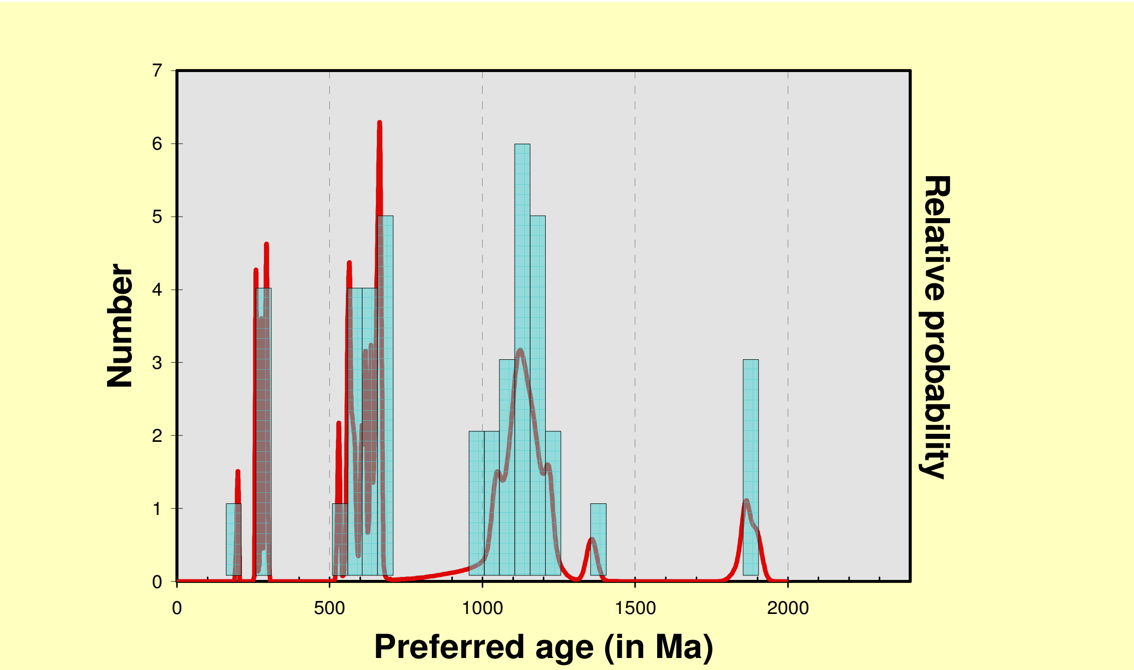


Figure 8.65 Lorelei: Concordia diagram and histogram of preferred ages Analyses by this author; samples collected by J.R. Jacob.

Lorelei is located immediately upstream from AACE (Figure 1.3), but along the right flank of the Orange River valley. The gravel sample from which these zircons were extracted, came from a local scour feature harbouring sediments that, on the basis of bedrock elevation and field relations, are thought to be of pre-proto age. As shown in Table 8.13, and with reference to Table 2.1, the entire thermal history of the Kaapvaal Craton, with the exception of the Archaean, is reflected in this zircon population with ages ranging from 197.5 ± 1.5 Ma to 1898.0 ± 17.4 Ma. The older ages among this zircon population reflect the fact that the Orange River valley transects the Vioolsdrif and Richtersveld Suites (Section 2.1.2) over a distance of about 30 kilometres before reaching Lorelei. East-bound drainages from the Kuboos pluton would have been responsible for the input of zircons of Cape Granite Suite age in the region of Grasdrif, about 21 kilometres upstream from Lorelei.

The age of 197.5 ± 1.5 Ma however is seen as significant in terms of the denudation history of the subcontinent. Table 2.1 shows that this age can only be correlated with those reported from the Lebombo range in northern Kwazulu-Natal, immediately east of the current headwaters of the Orange/Senqu River in northern Lesotho. The oldest age exposed in the Lesotho Highlands is only ± 182 Ma and this would indicate that the early Orange River drainage could have reached farther east than today, prior to the development of the Drakensberg Escarpment. The fact that this juvenile zircon occurred in pre-proto Orange River sediments, is in harmony with a denudation history that would have resulted in the erosion products from the highest region in the catchment area being deposited in some of the oldest sediments transported by the relevant drainage.

8.4.5.2 Snake Hill

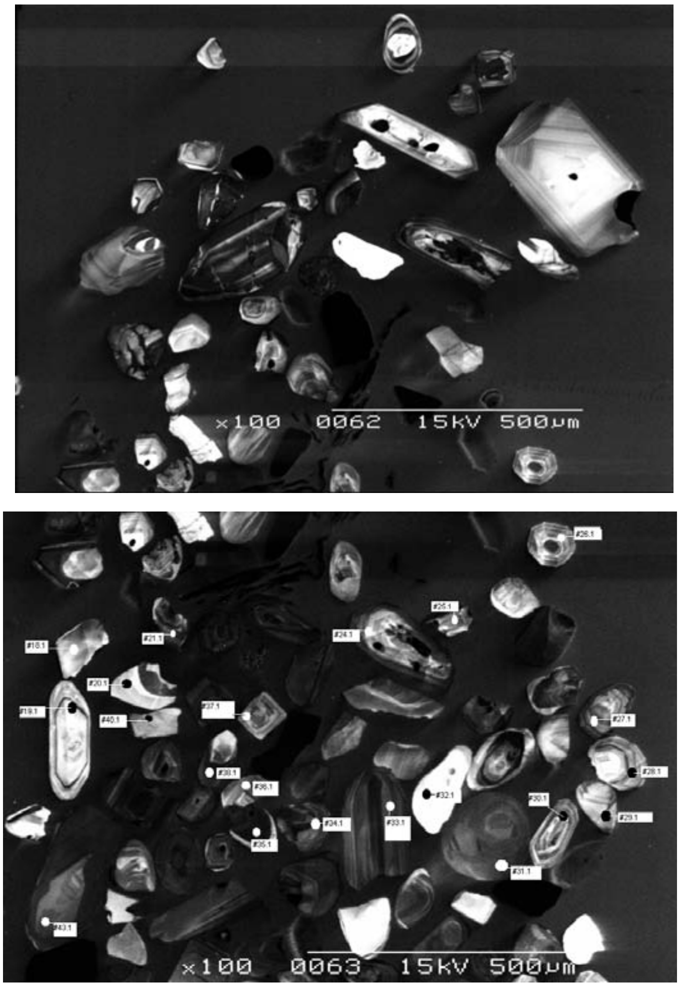


Figure 8.66 CL images of some of the zircon grains from the Snake Hill deposit. Samples collected by J. Jacob, SHRIMP analyses by this author.

TABLE 8.14 ANALYSES OF ZIRCONS FROM SNAKE HILL DEPOSIT.

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
SN-30.1	274.0	4.3	316	60	13	274.0	4.3
SN-1.1	503.2	8.4	467	103	-8	503.2	8.4
SN-15.1	504.8	8.5	362	270	-40	504.8	8.5
SN-28.1	525.4	8.4	396	129	-33	525.4	8.4
SN-38.1	537.2	8.3	534	151	-1	537.2	8.3
SN-37.1	537.5	9.1	501	32	-7	537.5	9.1
SN-9.1	562.3	8.4	521	44	-8	562.3	8.4
SN-13.1	569.8	8.6	632	30	10	569.8	8.6
SN-20.1	578.6	10.5	634	132	9	578.6	10.5
SN-18.1	583.0	10.3	372	189	-57	583.0	10.3
SN-31.1	592.0	9.0	541	33	-10	592.0	9.0
SN-43.1	594.3	9.1	599	22	1	594.3	9.1
SN-16.1	638.3	14.0	581	91	-10	638.3	14.0
SN-32.1	662.4	13.7	649	142	-2	662.4	13.7
SN-36.1	704.1	10.8	755	48	7	704.1	10.8
SN-12.1	758.6	11.3	860	42	12	758.6	11.3
SN-19.1	790.9	11.6	753	33	-5	790.9	11.6
SN-8.1	895.6	13.5	832	56	-8	832	56
SN-6.1	803.6	11.3	862	20	7	862	20
SN-33.1	972.3	14.3	821	53	-18	972.3	14.3
SN-44.1	981.1	13.9	984	18	0	984	18
SN-17.1	1039.5	14.1	1015	13	-2	1015	13
SN-40.1	999.5	19.8	1028	84	3	1028	84
SN-34.1	1065.0	15.1	1048	23	-2	1048	23
SN-2.1	1085.3	14.8	1048	19	-4	1048	19
SN-29.1	1027.1	15.6	1051	50	2	1051	50
SN-11.1	1068.5	15.9	1060	27	-1	1060	27
SN-3.1	1127.6	17.0	1072	25	-5	1072	25
SN-24.1	1114.6	15.8	1077	29	-4	1077	29
SN-35.1	1034.9	14.0	1077	9	4	1077	9
SN-23.1	932.8	12.8	1077	19	13	1077	19
SN-21.1	1030.5	18.2	1095	24	6	1095	24
SN-5.1	1122.8	16.1	1099	25	-2	1099	25
SN-45.1	1076.1	15.4	1107	18	3	1107	18
SN-22.1	1112.3	15.3	1200	11	7	1200	11
SN-25.1	1165.2	17.3	1206	15	3	1206	15

SN-39.1	1107.4	15.3	1219	14	9	1219	14
SN-7.1	1769.1	25.4	1750	19	-1	1750	19
SN-10.1	1696.3	22.0	1871	8	9	1871	8
SN-26.1	1870.9	24.5	1887	9	1	1887	9
SN-41.1	1841.9	24.1	1889	16	3	1889	16
SN-4.1	1776.7	23.4	1891	11	6	1891	11
SN-27.1	1868.5	25.1	1925	12	3	1925	12

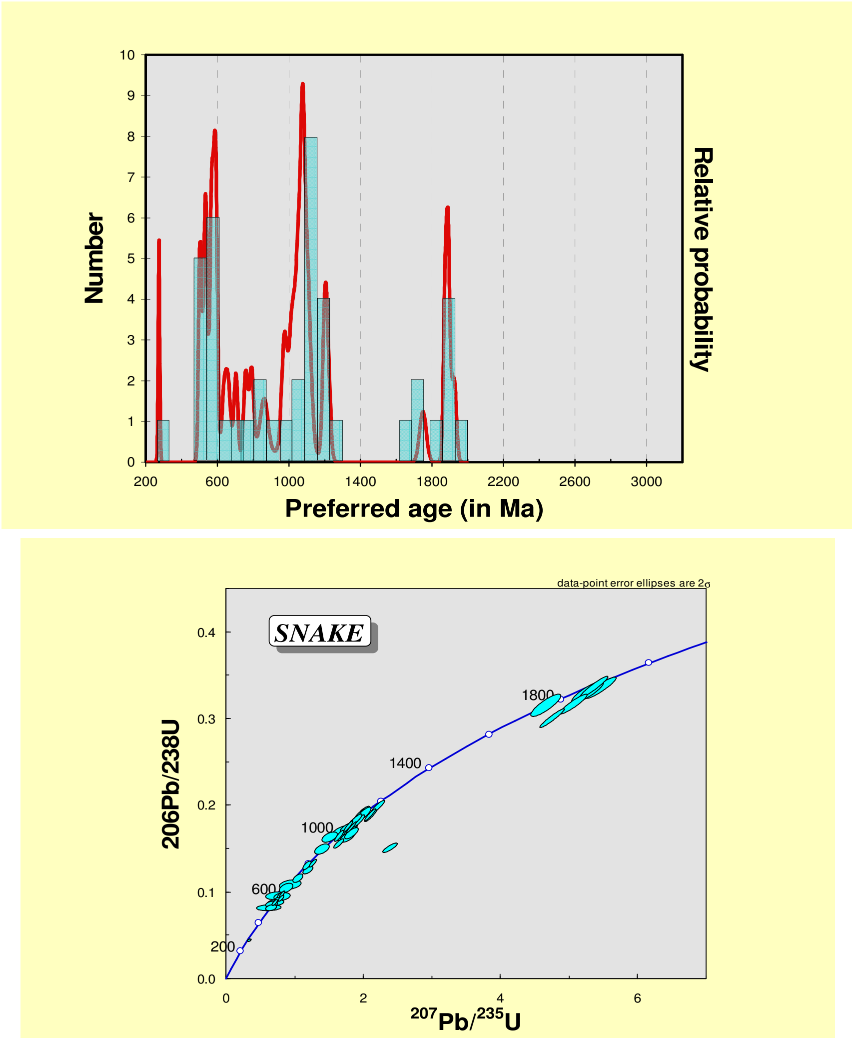


Figure 8.67 Histogram of preferred ages and Concordia diagram, Snake Hill zircons.

This sample was taken from an erosion remnant located along the right bank of the Lower Orange River between Reuning Mine and Sendelingsdrif. The bedrock elevation of this deposit (104 m.a.m.s.l., or 79.4 metres above present river bed) equates it with the early stages of the Orange River. The macro-clast assemblage described from this locality (Jacob, 2005) shows that it is younger than the Eocene but older than the pre-proto scours at

Lorelei, Auchas and Xarries, and as such represents the oldest preserved Orange River sediments after the Eocene-aged Buntfeldschuh deposit along the Sperrgebiet coast north of Oranjemund. This clast assemblage also shows that the >1750 Ma zircons in this sample were not derived from the nearby Vioolsdrif Suite.

The presence of a zircon dated at 274 ± 4.3 Ma implies that the Orange River drainage network in the Early Miocene was still eroding rocks from the Ecca Group (Hartzer *et al.*, 1998) in places, while the rest of the zircons found in the Snake Hill sample represent the thermal history of the western part of the Kaapvaal Craton from the intrusion of the Cape Granite Suite up to 1925 Ma which corresponds to the Kheis Orogeny (Moen, 1999). Thus the Zircon geochronology indicates that incision by the Lower Orange River into Archaean rocks had not taken place by the Late Oligocene-Early Miocene yet.

8.4.5.3 Transition Pre-proto to proto-Orange River, Bloeddrif

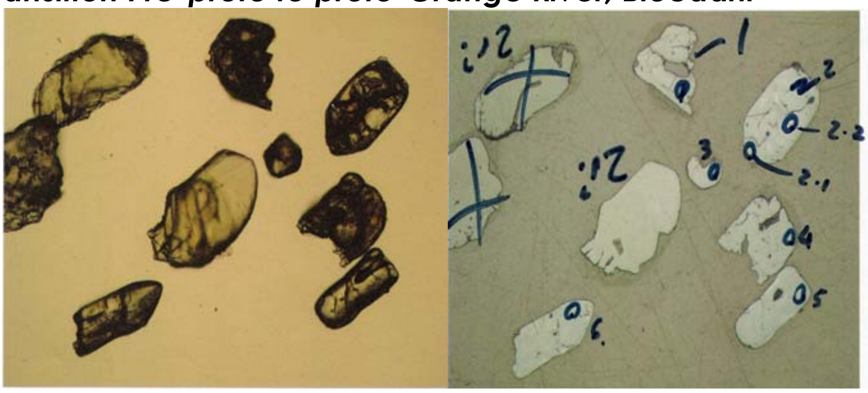


Figure 8.68 Samples 34 & 34R: Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	***Preferred Age***
34-1.1	*1555.0 ± 51.0 Ma*
34-2.1	*375.8 ± 4.5 Ma*
34-2.2	*1096.0 ± 13.0 Ma*
34-3.1	*1839.0 ± 17.0 Ma*
34-5.1	*605.9 ± 6.4 Ma*
34-6.1	*1098.0 ± 13.0 Ma*

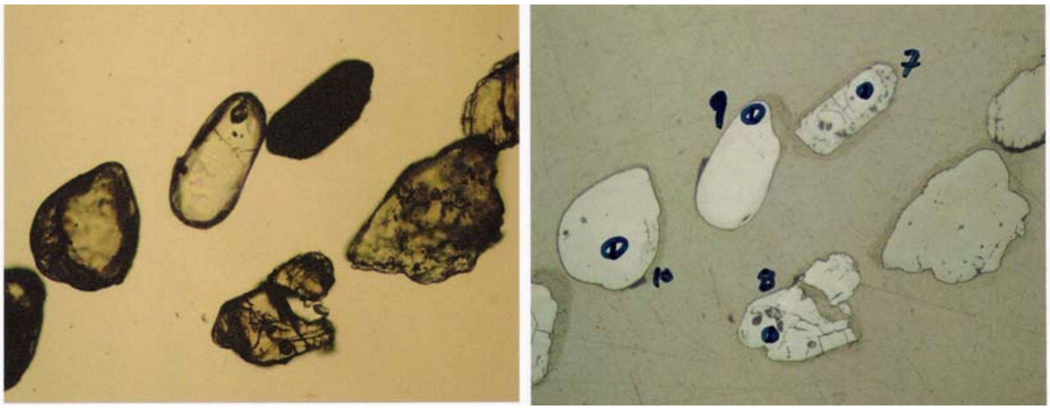


Figure 8.69 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	***Preferred Age***
34-8.1	*1183.0 ± 16.0 Ma*
34-9.1	*535.8 ± 6.2 Ma*
34-10.1	*1365.0 ± 52.0 Ma*

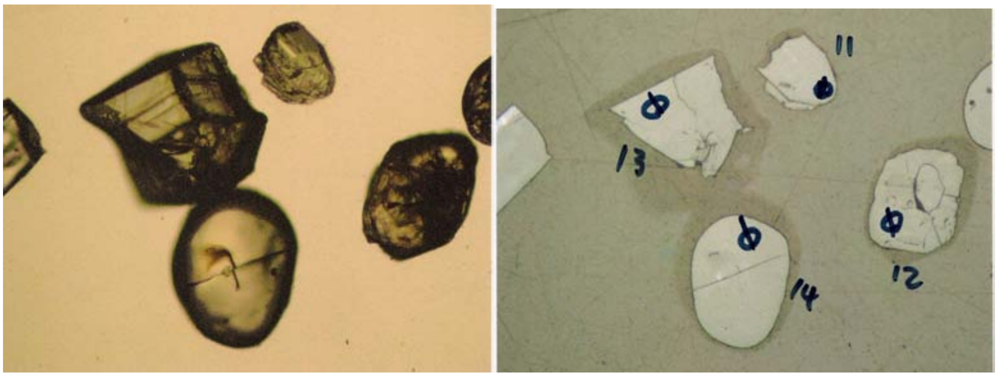


Figure 8.70 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	***Preferred Age***
34-11.1	*1180.0 ± 28.0 Ma*
34-12.1	*546.8 ± 6.6 Ma*
34-13.1	*1204.0 ± 30.0 Ma*
34-14.1	*1133.0 ± 28.0 Ma*

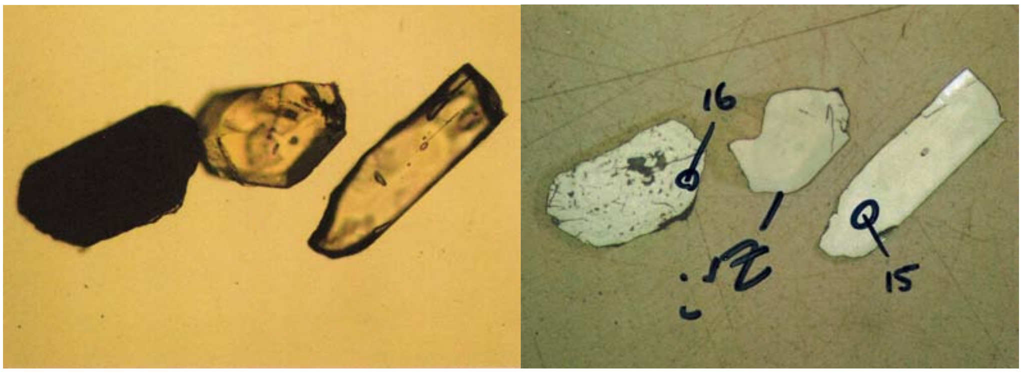


Figure 8.71 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	*Preferred Age*
34-15.1	*646.1 ± 10.8 Ma*

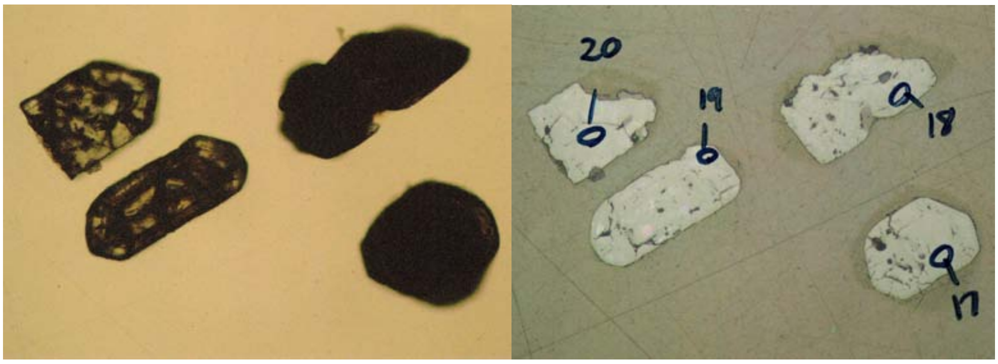


Figure 8.72 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	*Preferred Age*
34-17.1	*1060.0 ± 36.0 Ma*
34-19.1	*1099.0 ± 24.0 Ma*
34-20.1	*1189.0 ± 38.0 Ma*

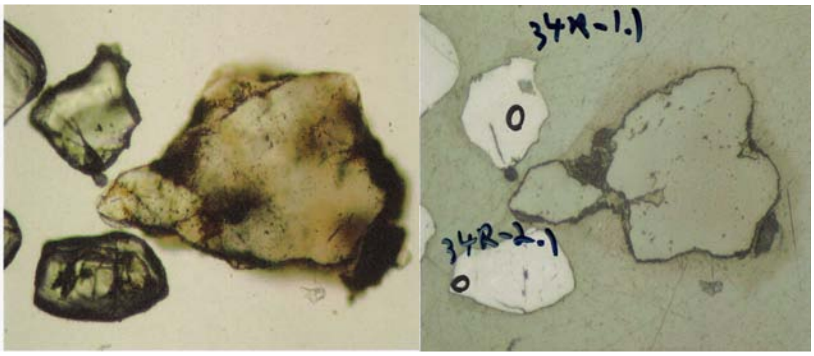


Figure 8.73 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	***Preferred Age***
34R-2.1	*1284.0 ± 18.0 Ma*

Figure 8.74 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	***Preferred Age***
34R-3.1	*661.2 ± 8.9 Ma*
34R-4.1	*1074.0 ± 89.0 Ma*
34R-5.1	*2111.0 ± 11.0 Ma*
34R-6.1	*1128.0 ± 45.0 Ma*
34R-7.1	*2062.0 ± 15.0 Ma*
34R-8.1	*308.4 ± 4.9 Ma*
34R-9.1	*1146.0 ± 56.0 Ma*
34R-10.1	*1098.0 ± 52.0 Ma*
34R-11.1	*658.8 ± 25.3 Ma*
34R-12.1	*1878.0 ± 12.0 Ma*
34R-13.1	*2661.0 ± 11.0 Ma*

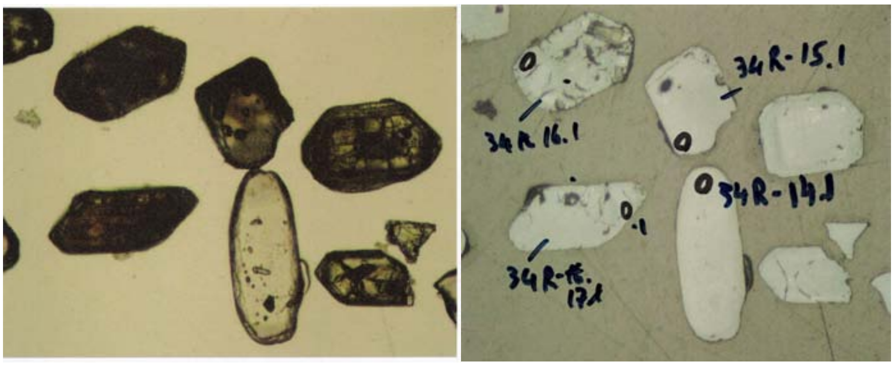


Figure 8.75 Application of transmitted light optical images (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light images (right).

GRAIN SPOT NUMBER	***Preferred Age***
34R-15.1	*1124.0 ± 35.0 Ma*
34R-16.1	*1917.0 ± 21.0 Ma*
34R-17.1	*1123.0 ± 28.0 Ma*

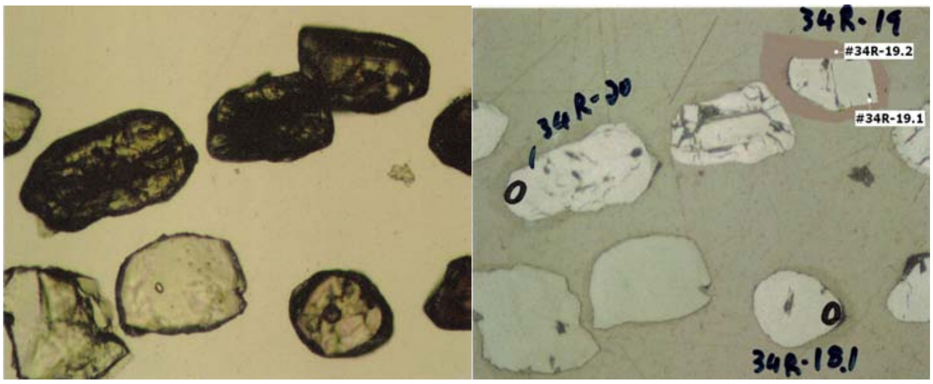


Figure 8.76 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
34R-18.1	*996.0 ±190.0 Ma*
34R-19.1	*1871.0 ± 17.0 Ma*
34R-19.2	*1167.0 ± 19.0 Ma*
34R-20.1	*1278.0 ± 31.0 Ma*

Grain spot numbers 34R-19.1 and 34-19.2 reveal two stages in the thermal history of this grain. Initial crystallization reflects the Kheis orogeny at 1871 ± 17 Ma, with subsequent crystallization during the Namaqua-Natal metamorphism – 1167 ± 19 Ma – resulting in the formation of a secondary rim. In the image on the right the full outline of the particular crystal (compare transmitted light image on the left) has been highlighted.

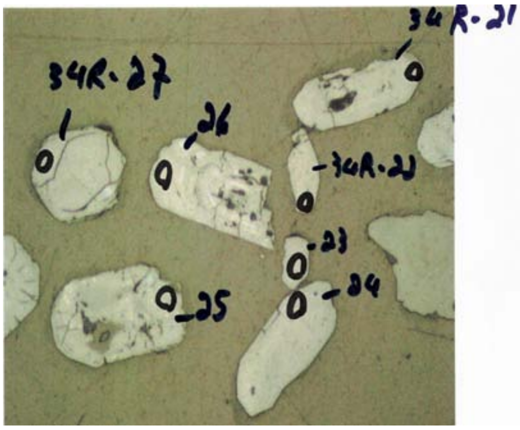
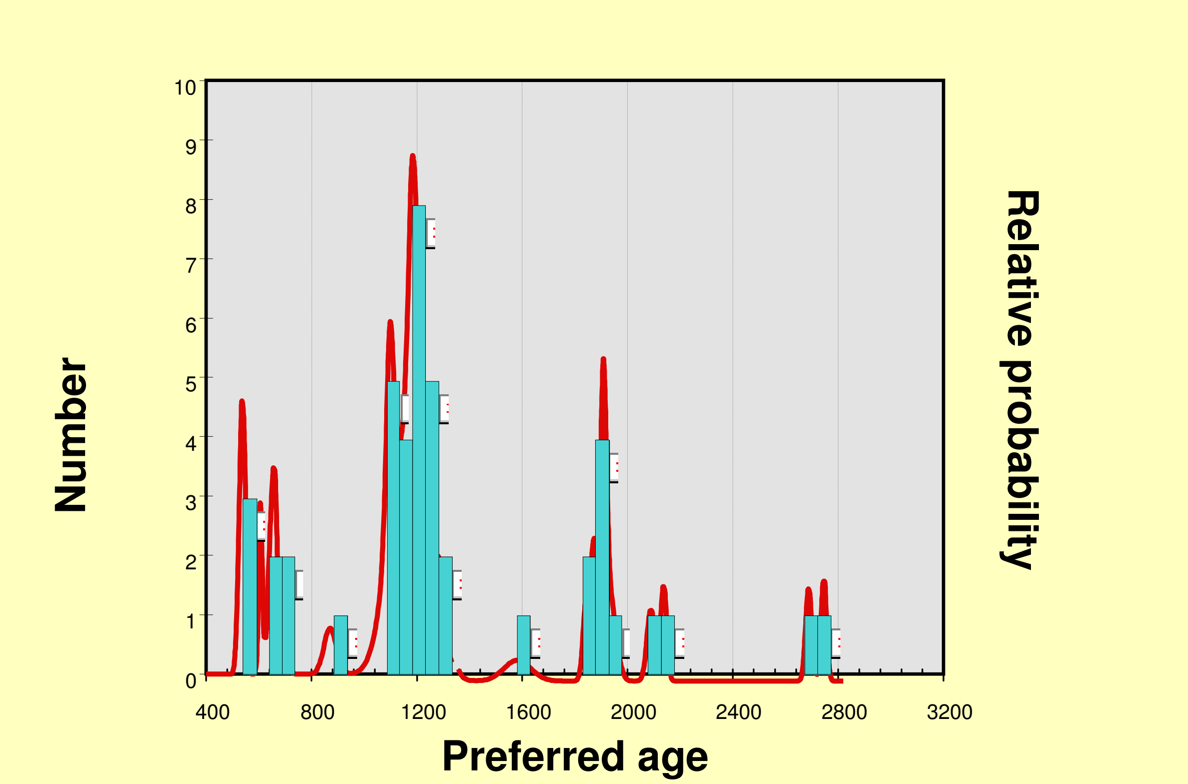


Figure 8.77 Actual sample spots shown in reflected light images.

GRAIN SPOT NUMBER	*Preferred Age*
34R-21.1	*1185.0 ± 17.0 Ma*
34R-22.1	*1845.0 ± 9.0 Ma*
34R-23.1	*1210.0 ± 47.0 Ma*
34R-24.1	*1122.0 ± 32.0 Ma*
34R-25.1	*1146.0 ± 75.0 Ma*
34R-26.1	*1185.0 ± 14.0 Ma*
34R-27.1	*1197.0 ± 29.0 Ma*
34R-28.1	*990.0 ± 49.0 Ma*
34R-29.1	*348.9 ± 5.3 Ma*
34R-30.1	*1212.0 ± 25.0 Ma*
34R-31.1	*525.8 ± 8.7 Ma*
34R32.1	*1818.0 ± 13 Ma*
34R-32.2	*1883.0 ± 9.0 Ma*
34R-33.1	*1141.0 ± 22.0 Ma*
34R-34.1	*870 ± 23.0 Ma*
34R-35.1	*1219.0 ± 38.0 Ma*
34R-36.1	*2719.0 ± 10.0 Ma*
34R-37.1	*1185.0 ± 17.0 Ma*



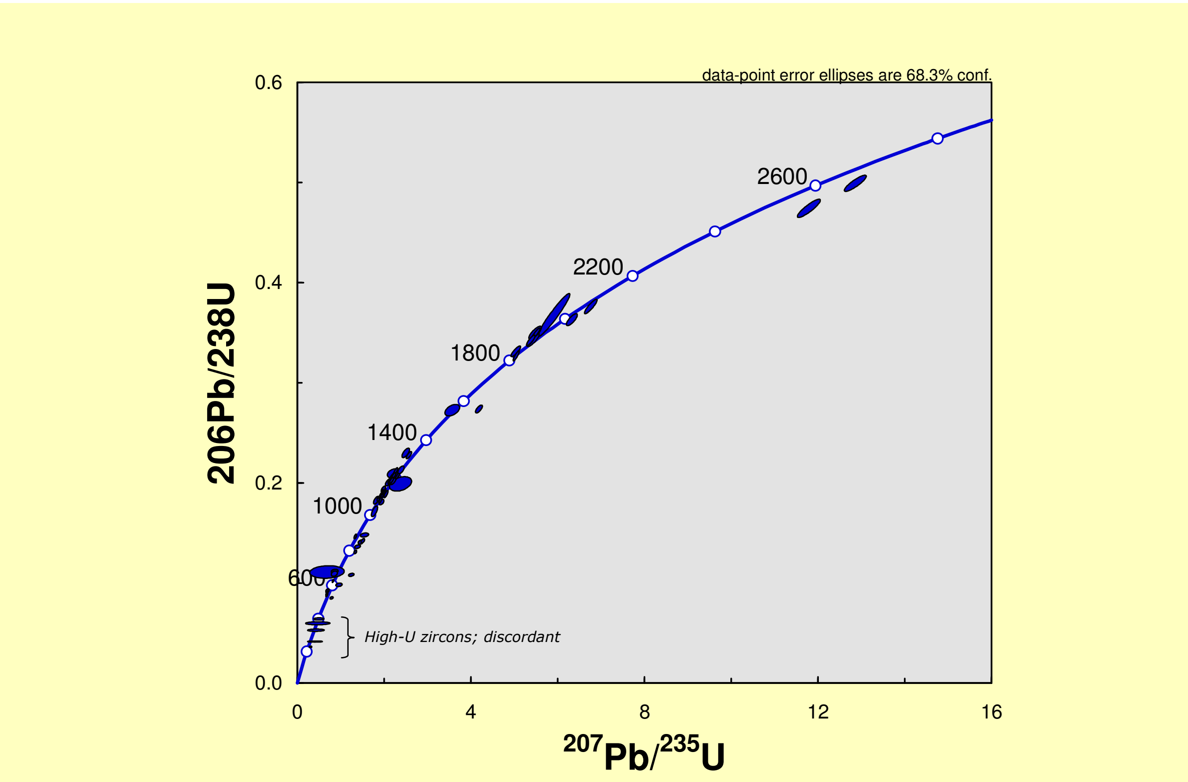


Figure 8.78 Histogram of preferred ages, and Concordia diagram. Sample No. 34, XAR-1, Bloeddrif.

TABLE 8.15 ANALYSES OF ZIRCON GRAINS FROM XARRIES-1, BLOEDDRIF

Spot name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
34R-31.1	525.8	8.7	577	56	9	525.8	8.7
34-9.1	535.8	6.2	rejected	n/a	10	535.8	6.2
34-12.1	546.8	6.6	rejected	n/a	1	546.8	6.6
34-5.1	605.9	6.4	rejected	n/a	4	605.9	6.4
34-15.1	646.1	10.8	rejected	n/a	-13	646.1	10.8
34R-11.1	658.8	25.3	44	891	-1414	658.8	25.3
34R-3.1	661.2	8.9	572	136	-16	661.2	8.9
34R-34.1	835.8	7.6	1180	28	29	870	23
34-17.1	1066.5	10.2	1141	22	7	1060	35
34-2.2	1174.2	12.5	1183	16	1	1096	13
34-6.1	1113.3	13.7	1123	28	1	1098	13
34-19.1	1055.3	10.2	1189	38	11	1099	24
34R-24.1	1321.8	17.1	1204	30	-10	1122	32
34R-17.1	236.4	3.5	1179	530	80	1123	28
34-14.1	1085.9	10.6	1096	13	1	1133	28
34R-33.1	1307.0	12.3	1284	18	-2	1141	22
34R-19.2	1002.9	19.4	1128	45	11	1167	19
34-8.1	1210.1	15.9	1164	84	-4	1183	16
34R-26.1	1173.7	9.8	1185	14	1	1185	14
34R-21.1	1076.1	9.9	1099	24	2	1185	17
34R-37.1	1063.0	14.2	1060	35	0	1185	17
34R-27.1	1165.1	12.6	1133	28	-3	1197	29
34-13.1	862.3	8.9	870	23	1	1204	30
34R-23.1	1197.7	11.3	1185	17	-1	1210	47
34R-30.1	1194.3	16.5	1210	47	1	1212	25
34R-35.1	1181.8	17.1	1186	27	0	1219	38
34R-20.1	1098.2	13.4	1217	21	10	1278	31
34R-2.1	1108.6	9.9	1098	13	-1	1284	18
34-1.1	1172.8	13.0	1167	19	-1	1555	51
34R-32.1	1086.8	12.0	1122	32	3	1818	13
34R-22.1	1223.4	11.8	1185	17	-3	1845	9
34R-19.1	1124.5	11.3	1089	28	-3	1871	17
34R-12.1	773.1	6.6	1124	35	31	1878	12
34R-32.2	805.3	7.1	1098	52	27	1883	9
34R-16.1	503.7	4.2	990	49	49	1917	21
34R-7.1	1170.5	11.7	1212	25	3	2062	15
34R-5.1	1200.1	13.8	1197	29	0	2111	11
34R-13.1	1230.8	13.6	1278	31	4	2661	11
34R-36.1	1198.7	17.8	1219	38	2	2719	10

Samples 34/34R were collected at the transition from pre-proto to proto-Orange sediments at Xarries, Bloeddrif. In Section 2.2.3 where the geology of the sample localities was discussed, a depositional age of about 23 Ma (Oligocene-Miocene transition) was concluded for the pre-proto deposits, while Corvinus and Hendey (1978) arrived at an "Early to Middle Miocene" age for the Proto deposits. Zircon ages recorded range from 525.8 ± 8.7 to 2719 ± 10 Ma.

The age of 2719 ± 10 Ma corresponds to the deposition of Ventersdorp volcanics (Tinker *et al.,* 2002; Eglington and Armstrong, 2004). Previously unrecorded outcrops of pyroclastic lava of the Ventersdorp Supergroup were observed in the bed of the Orange River immediately upstream from the confluence with the Vaal River near Douglas, during the course of this study (Figure 2.2).

The zircon geochronology indicates that by the transition of the Early to Middle Miocene, incision by the Orange-Vaal fluvial system had advanced into Archaean basement, with no input from Karoo rocks evident any longer.

The absence of any Karoo-aged grains in this sample lends support to the view that the presence of Archaean ages here indeed reflects on the drainage evolution as mentioned above, and is not the result of Archaean-aged zircons having been recycled *via* the Ecca, as suggested by an Archaean age among the samples from Fan A, Laingsburg.

The preponderance of grains reflecting the Namaqua Metamorphic event and Vioolsdrif Igneous Suite transected by the Orange River valley further upstream, is in agreement with the high incidence of litho-types from these source regions that were observed in these gravel samples.

8.4.5.4 Meso-3 Orange River gravel, XAR-5, Bloeddrif

The meso deposits are at least 12 Ma younger than the proto-Orange River deposits. This sample was collected from a sedimentary unit that is thought to be the youngest of the meso deposits along the Lower Orange River, because of field relationships (lower bedrock elevation, and incision into older meso-deposits). In terms of geochronology, information gained from this sample was expected to reflect a continuation of any trend observed in the older deposits.

Only three zircon grains (four SHRIMP analyses) could be extracted from this sample. While this does not approach a reliable statistical population it is of interest to note that all these ages reflect only the Namaqua-Natal Metamorphic event. Even this small sample population thus seems to confirm that, by the Plio-Pleistocene, Orange River incision through the Karoo Supergroup had advanced into underlying Precambrian rocks.

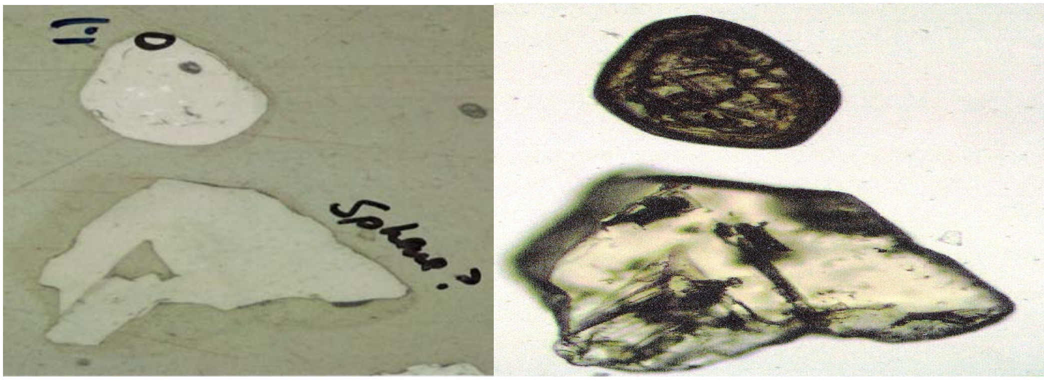


Figure 8.79 XAR-6, Bloeddrif - sample 37: Application of transmitted light optical image (right)) to locate appropriate spots for analyses on zircon grains, with actual sample spot shown in reflected light image (left).

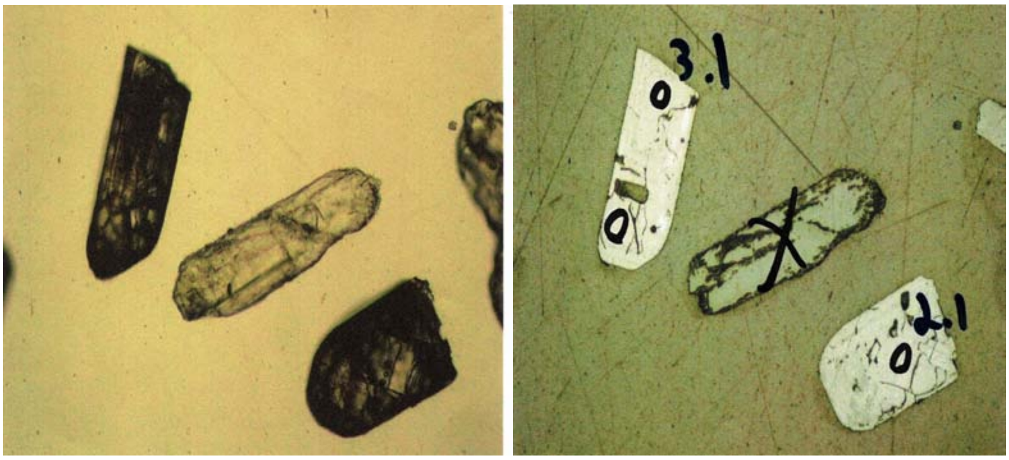


Figure 8.80 Bloeddrif - sample 37: XAR-6: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

TABLE 8.16 RESULTS OF ZIRCON ANALYSES, SAMPLE 37, XAR-6, BLOEDDRIF

Spot Name	ppm U	ppm Th	232Th /238U	204 corr $^{206}Pb/^{238}U$	1σ err	207corr 206Pb/238U Age	1σ err	208corr 206Pb/238U Age	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err
37-1.1	1153	70	0.06	864.8	8.7	852.7	9.0	864.3	8.8	1206	21
37-2.1	191	94	0.51	1137.5	13.0	1118.4	16.1	1124.1	16.0	1484	145
37-3.1	494	175	0.37	1027.8	8.8	1022.1	9.2	1029.8	9.4	1157	22
37-3.2	415	149	0.37	1232.4	11.2	1237.0	11.9	1233.8	11.8	1152	20

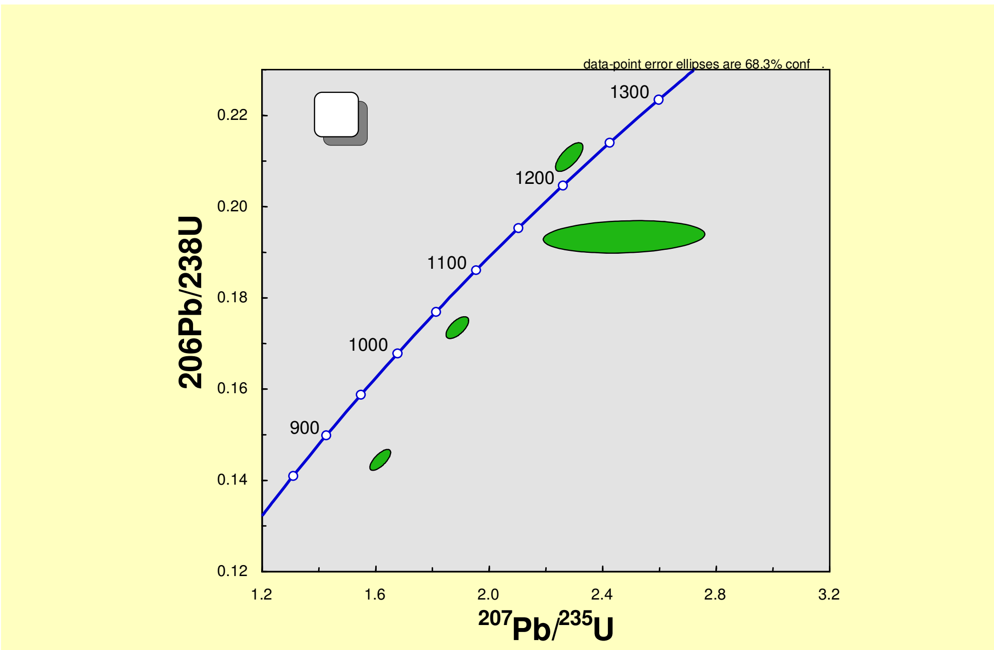


Figure 8.81 Concordia diagram, sample 37, XAR-6, Bloeddrif.

8.4.5.5 Koeskop-Swartwater palaeo-channel, Baken Mine (Sample 2)

Figure 8.82 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
2-1.1	*1178.0 ± 21.0 Ma*
2-2.1	*1180.0 ± 12.0 Ma*
2-3.2	*1163.0 ± 20.0 Ma*
2-4.2	*2000.0 ± 6.0 Ma*
2-5.1	*1201.0 ± 19.0 Ma*
2-6.1	*1234.0 ± 16.0 Ma*

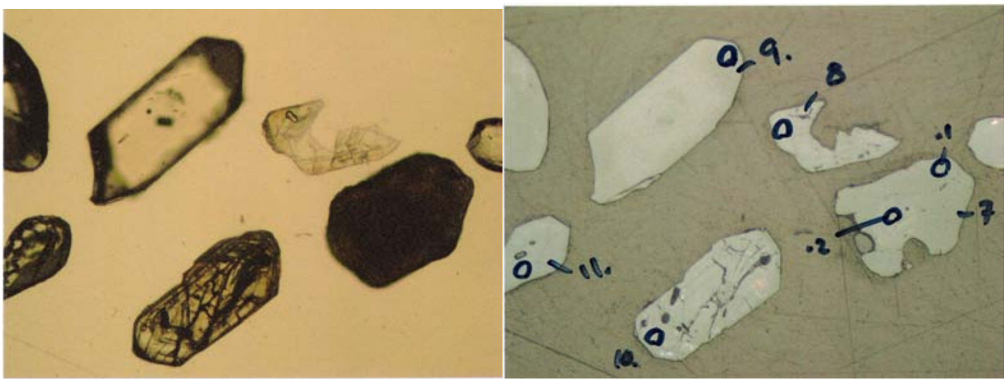


Figure 8.83 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
2-8.1	*1154.0 ± 8.0 Ma*
2-9.1	*523.4 ± 5.8 Ma*
2-10.2	*1205.0 ± 8.0 Ma*
2-11.1	*1106.0 ± 13.0 Ma*

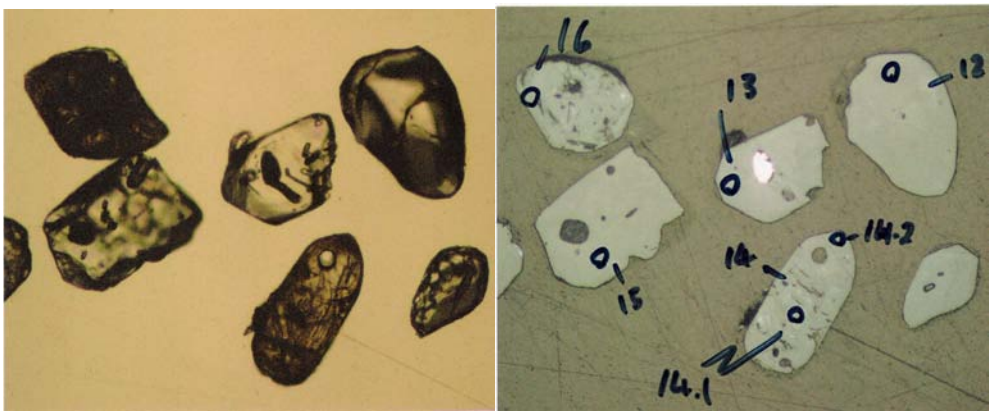


Figure 8.84 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
2-12.1	*648.5 ± 6.8 Ma*
2-13.1	*547.3 ± 6.8 Ma*
2-14.2	*1163.0 ± 15.0 Ma*
2-15.1	*1077.0 ± 30.0 Ma*

Figure 8.85 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
2-18.1	*1040.0 ± 18.0 Ma*
2-20.1	*1096.0 ± 265 Ma*
2-21.1	*1212.0 ± 17.0 Ma*
2-22.1	*1173.0 ± 33.0 Ma*

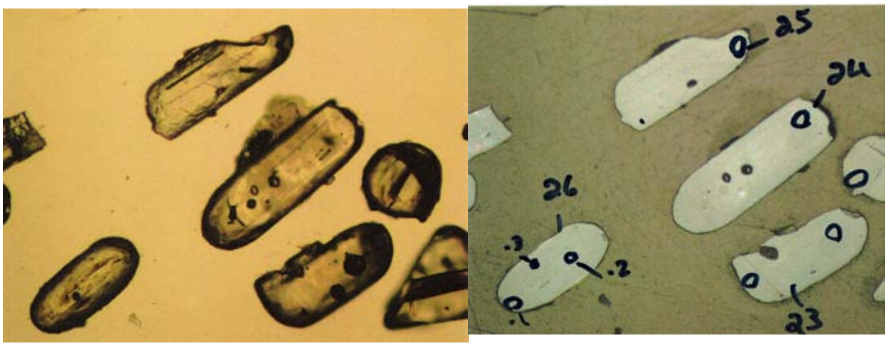


Figure 8.86 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	*Preferred Age*
2-23.1	*653.9 ± 9.5 Ma*
2-23.2	*631.6 ± 7.6 Ma*
2-26.1	*291.5 ± 3.4 Ma*
2-26.2	*490.8 ± 7.5 Ma*

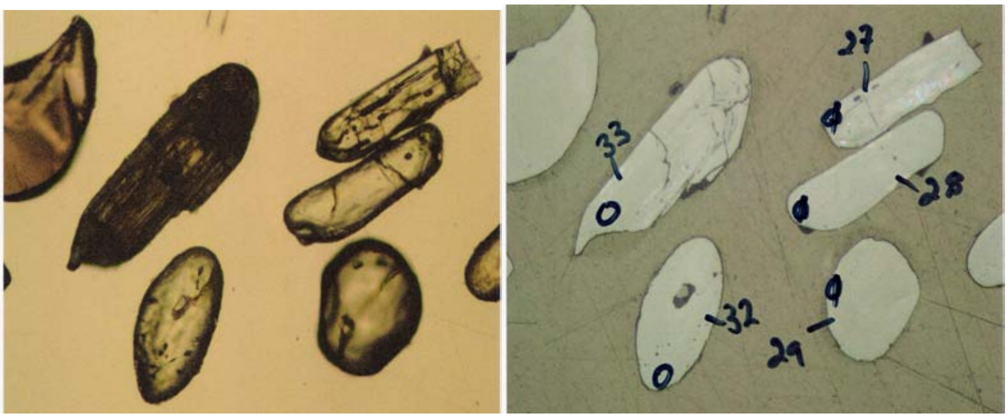


Figure 8.87 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	*Preferred Age*
2-29.1	*559.5 ± 6.4 Ma*
2-31.1	*651.2 ± 7.4 Ma*
2-32.1	*650.3 ± 7.2 Ma*
2-33.1	*1202.0 ± 16.0 Ma*

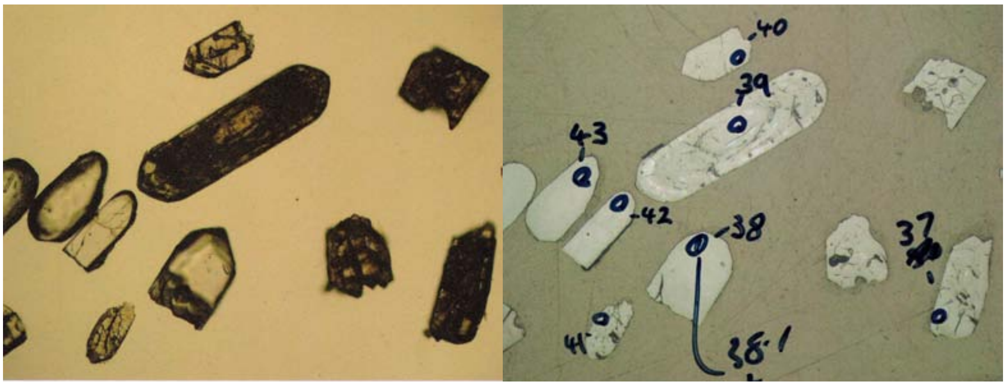


Figure 8.88 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	*Preferred Age*
2-38.1	*1092.0 ± 24.0Ma*
2-39.1	*1235.0 ± 18.0 Ma*
2-40.1	*1891.0 ± 6.0 Ma*
2-42.1	*1186.0 ± 16.0 Ma*
2-43.1	*565.0 ± 7.2 Ma*

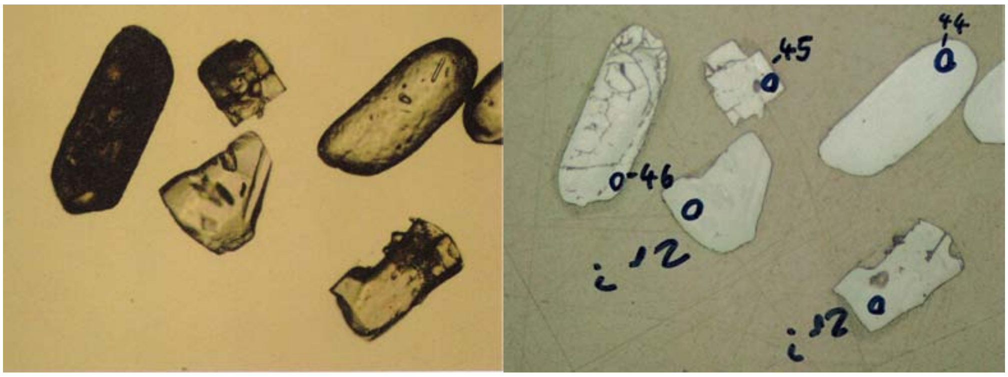
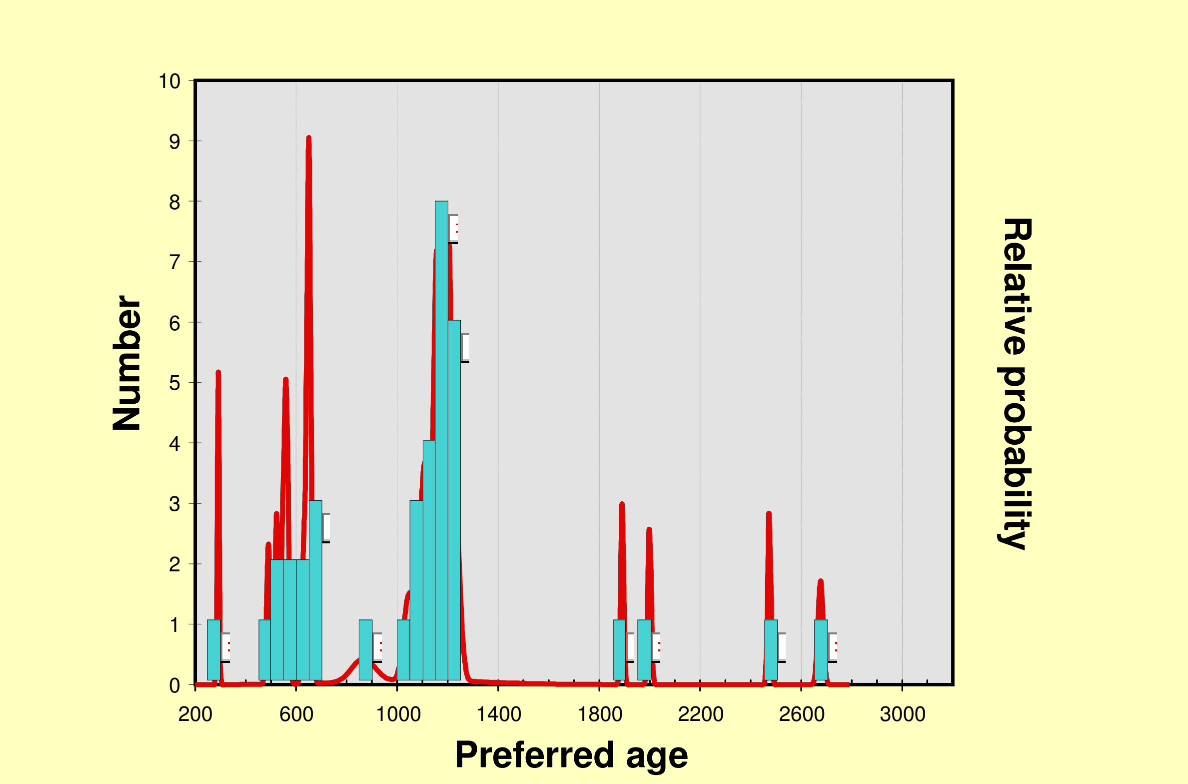


Figure 8.89 Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	*Preferred Age*
2-44.1	*866.0 ± 46.0 Ma*

As described in Section 2.2.3 the Baken Mine exploits a classic oxbow, or cut-off meander, of the palaeo-Orange River. The basal gravel in this 7 x 1.2 km feature where this sample was collected accumulated during an aggradation stage in the Early to Middle Miocene.



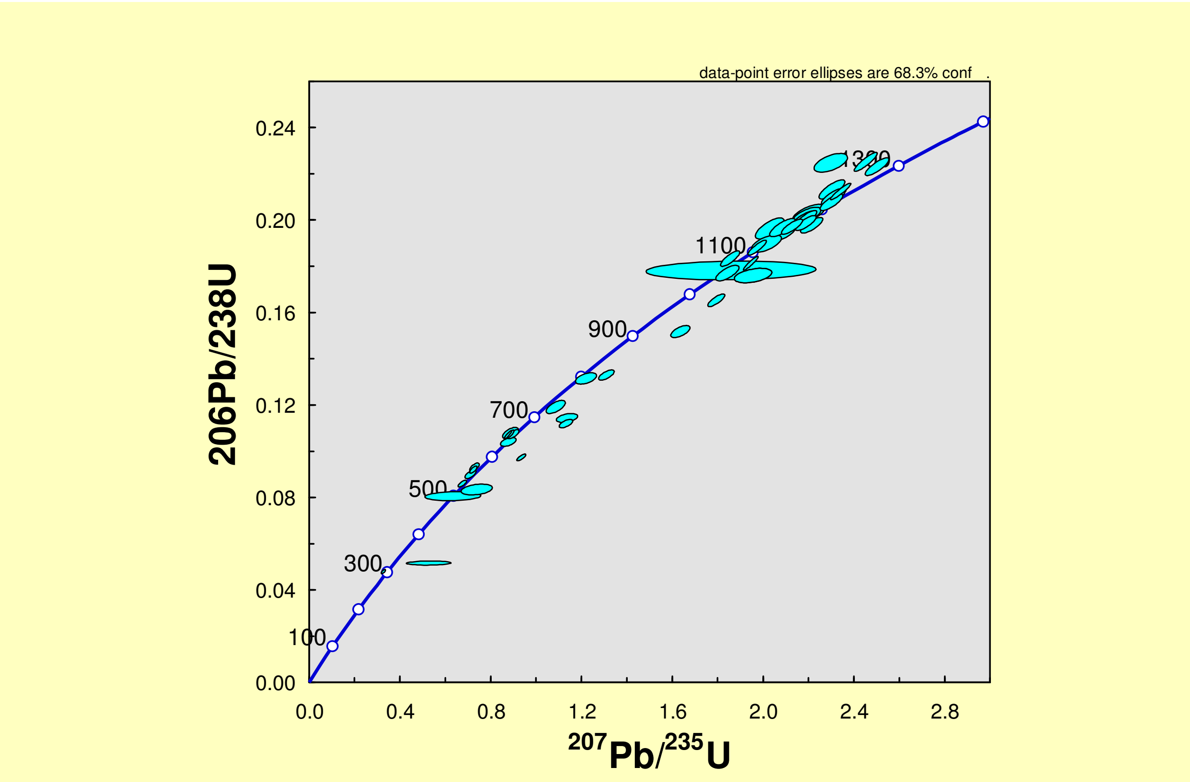


Figure 8.90 Histogram of preferred ages and Concordia diagram, Sample 2, proto-Orange gravel, Koeskop-Swartwater palaeo-channel, Baken Mine.

TABLE 8.17 ZIRCON ANALYSES FROM PROTO-ORANGE SEDIMENTS, BAKEN MINE

Spot Name	204corr 206Pb/238U Age	1σ err	207corr 206Pb/238U Age	1σ err	204corr 207Pb/206Pb Age	1σ err	% Discordant	Preferred Age	1σ err
2-26.1	291.5	3.4	291.4	3.4	303	27	4	291.5	3.4
2-9.1	523.4	5.8	523.1	5.9	542	23	4	523.4	5.8
2-13.1	547.3	6.8	547.2	7.0	552	33	1	547.3	6.8
2-29.1	559.5	6.4	559.8	6.6	546	25	-2	559.5	6.4
2-43.1	565.0	7.2	565.6	7.3	532	34	-6	565.0	7.2
2-23.2	631.6	7.6	630.6	7.7	679	47	7	631.6	7.6
2-12.1	648.5	6.8	649.3	6.9	611	10	-6	648.5	6.8
2-32.1	650.3	7.2	650.8	7.4	627	18	-4	650.3	7.2
2-31.1	651.2	7.4	651.0	7.6	660	28	1	651.2	7.4
2-23.1	653.9	9.5	654.5	9.8	625	43	-4	653.9	9.5
2-44.1	790.6	9.3	788.4	9.6	866	46	10	866	46
2-18.1	1081.2	12.2	1083.1	12.8	1040	18	-4	1040	18
2-15.1	1152.7	16.1	1156.5	17.0	1077	30	-7	1077	30
2-38.2	1048.0	12.2	1046.0	12.8	1092	24	4	1092	24
2-11.1	1108.1	11.8	1108.2	12.4	1106	13	0	1106	13
2-17.1	1155.0	14.3	1156.3	15.1	1129	23	-2	1129	23
2-27.1	1117.5	13.7	1116.8	14.4	1131	34	1	1131	34
2-34.1	1142.8	13.6	1142.9	14.3	1141	36	0	1141	36
2-8.1	1070.4	10.9	1066.4	11.4	1154	8	8	1154	8
2-14.2	1157.1	11.7	1156.8	12.3	1163	15	0	1163	15
2-3.2	1243.6	14.7	1248.2	15.7	1163	20	-6	1163	20
2-22.1	1186.7	14.8	1187.4	15.6	1173	33	-1	1173	33
2-34.1	1184.2	12.4	1184.7	13.1	1173	27	-1	1173	27
2-1.1	1173.5	13.8	1173.2	14.6	1178	21	0	1178	21
2-2.1	1307.2	14.3	1315.0	15.3	1180	12	-10	1180	12
2-42.1	1176.4	12.4	1175.9	13.1	1186	16	1	1186	16
2-5.1	1226.9	12.9	1228.4	13.7	1201	19	-2	1201	19
2-33.1	1165.3	11.7	1163.4	12.3	1202	16	3	1202	16
2-10.1	1238.9	12.6	1240.9	13.3	1205	8	-3	1205	8
2-21.1	1214.0	12.3	1214.1	13.0	1212	17	0	1212	17
2-6.1	1296.9	13.6	1300.8	14.6	1234	16	-5	1234	16
2-39.1	1160.6	12.0	1156.6	12.6	1235	18	6	1235	18
2-40.1	1926.3	18.7	1931.3	21.4	1891	6	-2	1891	6
2-4.2	1920.1	18.9	1908.5	21.6	2000	6	4	2000	6
2-30.1	2562.1	23.7	2589.5	32.1	2473	6	-3	2473	6
2-35.1	2738.3	30.7	2762.7	44.2	2677	10	-2	2677	10

This sample yielded the following range of ages:

- 291.5 Ma (later stages of Dwyka sedimentation, Veevers *et al.*, 1994b, Bangert *et al.*, 1999; volcanism in northern Patagonia, Kay *et al.*, 1989);

- 523.4 ± 5.8 – 653.9 ± 9.5 Ma (Cape Granite and Kuboos Pluton ages);
- 866.0 ± 46 Ma (Richtersveld Suite; Hartzer *et al.*, 1998)
- 1040.0 ± 18.0 – 1235.0 ±18.0 Ma (Namaqua-Natal Metamorphism; Thomas *et al.*, 1994; Eglington and Armstrong, 2004);
- 1891.0 ± 6.0 – 2000.0 ± 6.0 Ma (Vioolsdrif Suite; Reid *et al.*, 1987b);
- 2473.0 ± 6.0 Ma. (A correlation is indicated with zircons in air-fall tuffs intercalated with carbonate sediments from both central and Griqualand West depocentres of Transvaal Supergroup; Eglington and Armstrong, 2004);
- 2677.0 ± 10 Ma. High-grade metamorphism associated with development of Kaapvaal Craton (Eglington and Armstrong, (2004); Retief *et al.*,1990; Kröner *et al.*, 1999; Kreissig *et al.*, 2001; Reimold *et al.*, 2002; Schmitz and Bowring 2003).
- 2710 Ma (Ventersdorp volcanics, Tinker *et al.*, 2002; Eglington and Armstrong, 2004).

The time span covered by these zircon ages indicates that by the Middle Miocene, incision by the Orange-Vaal fluvial system had advanced into late Archaean basement. This is in line with the pattern already described at Lorelei, Snake Hill and Bloeddrif, namely that of denudation starting with the youngest, highest rocks in the catchment area of the Orange-Vaal drainage system, transporting material with increasing age as the older rocks became exhumed. Thus the oldest Cenozoic sediments of this fluvial system contain the youngest zircons and *vice versa*.

The presence of juvenile zircons in each of these proto-Orange River samples and those of Renosterkop (Section 8.4.5.7) is not necessarily in conflict with this model, since basal Karoo rocks in places still occupy the valley flanks of the current Orange River and its main tributary in the Richtersveld, the Fish River of Namibia.

8.4.5.6 *Auchas.* (Sample collected by R Jacob, SHRIMP analyses by this author).

TABLE 8.18 ZIRCON ANALYSES FROM MODERN ORANGE RIVER AT AUCHAS.

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
Auchas-17.1	527.7	7.0	672	49	27	527.7	7.0
Auchas-20.1	563.2	6.6	550	25	-2	563.2	6.6
Auchas-2.1	570.8	6.7	548	24	-4	570.8	6.7
Auchas-43.1	574.9	6.1	575	35	0	574.9	6.1
Auchas-32.1	584.7	6.5	575	73	-2	584.7	6.5
Auchas-23.1	613.6	8.0	606	36	-1	613.6	8.0
Auchas-38.1	654.0	10.0	764	295	17	654.0	10.0
Auchas-11.1	666.9	8.7	698	55	5	666.9	8.7
Auchas-29.1	670.7	7.7	637	22	-5	670.7	7.7
Auchas-16.1	683.2	7.4	835	68	22	683.2	7.4
Auchas-13.1	691.2	7.4	628	20	-9	691.2	7.4
Auchas-30.1	776.0	8.1	846	29	9	846	29
Auchas-19.1	864.6	9.5	868	37	0	868	37
Auchas-21.1	895.9	9.6	874	13	-2	874	13
Auchas-15.1	1008.2	10.5	1019	26	1	1019	26
Auchas-9.1	1013.8	10.9	1068	17	5	1068	17
Auchas-4.1	1042.5	12.5	1035	22	-1	1035	22
Auchas-14.1	1059.4	11.8	1069	16	1	1069	16
Auchas-37.1	1063.0	10.9	1148	14	8	1148	14
Auchas-31.1	1093.5	11.1	1171	11	7	1171	11
Auchas-41.1	1119.4	11.7	1040	12	-7	1040	12
Auchas-26.1	1145.8	13.1	1116	23	-3	1116	23
Auchas-34.1	1156.8	13.6	1155	18	0	1155	18
Auchas-1.1	1164.0	12.8	1105	15	-5	1105	15
Auchas-39.1	1174.5	12.7	1127	14	-4	1127	14
Auchas-28.1	1180.5	12.6	1140	13	-3	1140	13
Auchas-33.1	1204.1	12.4	1234	17	3	1234	17
Auchas-25.1	1230.9	12.7	1235	46	0	1235	46
Auchas-44.1	1237.7	13.0	1220	15	-1	1220	15
Auchas-3.1	1274.5	20.9	1199	38	-6	1199	38
Auchas-24.1	1406.5	15.2	1344	14	-4	1344	14
Auchas-6.1	1793.5	20.3	1786	15	0	1786	15
Auchas-12.1	1850.1	19.0	1821	8	-2	1821	8
Auchas-40.1	1884.4	19.1	1849	7	-2	1849	7
Auchas-18.1	2017.4	23.2	2132	11	6	2132	11
Auchas-8.1	2682.9	24.7	2596	4	-3	2596	4
Auchas-22.1	3083.2	29.7	2919	14	-5	2919	14

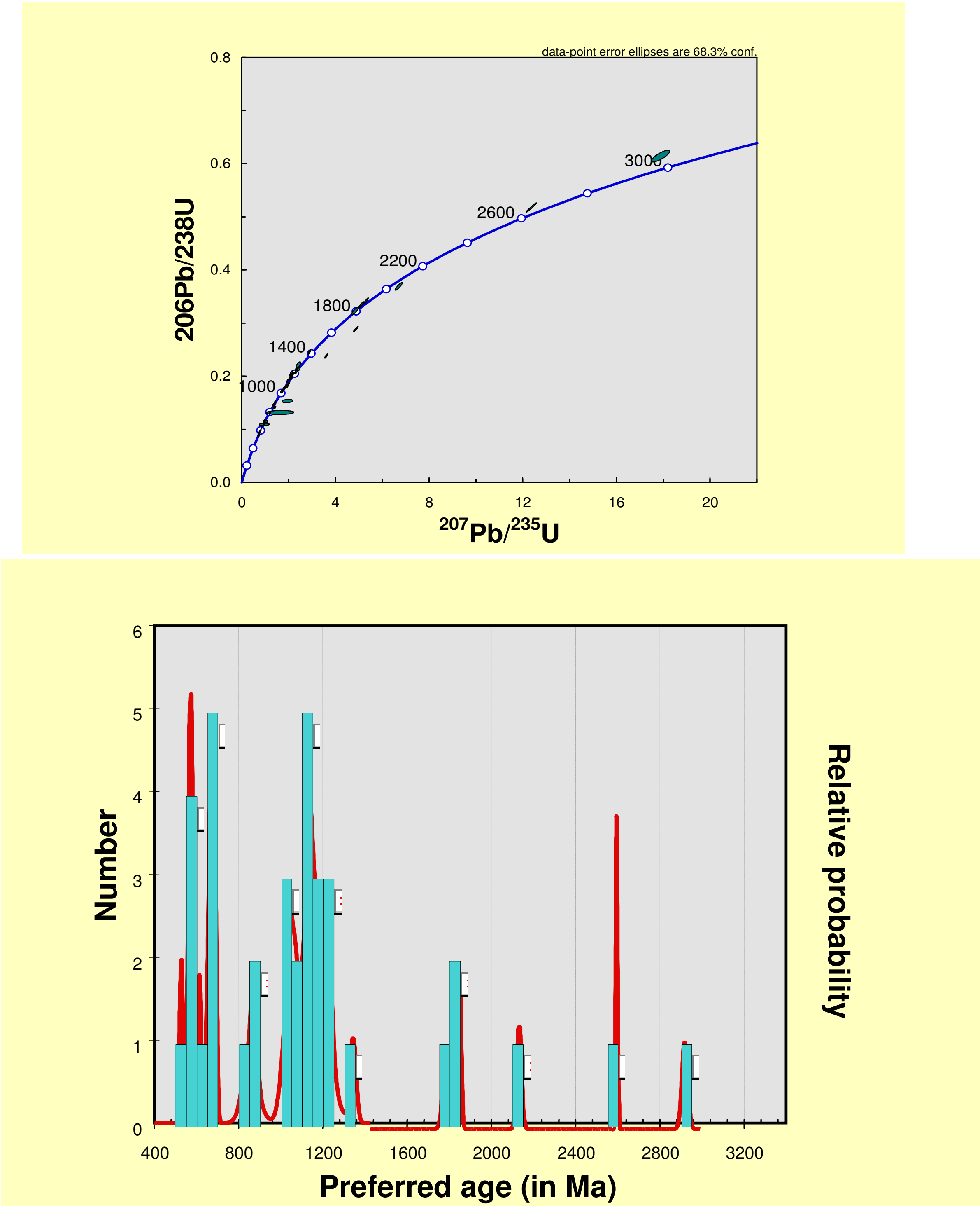


Figure 8.91 Concordia diagram and histogram of preferred ages for zircons from modern river, Auchas.

The zircon ages found in the modern river bed can be grouped as follows:

- 563.2 ± 6.6 – 527.7 ± 7.0 Ma (Cape Granite Suite; Eglington, 2006)
- 691.2 ± 7.4 – 570.8 ± 7.4 Ma (Gariep Supergroup; Frimmel *et al.*, 2001)
- 874 ± 13 – 846 ± 29 Ma (Richtersveld Suite: Hartzer *et al.*, 1998)
- 1344 ± 14 – 1019 ± 26 Ma (Namaqua-Natal Province: Hartzer *et al.*, 1998; Moen and Armstrong, 2004; Armstrong *et al.*, 1988; Petersson *et al.*, 2004; Moore *et al.*, 1990; Thomas *et al.*, 1994; Eglington and Armstrong, 2004)
- 1849 ± 7 – 1786 ± 15 Ma (Vioolsdrif Suite: Reid *et al.*, 1987b)
- 2132 ± 11 (Postmasburg Group: Eglington and Armstrong, 2004)
- 2596 ± 4 Ma (zircons in air fall tuffs intercalated with carbonate sediments, Asbestos Hills Subgroup: Eglington and Armstrong, 2004)
- 2919 ± 14 Ma (possibly Ventersdorp Supergroup).

These ages span the thermal history of the western part of the Kaapvaal Craton and the adjacent Namaqualand and Richtersveld from the intrusion of the Cape Granite Suite well into the Archaean. The complete absence of Karoo-aged zircons is taken as evidence that the older ages reflected in this sample population can be related to the evolution of the drainage system without the probability of older grains having been recycled *via* Ecca Group rocks. Based upon the zircon geochronology of this sample population the following conclusions can be drawn:

- Although the current Orange River valley transects portions of basal Karoo sediments between Hopetown and Prieska as well as between Vioolsdrif and Aussenkjer, pronounced erosion of the Ecca has ceased. Occasional input of Ecca-derived material may have taken place as suggested in the discussion on the Baken and Renosterkop proto-Orange River sample results.
- The observed incision of the modern river into Archaean bedrock is confirmed by the presence of zircons aged older than 2 500 Ma. The denudation model proposed earlier finds strong support in these results, with the oldest zircon ages of all the samples studied, coming out of the youngest sedimentary unit.

8.4.5.7 Renosterkop

Renosterkop is situated between Upington and the Augrabies Falls. The proto-Orange River gravel deposits found here (Section 2.1.2.2) represent the only officially recorded diamondiferous Cenozoic deposits between the Prieska region and the farm Daberas 8, located between Augrabies and Vioolsdrif/Noordoewer. (At the time of writing the first diamonds from the Miocene palaeo-Orange River valley discovered during the course of this study and located near Grootdrink between Groblershoop and Upington, had been recovered but this has not been published yet).

Situated more than 400 kilometres upstream from the Richtersveld where the other Orange River-linked zircons were collected, the contribution from its zircon geochronology makes Renosterkop an important controlling factor in drainage and denudation reconstruction.

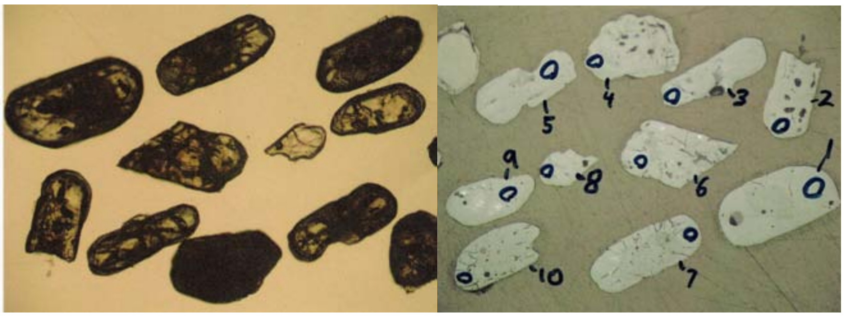


Figure 8.92 Renosterkop: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
Ren-2.1	*593.9 ± 5.7 Ma*
Ren-3.1	*1144.0 ± 93.0 Ma*
Ren-4.1	*1123.0 ± 21.0 Ma*
Ren-5.1	*1023.0 ± 63.0 Ma*
Ren-6.1	*973.0 ± 24.0 Ma*
Ren-7.1	*1143.0 ± 210.0 Ma*
Ren-8.1	*977.0 ± 40.0 Ma*
Ren-9.1	*1169.0 ± 22.0 Ma*
Ren-10.1	*1123.0 ± 40.0 Ma*

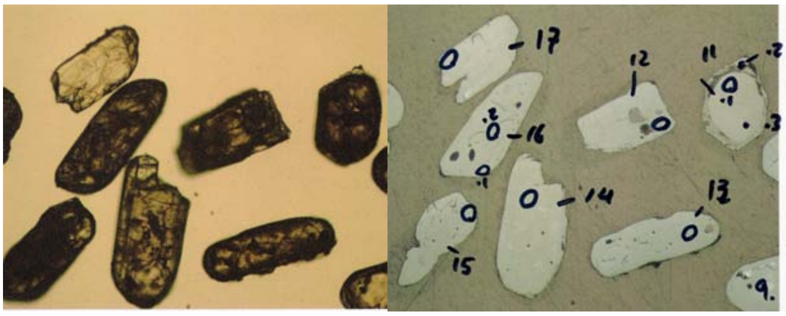


Figure 8.93 Renosterkop: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
Ren-11.1	*1006.0 ± 14.0 Ma*
Ren-12.1	*1244.0 ± 46.0 Ma*
Ren-13.1	*251.6 ± 6.9 Ma*
Ren-14.1	*1073.0 ± 16.0 Ma*
Ren-15.1	*1085.0 ± 24.0 Ma*
Ren-17.1	*1019.0 ± 43.0 Ma*

Figure 8.94 Renosterkop: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
Ren-18.1	*538.9 ± 3.0 Ma*
Ren-19.1	*1049.0 ± 87.0 Ma*
Ren-20.1	*502.3 ± 6.5 Ma*
Ren-20.2	*515.8 ± 4.7 Ma*
Ren-21.1	*769.0 ± 42.0 Ma*
Ren-23.1	*892.0 ± 74.0 Ma*
Ren-25.1	*815.0 ± 40.0 Ma*

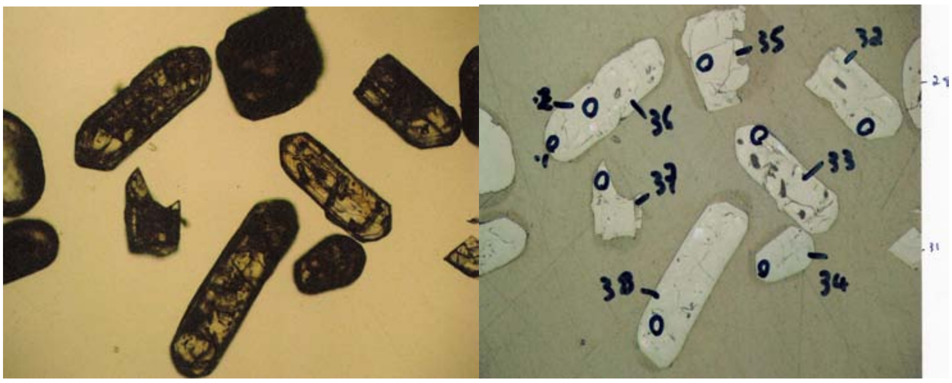


Figure 8.95 Renosterkop: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
Ren-26.1	*1107.0 ± 23.0 Ma*
Ren-28.1	*1719.0 ± 2.0 Ma*
Ren-29.1	*1037.0 ± 41.0 Ma*
Ren-30.1	*894.0 ± 44.0 Ma*
Ren-31.1	*657.0 ± 5.8 Ma*
Ren-33.1	*627.9 ± 5.8 Ma*
Ren-34.1	*1136.0 ± 18.0 Ma*
Ren-35.1	*1138.0 ± 29.0 Ma*
Ren-36.1	*653.2 ± 6.8 Ma*
Ren-37.1	*1162.0 ± 16.0 Ma*

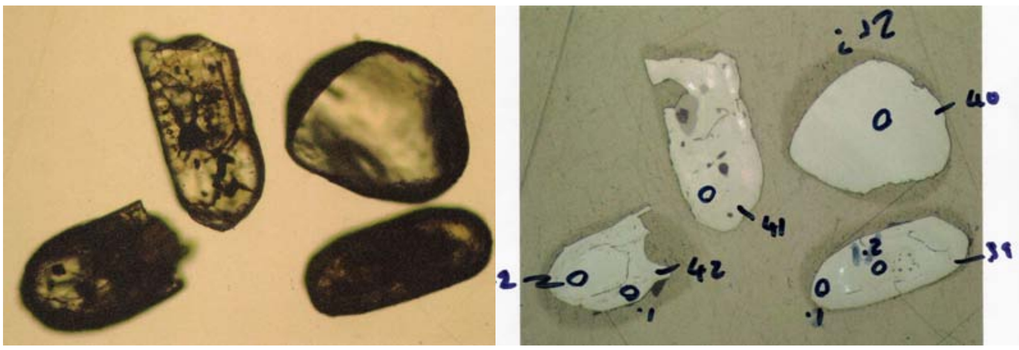


Figure 8.96 Renosterkop: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	***Preferred Age***
Ren-39.1	*982.2 ± 6.1 Ma*
Ren-40.1	*929.6 ± 10.9 Ma*
Ren-41.1	*395.1 ± 3.0 Ma*
Ren-42.1	*522.6 ± 6.9 Ma*

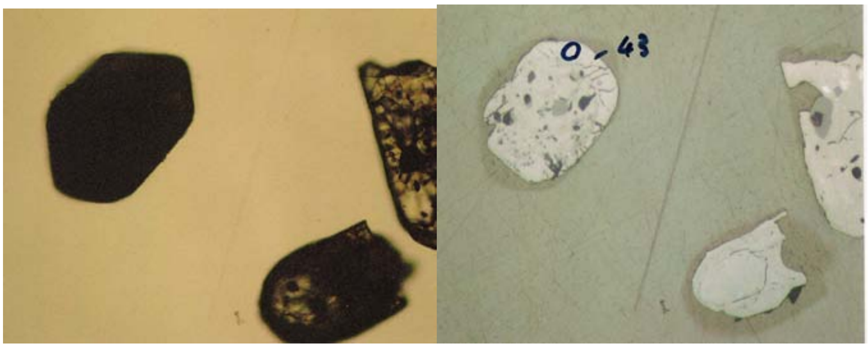


Figure 4.97 Renosterkop: Application of transmitted light optical image (left) to locate appropriate spots for analyses on zircon grains, with actual sample spots shown in reflected light image (right).

GRAIN SPOT NUMBER	*Preferred Age*
Ren-43.1	*1036.0 ± 11.0 Ma*

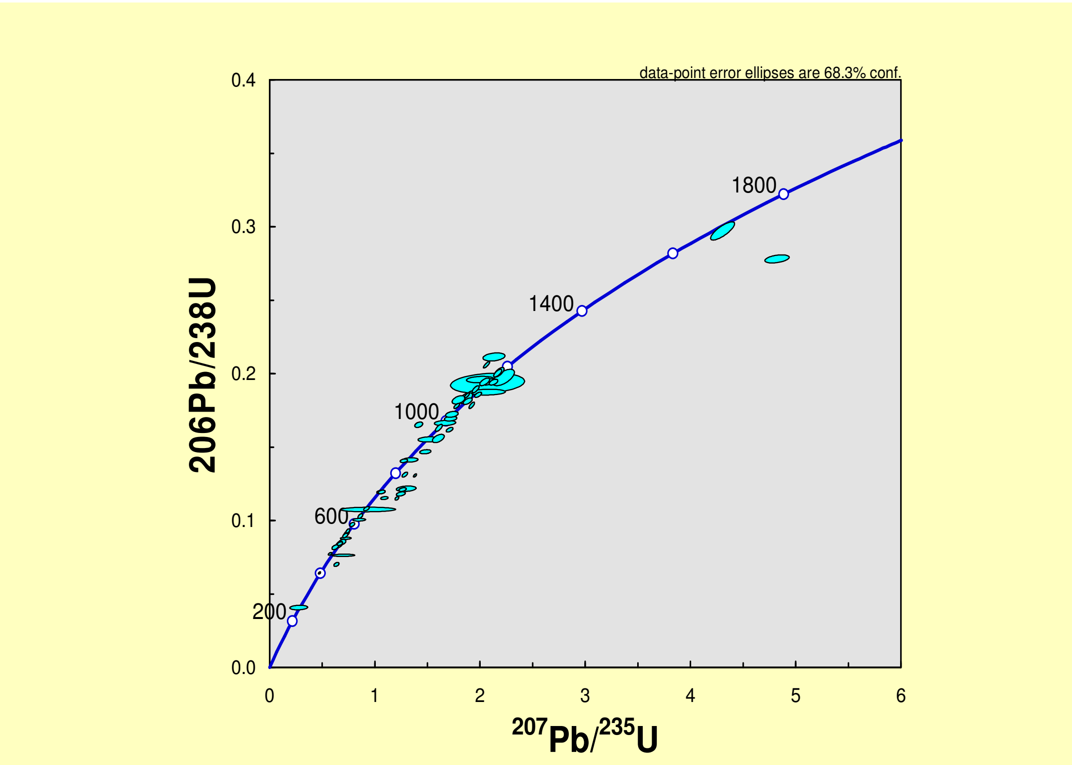
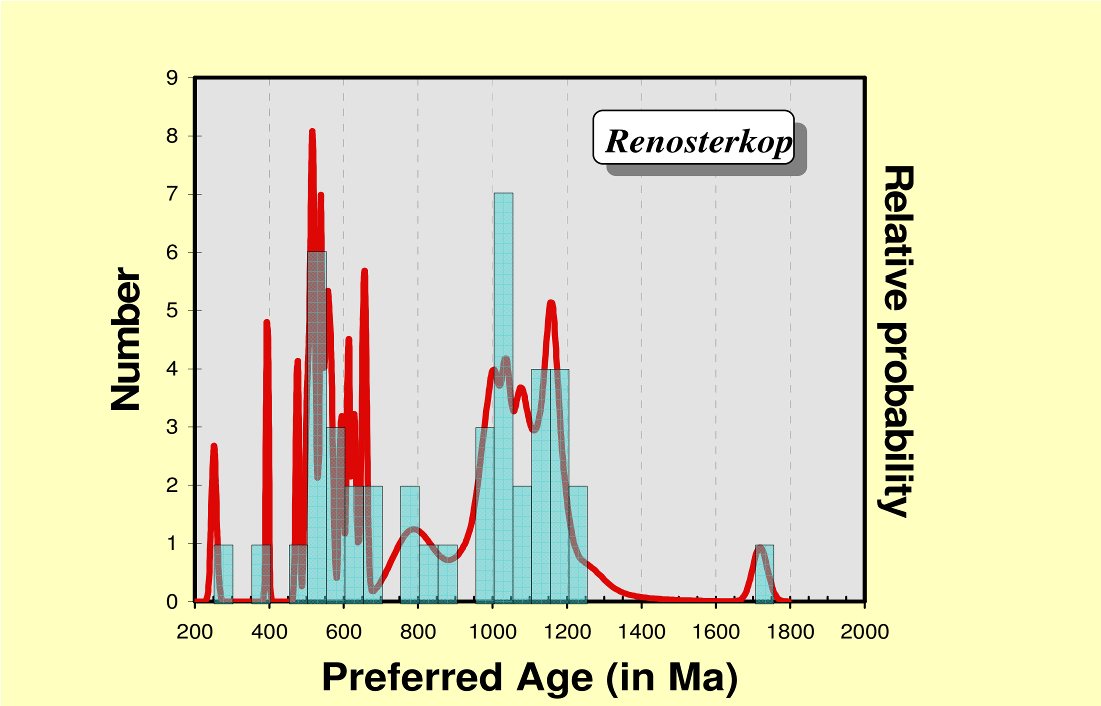


Figure 8.98 Concordia diagram, Renosterkop



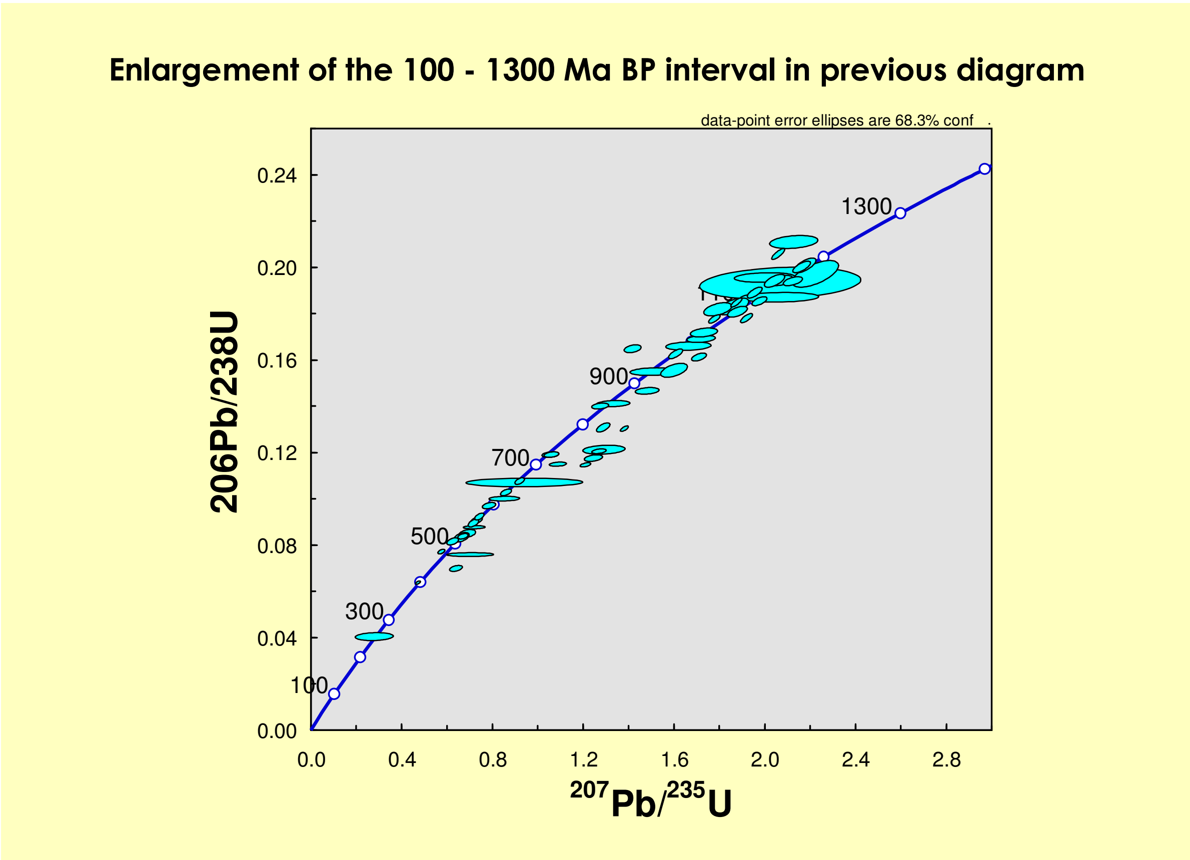


Figure 8.99 Histogram of preferred ages and enlargement of 100 -1300 Ma section of Concordia diagram in Fig. 8.96.

TABLE 8.19 RESULTS OF RENOSTERKOP ZIRCON ANALYSES

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
ren-13.1	251.6	6.9	rejected	n/a	-13	251.6	6.9
ren-41.1	395.1	3.0	rejected	n/a	-7	395.1	3.0
ren-24.1	475.6	4.0	rejected	n/a	-25	475.6	4.0
ren-22.1	502.3	6.5	rejected	n/a	-12	502.3	6.5
ren-62.1	513.6	8.2	rejected	n/a	2	513.6	8.2
ren-22.2	515.8	4.7	rejected	n/a	4	515.8	4.7
ren-42.1	522.6	6.9	rejected	n/a	9	522.6	6.9
ren-18.1	538.9	3.0	rejected	n/a	10	538.9	3.0
ren-59.1	549.7	6.2	rejected	n/a	-2	549.7	6.2
ren-27.1	557.1	6.0	rejected	n/a	-2	557.1	6.0
ren-61.1	566.7	5.8	rejected	n/a	-3	566.7	5.8
ren-2.1	593.9	5.7	rejected	n/a	-5	593.9	5.7
ren-44.1	612.4	3.9	rejected	n/a	9	612.4	3.9
ren-33.1	627.9	5.8	rejected	n/a	1	627.9	5.8
ren-36.1	653.2	6.8	rejected	n/a	12	653.2	6.8
ren-31.1	657.0	5.8	rejected	n/a	3	657.0	5.8
ren-46.1	723.6	4.3	rejected	n/a	4	755	48
ren-21.1	723.4	4.6	rejected	n/a	6	769	42
ren-25.1	843.2	4.6	rejected	n/a	-4	815	40
ren-23.1	848.7	5.2	892	74	5	892	74
ren-20.1	927.0	6.4	953	90	3	953	90
ren-8.1	1076.0	10.4	977	40	-10	977	40
ren-45.1	969.8	8.0	982	19	1	982	19
ren-11.1	1052.9	6.8	1006	14	-5	1006	14
ren-55.1	988.5	6.3	1010	80	2	1010	80
ren-17.1	1020.9	7.0	1019	43	0	1019	43
ren-43.1	1091.9	6.9	1036	11	-5	1036	11
ren-29.1	1005.9	6.0	1037	47	3	1037	47
ren-50.1	1082.6	13.5	1041	39	-4	1041	39
ren-19.1	1150.7	7.6	1049	87	-10	1049	87
ren-14.1	1115.3	8.3	rejected	n/a	-4	1073	16
ren-15.1	1070.3	8.3	rejected	n/a	1	1085	24
ren-26.1	1142.5	9.8	rejected	n/a	-3	1107	23
ren-34.1	1094.9	6.8	rejected	n/a	4	1136	18
ren-35.1	1142.3	7.9	rejected	n/a	0	1138	29
ren-7.1	1137.2	24.3	rejected	n/a	1	1143	219
ren-57.1	1055.1	7.2	rejected	n/a	9	1157	13
ren-37.1	1174.9	8.8	rejected	n/a	-1	1162	16
ren-9.1	1178.5	11.0	rejected	n/a	-1	1169	22
ren-58.1	1141.6	7.2	rejected	n/a	4	1187	22
renr-53.1	1104.3	7.2	rejected	n/a	8	1205	109
ren-12.1	1158.9	20.0	rejected	n/a	7	1244	46
ren-28.1	1675.7	20.8	rejected	n/a	2	1719	20

The following age groups are recognized in the Renosterkop population:

- 251.6 ± 6.9 Ma (Dwyka sedimentation, Veevers *et al.,* 1994b; Bangert *et al.,* 1999; volcanism in northern Patagonia, Kay *et al.,* 1989);
- 395.1 ± 3.0 Ma (granites of Argentina and Patagonia; Pankhurst *et al.,* 2001, 2003; Kay *et al.*, 1989)
- 502.3 ± 6.5–657.0 ± 5.8 Ma (Cape Granite and Kuboos Pluton ages; Eglington, 2006)
- 755.0 ± 48 – 892.0 ± 74 Ma (Richtersveld Suite; Hartzer *et al.*, 1998)
- 953.0 ± 90 – 1244.0 ± 46.0 Ma (Namaqua-Natal Metamorphism; Thomas *et al.*, 1994; Eglington and Armstrong, 2004);
- 1719.0 ± 20 Ma (Vioolsdrif Suite; Reid *et al.*, 1987b).

The youngest age recorded from the Renosterkop zircon population, 251.6 ± 6.9 Ma, apparently coincides with the deposition of the Beaufort Group (Table 2.1 and references therein). However, Nguema-Mve (2005) found that the bulk of the zircons that he recovered from Ecca sediments near Laingsburg were derived from the Choiyoi volcanism in the adjacent northern Patagonia prior to Gondwana break-up. He suggested that the absence of zircons younger than 253 Ma in his sample population was due to the fact that the Cape Fold Belt developed during the 258 Ma tectonic event to the extent that it prevented further supply of sediments into the Tanqua and Laingsburg subbasins, with the ±253 Ma zircon representing the end of the Ecca Group sedimentation. The Choiyoi volcanism prevailed between 290 and 210 Ma (Kay *et al,* 1989) and in the absence of any other known possible origin for the ± 251 Ma zircon in this sample, the Choiyoi volcanics must be considered as the most likely provenance. If this juvenile zircon entered the sediment load of the Miocene Orange River after liberation from exhumed lower Karoo rocks, it would imply that:

1. The end of Ecca sedimentation was indeed even younger than 253 Ma, namely ± 251 Ma BP, or this zircon was derived from exhumed Beaufort sediments (Duane *et al.* (1989).

2. The Orange River drainage network was still transporting erosion products of the Ecca/Beaufort Groups during the Middle Miocene. These could have been derived from Ecca/Beaufort exposures in valley flanks, or tributaries like the Brak River had not completed incision through the lower Karoo sediments by that time. Ecca Group outcrops in southern Namibia are located too far downstream from Renosterkop to be considered as possible contributors to this sample locality.

Further evidence for a contribution from the Ecca Group to the Renosterkop population, is found in the presence of two samples, dated at 395.1 ± 3 Ma and 475.6 ± 4 Ma respectively, which cannot be correlated with any known igneous event in southern Africa. They do however correspond to granites of Argentina and Patagonia (Kay *et al.,* 1989), indicating the Ecca Group as an intermediate source for these grains.

Another group of samples ranging from 502.3 ± 6.5 Ma to 593.9 ± 5.7 Ma corresponds to the age of the Cape Granite Suite (Eglington, 2006). However, a study of the geographic location of outcrops with this age (the Western Cape and the Richtersveld) in relation to that of Renosterkop shows that direct derivation from any of these outcrops is highly unlikely. These zircons most probably were also sourced from Ecca Group rocks in the southern Cape.

Other age groups identified in this sample population and which do not correlate with any known outcrops upstream from Renosterkop, are:

- 657.0 ± 5.8 Ma – 612.4 ± 3.9 Ma as well as 769 ± 42 Ma — 755 ± 48 Ma ; these ages are reminiscent of that of the Malmesbury Group, but the various successions of the Saldania Belt have only been dated by indirect methods (Gresse *et al.,* 2006) due to the paucity of zircon grains;
- 892 ± 74 Ma – 815 ± 40 Ma corresponding to the intrusion of the Richtersveld Suite. These outcrops are however located about 350

kilometres downstream from Renosterkop, implying a different source region. It is suggested that the above two groups of zircons originated in Neoproterozoic times (Vaughan and Pankhurst, 2008), and were recycled through the Dwyka and Ecca before reaching Renosterkop.

- The Namaqua-Natal igneous and metamorphic province is represented in a group of Renosterkop zircons that spans the period 1244 ±46 Ma – 953 ± 90 Ma. The proximal Keimoes Suite intruding the eastern part of the Kakamas Terrane (Cornell *et al.*, 2006), is favourably located as provenance for these.

- The oldest zircon found in the Renosterkop sample, 1719 ± 20 Ma, corresponds to the intrusion age of the Vioolsdrif Suite (1758 ± 64 Ma, Hartzer *et al.*, 1998), but these outcrops are located about 350 km *downstream* from Renosterkop. Moen (1999) put the end of Kheis Orogeny at ~1880 Ma. In the light of drainage and geomorphology it is therefore suggested that this zircon grain was derived from Kheis rocks upstream from Renosterkop.

8.4.5.8 Laingsburg

Zircons extracted from available drill core from the Ecca Group turbidite fans (Tanqua Karoo and Laingsburg) were analyzed by this author together with the zircons obtained from the gravel samples of this study. The Ecca zircons in general are more euhedral and show less abrasion of crystal edges than those recovered from the Lower Orange River gravel samples. This is not surprising, when the depositional environment of the Laingsburg turbidites is compared to the high-energy, highly abrasive nature of the Orange River gravel deposits as implied by the size, composition and physical appearance of the Orange River sedimentary clasts.

The Ecca Group in the southwestern Karoo basin comprises an approximately 1300 metre thick succession of siliciclastic sediments. It rests on the glaciogenic Dwyka Group, and is in turn overlain by the fluvial Beaufort Group. In this region the Ecca Basin is subdivided into two sub-basins, each with a separate sedimentary sequence. These are referred to as the Tanqua and Laingsburg Subbasins respectively. Both comprise a lower, fan complex overlain by deltaic deposits.

The fan complex of the Tanqua sub-basin consists of five predominantly arenaceous fan systems, numbered from 1 to 5 from the base up, and separated by shale units.

The Laingsburg sub-basin comprises the lower, Laingsburg Fan Complex (Vischkuil and Laingsburg Formations), overlain by the deltaic deposits of the Fort Brown and Waterford Formations. The Laingsburg Formation comprises six arenaceous fan systems, termed A – F from the base up.
(Wickens, 1994).

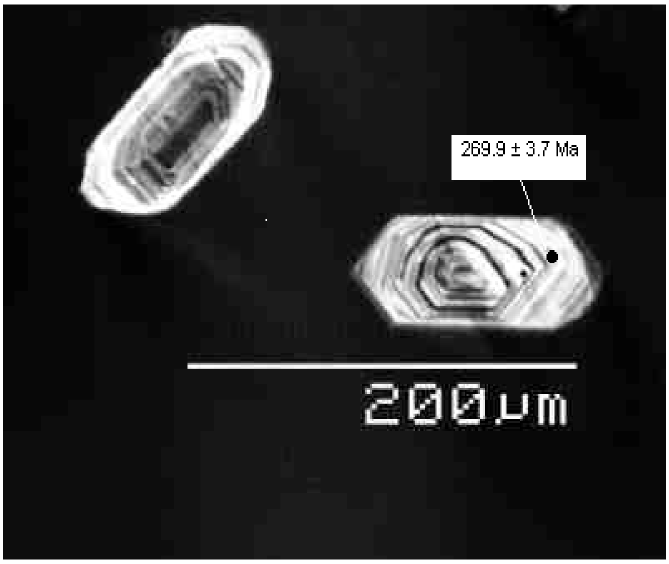


Figure 8.100 CL Image of zircons with sampling spot indicated, sample 63 – Tanqua Fans 3, 4 and 5.

TABLE 8.20 ZIRCON ANALYSES, TANQUA FANS 3, 4 AND 5

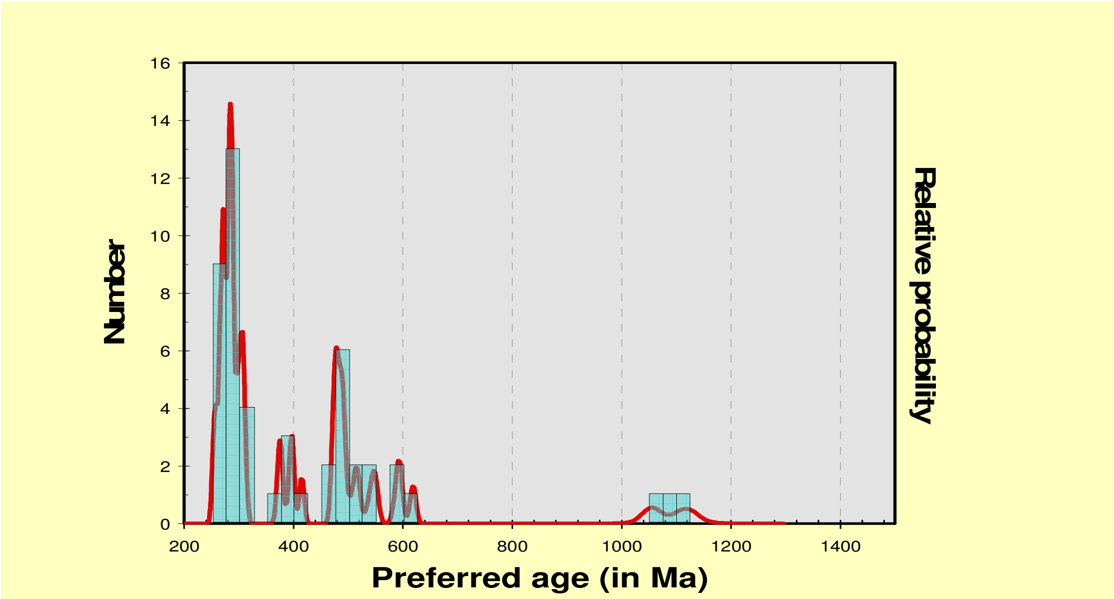
Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	*1σ err*
63-36.1	253.0	3.2	294	77	16	253.0	3.2
63-13.1	257.5	2.6	277	80	8	257.5	2.6
63-50.1	263.1	3.7	342	58	30	263.1	3.7
63-11.1	264.9	2.5	293	20	11	264.9	2.5
63-34.1	269.4	3.6	316	75	17	269.4	3.6
63-5.1	269.9	3.7	255	113	-6	269.9	3.7
63-24.1	271.6	2.9	256	33	-6	271.6	2.9
63-8.1	272.2	3.1	278	55	2	272.2	3.1
63-40.1	272.9	3.3	275	57	1	272.9	3.3
63-22.1	279.2	3.6	265	74	-5	279.2	3.6
63-26.1	280.7	3.4	315	51	12	280.7	3.4
63-43.1	280.9	4.4	277	87	-2	280.9	4.4
63-42.1	282.0	3.3	280	85	-1	282.0	3.3
63-47.1	283.9	3.8	349	94	23	283.9	3.8
63-38.1	285.2	4.5	323	85	13	285.2	4.5
63-51.1	285.2	3.6	260	139	-9	285.2	3.6
63-39.1	286.7	3.6	301	62	5	286.7	3.6
63-45.1	286.9	2.8	292	43	2	286.9	2.8
63-33.1	288.6	3.3	290	49	1	288.6	3.3
63-48.1	293.4	3.7	300	82	2	293.4	3.7
63-19.1	297.0	4.4	301	131	2	297.0	4.4
63-41.1	299.5	3.3	290	55	-3	299.5	3.3
63-4.1	304.2	3.6	305	67	0	304.2	3.6
63-35.1	306.6	3.6	328	51	7	306.6	3.6
63-17.1	307.9	4.8	410	204	33	307.9	4.8
63-46.1	309.8	4.4	321	94	4	309.8	4.4
63-27.1	374.2	5.2	389	82	4	374.2	5.2
63-2.1	376.3	4.5	346	69	-8	376.3	4.5
63-49.1	394.4	4.6	393	79	0	394.4	4.6
63-15.1	397.8	4.1	417	33	5	397.8	4.1
63-1.1	415.0	4.5	439	47	6	415.0	4.5
63-25.1	473.7	4.6	474	23	0	473.7	4.6
63-37.1	474.2	5.2	477	31	1	474.2	5.2
63-21.1	479.4	5.9	473	40	-1	479.4	5.9
63-20.1	479.7	4.6	480	35	0	479.7	4.6
63-28.1	481.3	6.7	494	87	3	481.3	6.7
63-29.1	488.3	5.3	563	45	15	488.3	5.3
63-18.1	489.0	5.4	471	32	-4	489.0	5.4
63-9.1	491.7	4.9	521	28	6	491.7	4.9
63-13.2	508.8	7.6	550	62	8	508.8	7.6

63-12.1	516.8	5.3	550	26	6	516.8	5.3
63-32.1	542.1	8.6	527	130	-3	542.1	8.6
63-23.1	548.7	6.2	560	32	2	548.7	6.2
63-10.1	589.2	6.5	592	57	1	589.2	6.5
63-7.1	594.7	5.4	669	14	12	594.7	5.4
63-16.1	618.6	5.5	593	24	-4	618.6	5.5
63-14.1	1037.8	9.8	1054	16	2	1054	16
63-3.1	985.2	16.8	1093	44	11	1093	44
63-6.1	*1102.2*	*11.4*	*1119*	*19*	*2*	*1119*	*19*

The following age groups are recognized in this population:

- 309.8 ± 4.4 – 253.0 ± 3.2 Ma (Choiyoi volcanism, Argentina: Kay *et al.*, 1989)
- 415.0 ± 4.5 – 374.2 ± 5.2 Ma (Granites of Argentina and Patagonia, Pankhurst *et al.*, 2001, 2003)
- 491.7 ± 4.9 – 473.7 ± 4.6 Ma (Deseado Massif, southern Patagonia: Pankhurst *et al.*, 2003)
- 589.2 ± 6.5 – 508.8 ± 7.6 Ma (Cape Granite Suite: Eglington, 2006)
- 618.6 ± 5.5 – 594.7 ± 5.4 Ma (Malmesbury and Gariep: Frimmel, 2000; Eglington 2006)
- 1119.0 ± 19 – 1054.0 ± 16 Ma (Namaqua-Natal Province: Hartzer *et al.* 1998, Eglington and Armstrong, 2004).

While zircons older than 500 Ma can be related to relatively proximal geological terranes in the western and southern Cape, those from the > 200 < 500 Ma period have no southern African analogues and can only be attributed to volcanic and granitic rocks currently located in Argentina and Patagonia.



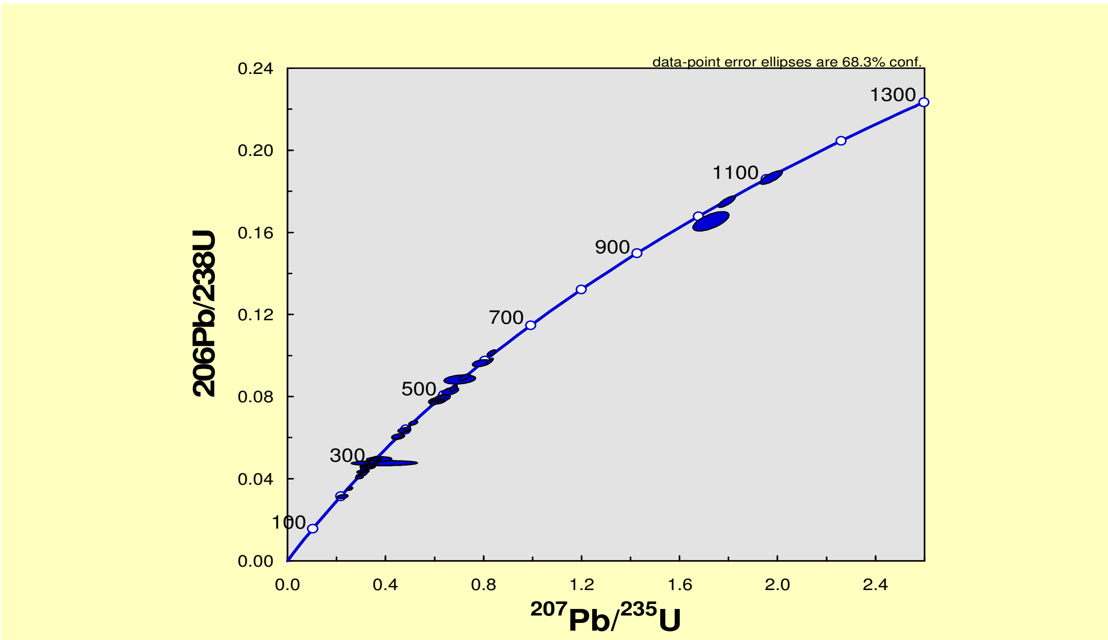


Figure 8.101 Histogram of preferred ages, and Concordia diagram, Tanqua Fans 3, 4 and 5 (sample number 63).

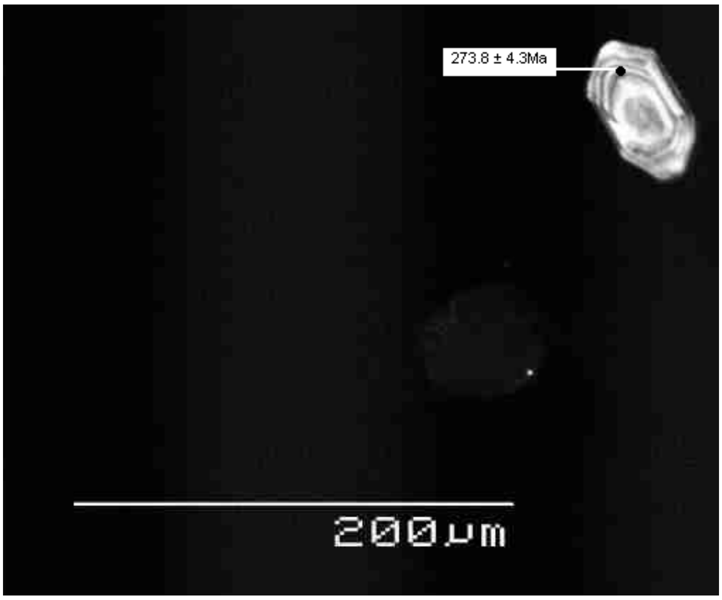


Figure 8.102 CL Image of zircon grain with sampling spot indicated, Fan F, Laingsburg.

TABLE 8.21 ZIRCON ANALYSES, FAN F, LAINGSBURG

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
64-1.1	518.3	5.4	551.0	36	6	518.3	5.4
64- 2.1	263.3	3.0	452.0	140	42	263.3	3.0
64-3.1	1356.0	13.0	1331.0	39	-2	1356.0	13.0
64- 4.1	273.8	4.3	452.0	400	39	273.8	4.3

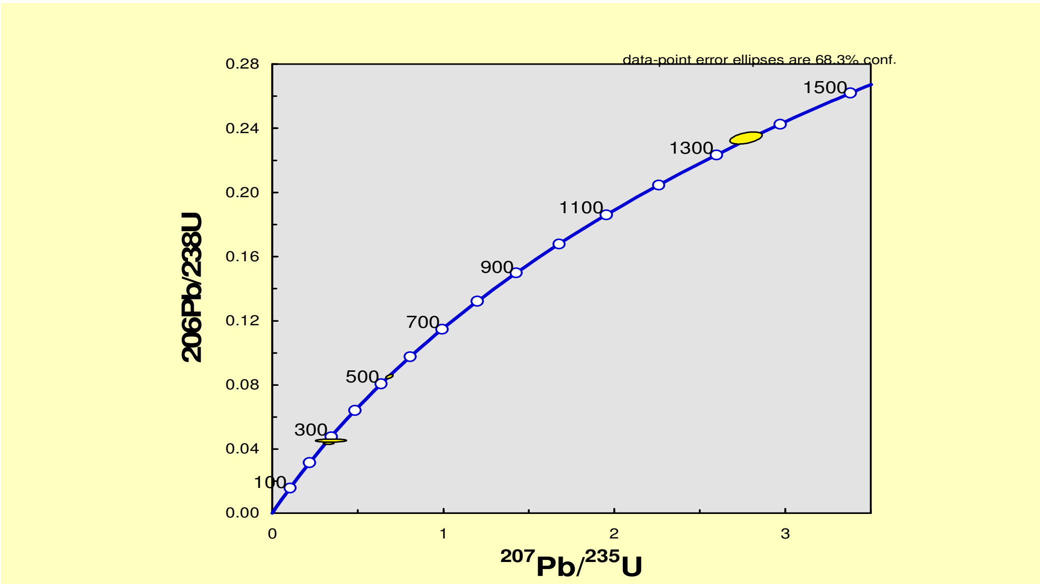


Figure 8.103 Concordia diagram, zircons from Fan F, Laingsburg (sample 64).

The number of zircons extracted from this sample is very small, but their ages reflect a similar provenance history to that of Tanqua Fans 3, 4 and 5 discussed in the previous section, namely derivation from South American sources, the Cape Granite Suite and the Namaqua-Natal Province.

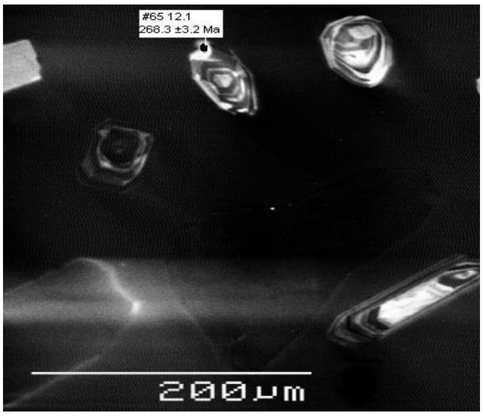
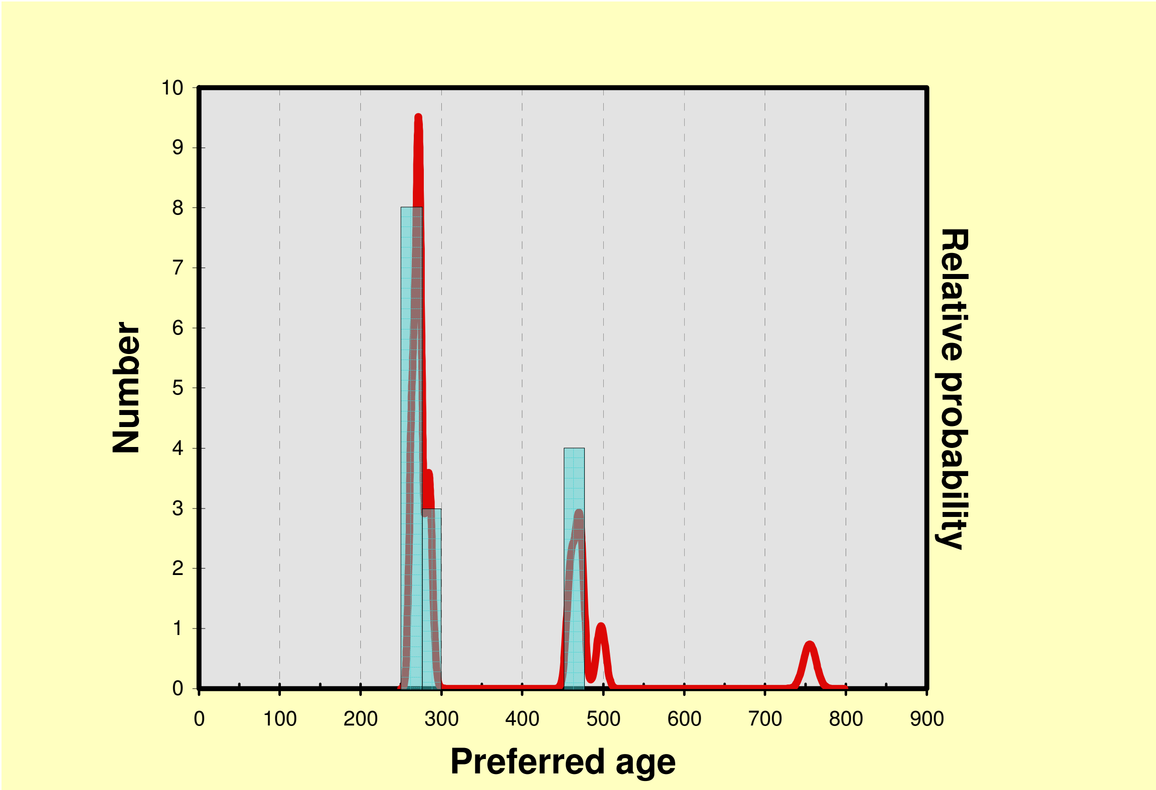


Figure 8.104 CL Image of zircon grains with sampling spot indicated, Slope Sandstone.

TABLE 8.22 ZIRCON ANALYSES FROM THE SLOPE SANDSTONE, TANQUA

Spot Name	204 corr $^{206}Pb/^{238}U$	1σ err	204 corr $^{207}Pb/^{206}Pb$	1σ err	% Discordant	Preferred Age	1σ err
65-2.1	262.7	3.1	266	71	1	262.7	3.1
65-19.1	263.0	3.4	313	75	16	263.0	3.4
65-12.1	268.3	3.2	268	169	0	268.3	3.2
65-16.1	268.4	3.9	395	147	32	268.4	3.9
65-15.1	270.4	2.9	276	41	2	270.4	2.9
65-7.1	272.0	3.2	295	87	8	272.0	3.2
65-18.1	273.4	2.9	315	30	13	273.4	2.9
65-13.1	273.4	2.9	182	91	-51	273.4	2.9
65-9.1	281.6	6.4	563	786	50	281.6	6.4
65-11.1	282.2	3.4	358	67	21	282.2	3.4
65-10.1	286.8	3.5	441	134	35	286.8	3.5
65-4.1	459.3	4.7	493	111	7	459.3	4.7
65-3.1	463.3	6.0	458	56	-1	463.3	6.0
65-14.1	471.3	5.1	440	42	-7	471.3	5.1
65-6.1	471.5	4.6	445	30	-6	471.5	4.6
65-8.1	497.4	5.6	579	87	14	497.4	5.6
65-1.1	755.5	8.0	778	80	3	755.5	8.0



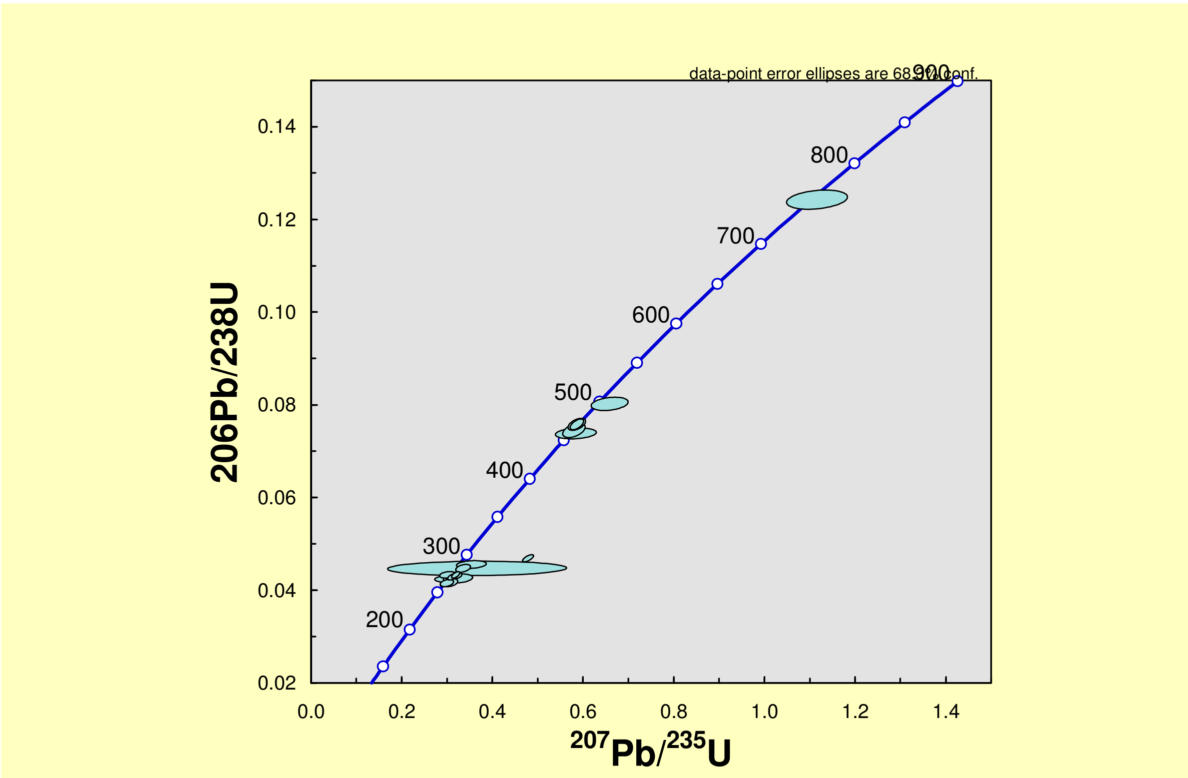


Figure 8.105 Histogram of preferred ages, and Concordia diagram for detrital zircons from The Slope Sandstone, Tanqua Fan Complex (sample # 65).

Only three distinct age groups are recognized in this population. These can be summarized as follows:

- 286.8 ± 3.5 – 262.7 ± 3.1 Ma (Choiyoi volcanics, Argentina: Kay *et al.*, 1989)
- 471.5 ±4.6 – 459.3 ± 4.7 Ma (Deseado Massif, southern Patagonia: Pankhurst *et al.*, 2003, Stuart-Smith *et al.,* 1999)
- 755.5 ± 8.0 Ma (Pan African origin, recycled *via* Dwyka?)

The age groups recognized in this population show a more restricted range than those observed in the other Ecca samples from the Laingsburg region. This is the only sample from this area where no >755.5 ± 8.0 Ma ages feature.

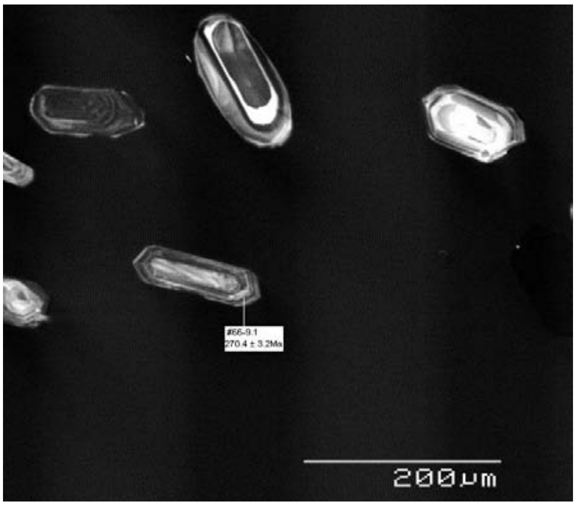
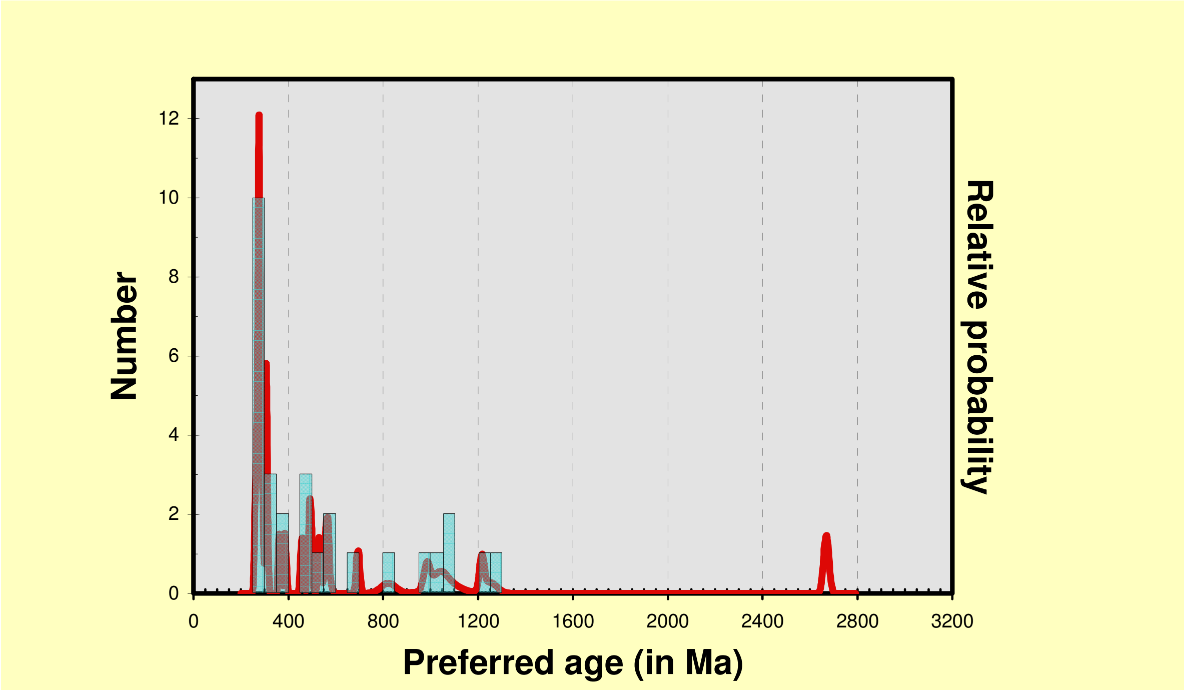


Figure 8.106 CL Image of zircon grains; sampling spot indicated, Fan A, Laingsburg.

TABLE 8.23 ZIRCON ANALYSES FROM FAN A, LAINGSBURG

Spot Name	204corr 206Pb /238U Age	1σ err	204corr 207Pb/206Pb Age	1σ err	% Discordant	Preferred Age	1σ err
66-27.1	260.3	3.3	274	190	5	260.3	3.3
66-21.1	270.3	3.1	340	68	20	270.3	3.1
66-9.1	270.4	3.5	467	265	42	270.4	3.5
66-14.1	276.8	3.2	238	73	-16	276.8	3.2
66-17.1	277.3	3.0	264	37	-5	277.3	3.0
66-3.1	278.0	3.6	340	99	18	278.0	3.6
66-7.1	278.6	3.8	283	132	2	278.6	3.8
66-10.1	279.2	2.9	282	82	1	279.2	2.9
66-12.1	284.3	3.3	275	75	-3	284.3	3.3
66-25.1	291.2	3.1	285	47	-2	291.2	3.1
66-36.1	306.6	4.3	315	205	3	306.6	4.3
66-35.1	307.8	3.9	270	150	-14	307.8	3.9
66-23.1	309.3	3.8	421	215	27	309.3	3.8
66-16.1	363.9	4.2	391	303	7	363.9	4.2
66-20.1	386.2	4.7	440	539	12	386.2	4.7
66-1.1	457.7	5.5	472	94	3	457.7	5.5
66-18.1	488.4	5.2	523	35	7	488.4	5.2
66-29.1	496.1	4.9	495	27	0	496.1	4.9
66-19.1	531.2	5.5	547	23	3	531.2	5.5
66-5.1	563.7	12.0	597	60	6	563.7	12.0
66-15.1	563.7	5.5	546	27	-3	563.7	5.5
66-8.1	694.1	7.1	694	18	0	694.1	7.1
66-34.1	833.5	9.0	822	32	-1	822	32
66-30.1	932.8	8.6	985	13	5	985	13
66-32.1	1016.4	11.6	1039	29	2	1039	29
66-24.1	1045.6	12.9	1058	63	1	1058	63
66-31.1	1101.3	11.0	1061	53	-4	1061	53
66-13.1	1160.8	10.6	1216	10	5	1216	10
66-6.1	1305.6	14.8	1250	30	-4	1250	30
66-2.2	2413.4	24.0	2667	11	9	2667	11
66-2.1	2455.6	21.0	2671	11	8	2671	11



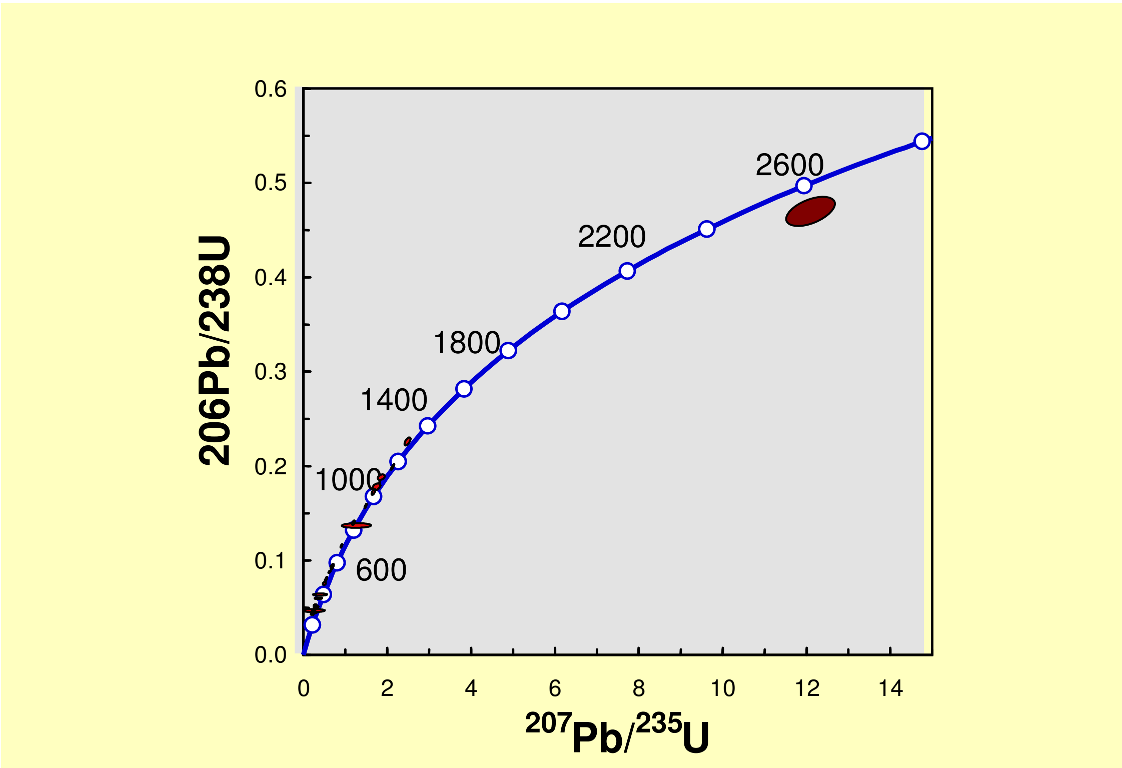


Figure 8.107 Histogram of preferred ages, and Concordia diagram - Fan A, Laingsburg (sample #66).

As illustrated in Table 8.23 and Figure 8.107, this sample population has the widest age distribution of all the Ecca zircon groups used in this study. In summary it shows the following:

- 309.3 ± 3.8 – 260.3 ± 3.3 Ma (Choiyoi volcanism, Argentina: Kay *et al.*, 1989).
- 386.2 ± 4.7 – 363.9 ± 4.2 Ma (granites of Argentina and Patagonia: Pankhurst *et al.*, 2001, 2003).
- 496.1 ± – 457.7 ± 5.5 Ma (Deseado Massif, southern Patagonia: Pankhurst *et al.*, 2003, Stuart-Smith *et al.*, 1999).
- 563.7 ± 5.5 – 531.2 ± 5.5 Ma (Cape Granite Suite: Eglington, 2006).
- 694.1 ± 7.1 Ma (Corresponding to the indicated ages of the Malmesbury and Klipheuwel Groups, Saldania Belt. However, zircons could not yet be extracted from these rocks for the purposes of geochronology, making them unlikely sources for the zircons studied).
- 822.0 ± 32 Ma (Richtersveld Suite, but geographic location of Richtersveld Suite outcrops rule them out as possible sources for these zircons).
- 1250.0 ± 30 – 985.0 ± 13 Ma (Namaqua-Natal; Hartzer *et al.*, 1998).
- 2671.0 ± 11 – 2667.0 ± 11 Ma (Klipriviersberg Group, Ventersdorp Supergroup: Walraven *et al.,* 1990).

It is concluded that the 694.1 ± 7.1 – 822.0 ± 32 Ma zircons originated during the Neoproterozoic and were recycled through the Dwyka glacial rocks before incorporation into Ecca Group sediments.

8.5 A brief history of placer and other diamond discoveries in southern Africa

Early in 1867: The fifteen year-old Erasmus Jacobs picked up a 21.75ct diamond on a terrace bordering the Orange River on the farm De Kalk about 15 km upstream from the confluence of the Vaal and Orange Rivers (Coetzee, 1976).

1869: A Griqua herdsman found an 82.5 carat gem which was later named "The Star of South Africa" (Coetzee, 1976).

These finds resulted in the country's first "mineral boom", with alluvial diamond diggings springing up along the valleys of both the Orange and Vaal Rivers.

1870: Discovery of the diamondiferous kimberlite on the farm Jagers Fontein 14 (in the then Orange Free State Republic) by a farmer named De Klerk. This discovery was soon followed by those known today as Du Toitspan, Bultfontein, De Beers, Kimberley, Koffiefontein, Wesselton and Premier in that order (Coetzee, 1976).

1887: H.C. Lewis (Lewis, 1887) reported the results of his petrological studies on this "new" volcanic rock, and proposed the term "kimberlite", most probably after the town of Kimberley (Coetzee, 1976).

At the end of the 19th Century: A single detrital diamond found near the village of Berseba in southern Namibia led to the discovery of a kimberlite province (the Gibeon-Berseba cluster) which was explored under supervision of Georg Hartmann for the "Gibeon Schürf- und Handelsgesellschaft" between 1906 and 1910 (Gevers, 1953). Further discoveries brought the total number of kimberlites in the Gibeon-Berseba cluster to about 60, but not a single diamond was found (Stocken, 1976).

1903: Somabula alluvial diamond field in Zimbabwe discovered (Webster, 1975).

1905 – 1906: The first discovery of marine coastal diamonds in Namibia on the British owned guano islands along the coast, but permission to further explore these was not granted (Von Bezing *et al*, 2007).

1908: Zacharias Lewala, one of August Stauch's team constructing the railway line to Lüderitz, recognized diamonds in aeolian surface deposits at Kolmanskop near Lüderitz in southern Namibia. Maree (1966) and Wagner (1914) put this date as April 1908, while Merensky (1909) puts it as February 1908. Government geologist Paul Range verified the identification of the first diamonds found at Kolmanskuppe (Von Bezing *et al.* op cit).

January 1909: Fabulously rich deposits at Pomona discovered by Robert Scharbe and August Stauch (Von Bezing *et al.,* op cit).

1909: E. Martin discovered seven small diamonds near Buchuberg south of the Orange River but did not follow up on this find (Wagner and Merensky, 1928).

1910: The diamondiferous nature of the marine sediments on the west coast islands Possession, Halifax, Penguin and Pomona was confirmed by a South African Government expedition (Maree, 1966).

1910: A clear yellowish rhombic dodecahedron weighing 3.75 carats found south of the mouth of the Little Omaruru River, marks the first recorded diamond find along the Skeleton Coast of Namibia (Voit, 1910; Reuning, 1931). Reuning (*op cit.*) also reported on a clear rhombo-dodecahedron of 0.25 carats which he found in the 15 metre terrace between the mouth of the Hoarusib River and Guano Cape, but did not mention the date of this discovery.

Circa 1911: H. S. Harger examined what was called "high-lying diamondiferous river terrace relics" in the Lichtenburg district of the North-West Province. Due to peculiar legal problems and opposition to his research by major land-owning companies, his work was obstructed, but he nevertheless wrote (Harger, 1913; Reuning, 1931) "But the presence of such diamondiferous gravels over a restricted portion of the Transvaal convinces me, after extended investigations that enormous wealth, in the form of rich diamond mines, awaits discovery and exploitation in the Western Transvaal". This prognosis proved to be correct with the discovery of the rich deposits near Bakerville in the Lichtenburg district during 1925 and subsequent discoveries in the districts of Ventersdorp, Schweizer-Reneke, Wolmaransstad, Bloemhof, Christiana, Warrenton, Windsorton and Barkly West.

August 1925: Jack Carstens found a diamond at Oubeep 10 km south of Port Nolloth (Hallam, 1959).

The year 1926 saw a number of discoveries along the Namaqualand coast:

- A building contractor, Alberts, discovered diamonds near the mouth of the Buffels River, the site of the present Kleinzee Diamond Mine;
- Rabinowitz at Buchuberg;
- Kennedy, Misdall and White at The Cliffs, 19km north of Port Nolloth;
- Scholtz, Gordon and De Villiers on the right bank of the Buffels River (Hallam, 1959).

This led to the discovery of more diamond occurrences in the area, including lucrative mines (some only discovered about 40 years later) along the Buffels River valley all the way from the foot of the escarpment down to the coast (Van der Westhuizen, 1997 and references therein, Figure 1.3).

February 1927: Extremely rich diamond deposits discovered in marine beach terraces as well as fluvial terraces near the mouth of the Orange River (Reuning, 1928). During 1927 the Government of the Union of South Africa proclaimed a State Alluvial Diggings at Alexander Bay and suspended prospecting for precious stones on the rest of the State owned land in Namaqualand (Hallam, 1959).

Figure 1.108: Drs. Merensky and Wagner examining a prospecting trench in the Alexander Bay diamond field (Mining and Industrial Magazine, 30/11/1927)

1928: Werner Beetz identified diamondiferous beach sequences north of the Orange River estuary. This changed the focus of secondary diamond mining on the west coast of southern Africa to the extent that Consolidated Diamond Mines of South West Africa (CDM) moved its entire operation from Kolmanskop to Oranjemund in 1941 (Hallam, 1959; Corbett, 1996).

1938: The Upper (Gemsbok) Terraces at Oranjemund discovered (Hallam, 1959).

1944 to 1952 : Kaokoveld Exploration (a consortium comprising De Beers and the South West Africa Company) found diamonds of gem quality in raised beach deposits both north and south of the main rivers entering the Atlantic Ocean along the Skeleton Coast from the Ugab in the south to the Kunene River in the north. This led to small scale mining by De Beers Consolidated Mines Ltd. at the Hoanib River in 1957, and at the Huab River in 1958 (Hallam, 1959, 1964; Baxter-Brown, 1979).

*1959***:** Sammy Collins and his team recovered the first offshore marine diamonds (after the 1910 expedition to the West Coast islands mentioned above) from the "Emerson K", a converted Royal Navy salvage tug, at Wolf Bay (Corbett, 1996). Offshore production by the Marine Diamond Corporation established by Collins commenced in 1962 and the company was bought by De Beers shortly afterwards. Today De Beers Marine is a world leader in deep-water diamond mining, contributing substantially to the diamond production of south-western Africa (Corbett, 1996).

Shortly after the discovery of the coastal diamond deposits, their possible source became a contentious issue among some of the geologists involved. One of the main theories (Lotz, 1909; Cornell, 1920; Reuning, 1931) identified the Orange River as a likely conduit for the transportation of diamonds from the hinterland of southern Africa to the Atlantic. Numerous unsuccessful prospecting attempts to search for diamondiferous erosion remnants of earlier deposits along the Lower Orange River valley followed, amongst others by Reuning himself at Swartpoort shortly before the Government banned all prospecting for precious stones on State Land in Namaqualand in 1927.

*1963***:**

- Asam Minerals (R. Baxter-Brown and H. Jenner-Clarke) discovered diamonds in a basal marine conglomerate of the "Table Mountain Series", northeast of Van Rhynsdorp (Baxter-Brown, 1963b).

- The ban on the prospecting for precious stones on State Land in Namaqualand was lifted and applications for diamond prospecting over a number of State-owned properties were invited.

12 October 1966: The first economic diamond discovery along the Lower Orange River valley by R. Baxter-Brown for Nababeep Mineral Exploration Company, in Miocene sediments at Sendelingsdrift. Baxter-Brown named the mine that soon developed here "Reuning Mine' in honour of the man whose insight eventually led to this discovery (Van der Westhuizen, 1997). Similar occurrences were subsequently found both down- and upstream from Reuning.

1967: Orapa diamondiferous kimberlite (for many years the largest open cast diamond mine world wide) in Botswana discovered (www.wikimapia.org).

1968:

- The first recorded economic diamond discovery in Miocene sediments along the right bank of the Lower Orange River made at Lorelei by geologists R. Baxter-Brown and H. Jenner-Clarke (Jacob *et al.,* 1999);
- The Lethlekane diamondiferous kimberlites in Botswana discovered (www.debswana.com).

1966-1968: H. Jenner-Clarke, on behalf of Allied Minerals, proved the diamondiferous nature of the Xheis terraces (Miocene sediments) south of the village of Sanddrif along the left bank of the Orange River, and discovered the Koeskop-Swartwater palaeo-channel about 5km further downstream. Trans Hex Group Ltd, through its operating subsidiary Buffelsbank Diamante Bpk bought the company Baken Diamante from Allied Minerals and started its own exploration program on 1 April 1972. Initially bulk sampling was restricted to the Xheis area with only limited work carried out in the Koeskop-Swartwater ox-bow. After a prolonged interruption in activities, full scale mining operations resumed during 1981 in the Koeskop-Swartwater areas and has continued unabated (Van der Westhuizen, 1997).

1973: The Jwaneng diamondiferous kimberlite in Botswana discovered (www.Debswana.com).

1974: Discovery of the Ehlane fluvio-sedimentary diamond deposits in Upper Karoo sandstone and grit, NE Swaziland, and shortly afterwards the diamondiferous Dokolwayo kimberlite cluster 30 km toe the NNW (Hawthorne *et al.,* 1979).

1979: The Venetia diamondiferous kimberlite cluster (Limpopo Province) discovered.

2001: Discovery of the Chiadzwa alluvial diamond field in the upper reaches of the Makodzi River, south-eastern Zimbabwe.

2005: Discovery of the Marange alluvial diamond field, downstream from Chiadzwa (AIM listing of African Consolidated Resources plc, June 2006).

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