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**GEOLOGY, REGIONAL DIAMOND EXPLORATION  
AND DIAMOND PROVENANCE OF THE  
PROTEROZOIC DIAMONDIFEROUS UMKONDO  
CONGLOMERATES, UMKONDO GROUP, EASTERN  
ZIMBABWE**

BY

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**Declaration:**

I, Takawira Zhou declare this dissertation to be my own work. It is submitted in fulfillment of the Degree of Master of Science at the University of Rhodes. It has not been submitted before for any degree or examination in any other University or tertiary institution.

Signature of the candidate: .....

Date.....

**Dedicated to:**

Wife Susan, daughter Tanatswa, and son Kudzai who spent days without me during my study time at Rhodes University.

## **Abstract**

The Umkondo Sedimentary Basin in eastern Zimbabwe has been studied by various individuals and organizations since 1901. Their interest had been in finding limestone and beryl and base metal deposits, especially copper, iron and uranium, but these occurrences had proved to be of no economic value (Watson, 1969). The recent discovery of placer diamonds within the Proterozoic basal conglomerates of the Umkondo Sedimentary Basin has now attracted worldwide interest in the basin's diamond economic potential, in understanding of the geology, and the diamond provenance of the Umkondo conglomerates. The Umkondo Sedimentary Basin basal conglomerate placer deposit might narrowly be defined as a mega-placer because of its sheer large size and high grades, especially on the 70,000 hectare western margin diamond dispersion halo where alluvial diamonds are being mined.

Bluck, et al., (2005, pp 213) defines a diamond mega-placer as:

... a number of linked deposits that are a result of one or a continuous process of transportation and deposition and holds or have held at least  $\geq 50$  million carats at  $\geq 95\%$  gem quality, for example, the Orange-Vaal dispersal, off the Kaapvaal craton in South Africa. On craton placers are residual, and transient placers are eroded and deposited into the exit drainage, while terminal placers, the final depositories of diamonds with the highest chances of being mega-placers are deposited into terminal basins like oceans and foreland basins.

Though data is limited at the moment, the Umkondo conglomerates caratage is likely to run into hundreds of millions of carats, with a diamond gem content of between twenty and twenty-five percent, as is indicated from recent diamond production data. The greater part of the Umkondo diamonds are likely to be lodged beneath the deep gravels of the Middle and Lower Save River basin, because small remnant tilted mountain blocks and inselbergs forming the caps of hills are what remains of the host conglomerate on the western margin of the Umkondo Basin.

Areas to be examined in this document will be the geology; the mode of formation of the Umkondo basin and its sedimentary system; the regional kimberlite exploration around the basin; and diamond production in the Marange diamond field, in order to come up with indications of the provenance of the diamonds within the Umkondo conglomerates. The

kimberlite clusters in and around the Umkondo sedimentary basin have all proved to be barren or only nominally diamondiferous and that the kimberlites are between 200Ma and 500Ma and thus much younger than the greater than 1.1Ga Umkondo diamondiferous conglomerates. Studies so far undertaken have not managed to point to the origin, or provenance, of the Umkondo or Marange diamonds, which were discovered on the western edge of the Umkondo Basin and in the east of the basin below the Chimanimani Mountains along the Haroni River. This paper is an attempt to clear up some of the misconceptions surrounding the Marange diamond deposit and to raise interest in the urgent requirement to study and understand the Umkondo Basin and the origin of its diamonds. The only meaningful studies on diamond occurrence and diamond exploration of the basin were undertaken from 1996 to 2006 by Kimberlitic Searches Zimbabwe (Pvt) Ltd, the then Zimbabwe kimberlite exploration arm of De Beers, Zimbabwe, in their quest to find kimberlites, which were thought to be related to the Umkondo alluvial diamond deposit. As will be shown in the following chapters, many of the discovered kimberlites range from very low grade to non-diamondiferous, and are much younger than the Umkondo conglomerates, whose diamonds are in turn a great deal older. Thus the basic question concerning the origin or provenance of the Umkondo placer diamonds still remains unresolved.

Because of the sheer size of the basin, modern, wide-area-coverage, geophysical exploration methods become appropriate to effectively generate diamond potential targets for further examination. This document will attempt to collate various data available to paint a true picture of the state of exploration within the Umkondo Basin.

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## **1.0 CHAPTER ONE**

### **REGIONAL DIAMOND EXPLORATION IN AND AROUND THE UMKONDO BASIN**

#### **1.1 Kimberlite exploration techniques**

The first and most critical steps in the selection of a regional kimberlite exploration area are based upon geotectonic controls and previous geochemical knowledge. The prediction of regions in which diamonds may have been formed, the selection of those areas where diamonds may have survived to be sampled by younger kimberlites, and the establishment of regional tectonic and local structural controls for the emplacement of kimberlites in an appropriate area (Helmstaedt, and Gurney, 1995) are critical factors in regional kimberlite exploration area selection. Muggeridge, (1995) states the other critical criteria in regional kimberlite exploration area selection as the presence of known kimberlites, lamproites or related intrusive bodies, diamond indicator minerals, or detrital diamonds in the area of interest.

In the following section, the exploration techniques for kimberlites are summarized.

##### **1.1.1 Geochemical soil sampling surveys**

The purpose of geochemical soil sampling surveys in kimberlite exploration is to test whether a drainage catchment contains characteristic kimberlite indicator minerals which when found in secondary environments can be traced back to source. The ability of diamonds and indicator minerals to travel considerable distances in active alluvial systems makes them the most important pathfinder minerals in diamond exploration. The heavy minerals are concentrated by fluvial action in suitable trap sites and, in more arid regions with little drainage, wind deflation produces a thin layer enriched in resistate heavy minerals. This layer provides the basis for loam sampling in which samples of top soil are skimmed, often on a regular grid pattern. The trap sites, such as potholes, bases of waterfalls, gravel-filled depressions, areas in the lee of rock bars, basal gravels, areas under tree roots, and boulder bars, crevices and joints cutting across the drainage, are chosen for their likely maximum natural concentration of heavy minerals including diamonds.

In humid, warm climates, the less chemically resistate minerals such as olivine and chrome diopside in kimberlites and lamproites are destroyed by near surface weathering, and their detection therefore usually indicates proximity to source (Muggeridge, 1995), whilst in hot, tropical conditions, even garnet may be destroyed in the laterite or weathering profile.

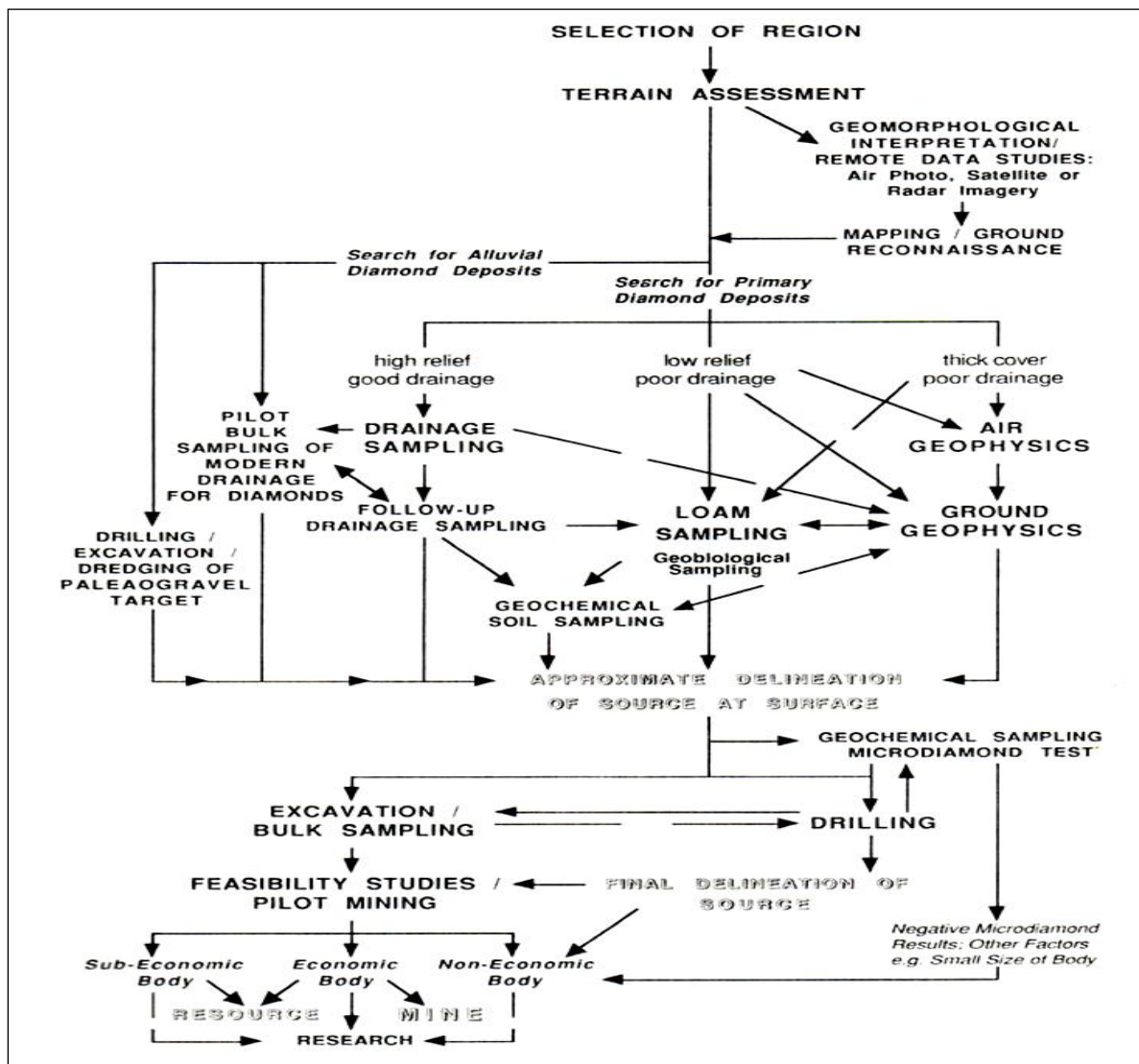


Fig. 1.1: Exploration flowchart for locating diamond deposits. From: Muggeridge, (1995).

Dispersion trains from pipes for the more resistate mineral species such as chromite are often of the order of several tens of kilometers along drainage lines in arid and semi-arid climates. Dispersal haloes in surface loams may be ill defined but extensive in the finer mesh size, and of the order of several hundred meters. In contrast, in cold climates there is little chemical

weathering, and minerals such as olivine can travel for up to 100 kilometers. Glaciated terrains provide a particular problem of widespread dispersion and dilution of indicator mineral concentrations. The diagram, Fig. 1.1, summarizes the indicator minerals sampling techniques for locating kimberlites and lamproites.

The indicator minerals include pyrope and eclogite garnets, chrome diopside, chrome and magnesian ilmenite, chrome spinel, kimberlitic zircon, andradite garnet, and microdiamonds with a specific gravity of  $>3.0\text{g/cm}^3$  (Muggeridge, 1995 citing Mitchell, and Bergman, 1991). The objective of the sampling programme is to discover indicator mineral anomalies. Typically, about 10 kilograms of minus 0.84 millimeter stream sediment grain sizes is collected within heavy mineral trap sites and deflation surfaces. The samples are then submitted to the laboratory for concentration of the heavy minerals using a combination of jigging, heavy liquids (tetrabromoethane, lithium tungsten or methyl iodide) and magnetic methods. The final produced concentrate is sorted under a binocular microscope and the indicator minerals removed and counted, and then submitted for microprobe and mineral chemistry analyses.

### **1.1.2 Geophysical surveys**

Magnetic and electromagnetic (conductivity) surveys have been the primary successful airborne and ground geophysical methods used in kimberlite exploration. Magnetic susceptibilities for kimberlites range from 10 to 10,000 cgs units  $\times 10^{-5}$  and for lamproites from 180 to 1,800 cgs units  $\times 10^{-5}$ . The magnetic susceptibility in kimberlites and lamproites is due to the presence of magnetite, ilmenite and ulvospinel in solid solution in their groundmass). The majority of kimberlites in Africa are characterized by weakly developed dipoles with a magnetic high in the north and a poorly developed low in the south (Daniels, 1991).

Generally, the kimberlite intrusions appear as circular magnetic lows with coincident conductivity anomalies on the airborne imagery. An understanding of the regional geology and structure is fundamental to interpretation of geophysical anomalies.

Ground geophysical methods are used to evaluate and discriminate airborne geophysical anomalies and to delineate kimberlite intrusions. Ground magnetic anomalies over kimberlite

pipes may appear as negative or positive features relative to the surrounding rocks. Other geophysical techniques that can be applied in kimberlite exploration include electromagnetic (EM), very low frequency (VLF), and gravity. EM surveys are effective in areas where kimberlites are strongly weathered and hence show up as strong conductors relative to the surrounding lithologies. EM–VLF surveys are effective in pinpointing structures related to kimberlite emplacement.

Gravity surveys rely on density contrasts between the kimberlite and other lithologies. The density of kimberlite and lamproite ranges from 1.8 to 2.8g/cm<sup>3</sup>, depending on the degree of oxidation and the rock texture. As pipe mineralogy is often extensively altered to clays, especially in upper near-surface levels, gravity anomalies are often negative, compared to less weathered country rocks. Geophysical techniques such as seismic and ground-probing radar can give depth to bedrock and therefore may identify the location of channel deposits in alluvial diamond exploration. The radar technique has been used to distinguish sand overburden from basal gravels.

### **1.1.3 Mineral geochemistry surveys**

Gurney, (1984) discusses an effective method for discriminating between diamondiferous and barren kimberlite source rock using mineral chemistry data. The method is based on the observation that garnet and chromite occur as inclusions in diamonds. The chemical compositions of these inclusions reveal characteristic fields, which include the subcalcic G10 pyrope garnets, magnesian ilmenite, spinel, diamond inclusion chrome, and high sodium eclogite garnet. The critical point in the application of mineral chemistry to diamond potential in kimberlite exploration is that the composition of heavy mineral indicators should be carefully compared to the compositions of indicator minerals from dispersion systems directly related to known barren, weakly- and strongly-diamondiferous kimberlites.

#### **1.1.3.1 Garnet**

Daniels, (1991), citing Gurney, and Switzer, (1973) and Sobolev et al., (1973), recognizes the close relationship between the composition of peridotitic garnets in diamondiferous kimberlite concentrates and peridotitic diamond inclusion garnets. Daniels, (1991), notes that these extensively used “subcalcic, chromium-enriched garnets (G10s) in diamond exploration

can be applied in predicting the presence of diamonds in kimberlites”. The technique is based on the assumption that the majority of the diamonds in a kimberlite are derived from the disaggregation of diamond-bearing xenoliths and, therefore, the higher the percentage of G10 garnets within the population of peridotitic garnets within a given kimberlite, the better the diamond potential of the kimberlite.

Also noted by Daniels is Sobolev, (1973)’s suggestion that “the sodium content of  $>0.06\text{wt}\%$  in mantle derived eclogite garnets is associated with diamondiferous kimberlites”. The  $\text{Na}_2\text{O}$  content of diamond inclusion eclogitic garnets from Southern Africa is greater than  $0.06\text{wt}\%$ , and, based on the same assumptions, the peridotitic G10 method is applied to determine the presence of diamonds in a kimberlite. The Newlands kimberlite, in South Africa, contains a significant proportion of garnets with elevated sodium contents, consistent with the presence of both diamondiferous eclogites and diamonds in the kimberlite.

Daniels, (1991) also agrees with Gurney, and Moore, (1993) that:

. . . kimberlites also contain garnet megacrysts which are not directly related to diamonds but show strong igneous trends that allow them to be differentiated from eclogitic garnets on the basis of simple linear plots.

It is assumed that the sodium content of megacryst garnets is related to the depth of crystallisation, and that the  $\text{Na}_2\text{O} > 0.06\text{wt}\%$  is consistent with the depth of origin in excess of 150 kilometers (45 kilobars), and therefore within the diamond stability field. Megacrysts with elevated sodium contents may be found in diamondiferous and off-craton barren kimberlites. Kimberlites originating from depths shallower than the diamond stability field are unlikely to have elevated sodium contents in the megacryst suite.

### **1.1.3.2 Ilmenite**

Daniels, (1991), citing Egger, (1983), and Haggerty, and Tompkins, (1983), notes that “the rare ilmenite inclusions in diamonds are used to calculate redox conditions of melts in the upper mantle, and therefore of the kimberlitic melt”. When transporting diamonds to the surface out of the diamond stability field, and the rate of transportation is slow or the redox evolution of the kimberlite melt is towards increased oxygen activity, the diamonds may be

converted to graphite or CO<sub>2</sub>. This resorption affects the grade of a kimberlite. A diamond being resorbed from an octahedron to a dodecahedron can lose approximately fifty percent of its original mass. Gurney, and Moore, (1991) note that “ilmenite compositions with elevated inferred Fe<sub>2</sub>O<sub>3</sub> contents are not associated with high grade kimberlites because an increase in Fe<sub>3+</sub>/Fe<sub>2+</sub> ratio is consistent with an increase in oxygen fugacity”. Kimberlitic ilmenites with high Fe<sub>3+</sub> are associated with low MgO. High Cr<sub>3+</sub> can be found with either high or low MgO, but is only a positive actor when it occurs with high MgO concentrations.

Ilmenites with low Cr<sub>2</sub>O<sub>3</sub> content and MgO <7% are indicative of conditions promoting resorption of diamonds. Ilmenites with compositions consistent with the preservation of diamonds may be found in off-craton kimberlites although no diamonds may be present in the kimberlite itself. The majority of ilmenites from Kimberley kimberlite have MgO >7wt%, while some of the ilmenites have MgO < 7wt%, suggesting that a major degree of diamond resorption may have taken place in the kimberlite melt. No MgO-poor ilmenites were found in the economic Orapa AK1 kimberlite (Daniels, 1997).

### 1.1.3.3 Spinel

Chromium-rich (>60wt% Cr<sub>2</sub>O<sub>3</sub>) spinels occur in kimberlitic concentrates and as diamond inclusions. Gurney, (1984) defines a spinel diamond inclusion field by plotting MgO against Cr<sub>2</sub>O<sub>3</sub> and suggests that concentrate spinels plotting inside the inclusion field are indicative of the presence of diamonds in the kimberlite. Daniels, (1991) evaluated the major and trace element compositions of the concentrate and diamond inclusion spinels from the Dokolwayo kimberlite and found that the spinels could be divided into TiO<sub>2</sub>-rich and TiO<sub>2</sub>-poor populations, but both populations may contain Cr<sub>2</sub>O<sub>3</sub>> 60wt%. All diamond inclusion spinels from Southern Africa are characterised by “TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> < 0.2, Cr<sub>2</sub>O<sub>3</sub>>57wt% and TiO<sub>2</sub><0.7wt%, and thus a combination of TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>/Cr<sub>2</sub>O<sub>3</sub> plots best evaluate the spinel concentrates of kimberlites. Daniels (1991) also notes that the spinels from the off-craton barren Melton kimberlite plot are:

. . . outside the diamond inclusion field and 40% of the concentrate spinels from the Kao kimberlite in Lesotho plot within diamond inclusion field and have less than 57wt% Cr<sub>2</sub>O<sub>3</sub>, which is consistent with the low grade of 3 carats per 100 tons for the kimberlite.

Daniels, (1991) further infers that:

. . . the Cr/(Cr +Al) ratio of spinels coexisting with garnet increase with an increase in pressure. The average Cr/(Cr+Al) ratio of the concentrate spinel population may be indicative of the economic potential of the kimberlite and thus kimberlites with a concentrate spinel population with an average Cr/(Cr+Al) > 0.8 are economic without exception.

#### **1.1.4 Lithological geochemistry survey**

The geochemical signature of a kimberlite is represented by enrichment in elements typical of ultramafic rocks (Mg, Cr, Ni, etc.) combined with alkalis and incompatible elements such as K, Ba, Sr, Zr. Chemical analysis of drill cuttings or of outcrops of weathered igneous rocks is therefore a useful way of confirming the identity of a suspected kimberlitic or lamproitic rock. Geochemical haloes in soil around pipes typically extend for a few tens of metres away from the pipe boundary, and the haloes in creeks persist for a few hundred meters downstream.

The relatively small dispersion pattern in the geochemistry is in contrast to that for indicator minerals, and is the main reason why the geochemical method has not been widely used during reconnaissance exploration for primary diamond sources. However, it can define relatively cheaply the boundaries of pipes, as an adjunct to geophysics or as an alternative to drilling, especially when access for a drill is difficult.

#### **1.1.5 Drilling, pitting and trenching**

Drilling, whether by auger, rotary air blast, percussion, air core or conventional diamond drilling, is normally the last stage of exploration to find a kimberlite, to define its margins, or even to sample it for diamonds. If the reconnaissance and follow-up results are sufficiently encouraging to warrant more detailed work, follow-up geochemical heavy mineral sampling programmes are initiated to develop drill targets. The objectives of a drilling program are to confirm the presence of kimberlite intrusions, to obtain preliminary pipe size data, and to collect samples for microdiamond and mineral chemistry analysis. Diamond drilling using NQ (5 centimeter diameter core) has been the main method for evaluating potential kimberlites, because it prevents contamination of the microdiamond samples.

The extraction of a small bulk sample (50–200 tons) using large-diameter core drilling, reverse circulation, and pits is intended to obtain a preliminary grade figure and a qualitative quality evaluation of the diamonds. Pitting or excavation is preferred where practical as it is the most cost effective, and a grid can be designed so that effectively the bulk sampling program will also delineate the surface area of the pipe. One drawback to excavation as a bulk sampling method is that the maximum vertical extent of the kimberlite that can be tested is approximately 10 to 20 meters. Reverse circulation drilling can be applied where the targets are by lake water and sediments. With reverse circulation, kimberlite delineation can be carried out concomitant with the bulk sampling program.

### 1.2 Summary of kimberlite mineral chemistry plots for the prediction of diamond potential of a kimberlite.

Plot	Indicator mineral	Parameter
Na <sub>2</sub> Owt% v TiO <sub>2</sub> wt% Cr v Ca	Pyrope Garnet	Na <sub>2</sub> O > 0.07wt% Cr <sub>2</sub> O <sub>3</sub> < 0.75wt%
Cr <sub>2</sub> O <sub>3</sub> wt% v MgOwt%	Ilmenite	MgO > 7wt%; Cr <sub>2</sub> O <sub>3</sub> > 1wt%
TiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> < 0.2	Spinel	TiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> < 0.2
Cr <sub>2</sub> O <sub>3</sub> > 57wt%/TiO <sub>2</sub> < 0.7wt%		Cr <sub>2</sub> O <sub>3</sub> > 57wt%
Cr/(Cr + Al) > 0.8		TiO <sub>2</sub> < 0.7wt%
(Cr+Al) v (Na+Ti)	Chrome diopside	Cr <sub>2</sub> O <sub>3</sub> > 0.5 < 4.5wt%, Al <sub>2</sub> O <sub>3</sub> < 4wt%

Fig. 1.2: The diamondiferous kimberlites mineral chemistry parameters. Data compiled from: Daniels, (1991).

### 1.3 Kimberlite occurrences to the west of the Umkondo Basin

The serious diamond-exploration-focused programs within and in the periphery of the Umkondo Basin began in 1999–2006 under Kimberlitic Searches Private Limited, a De Beers kimberlite exploration concern. Large tracts of land were explored for diamonds under the Exploration Prospecting Orders (EPOs) given by the government of Zimbabwe.

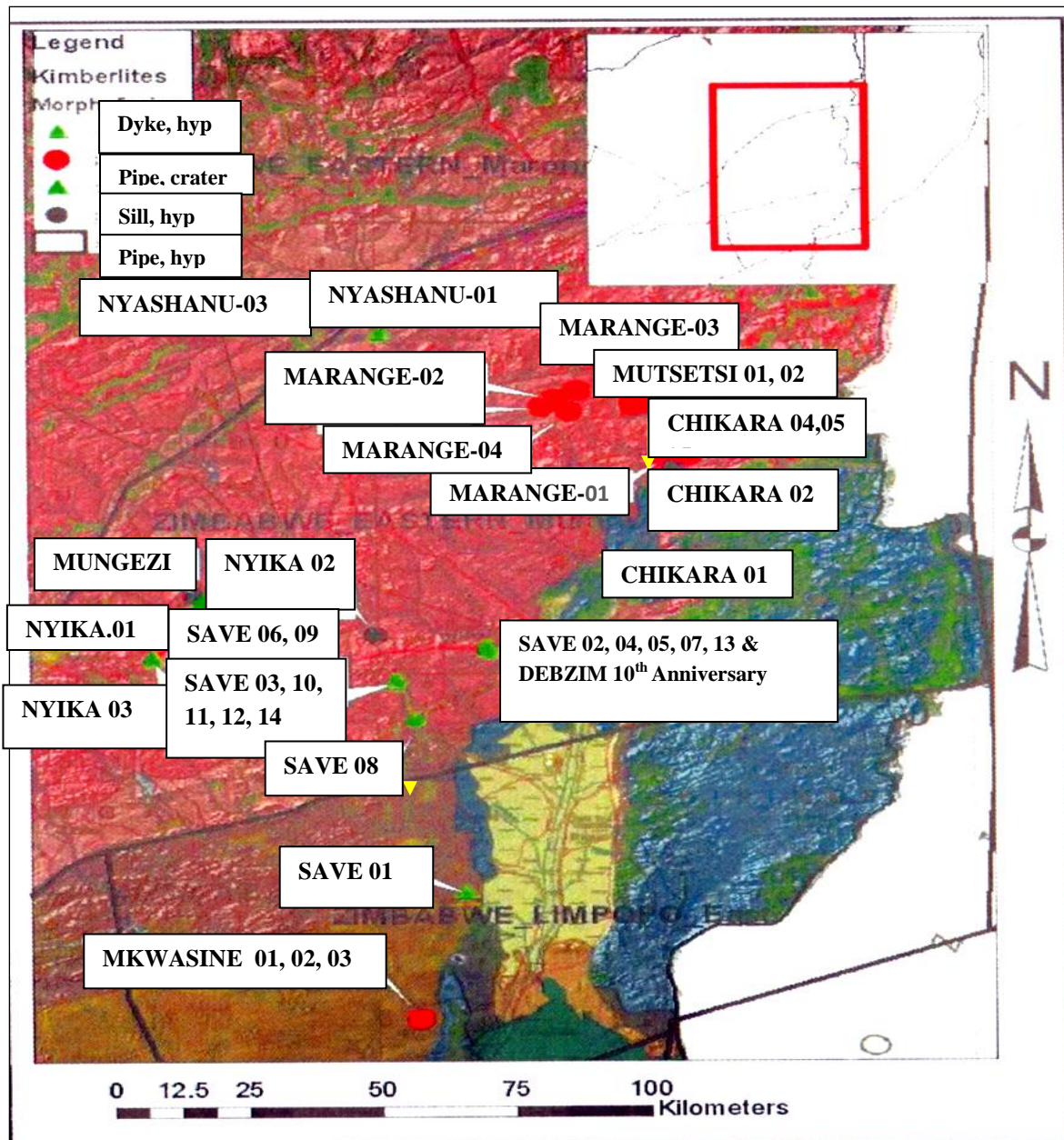


Fig. 1.3: Kimberlite clusters so far discovered on the western edge of the Umkondo Basin.

From: Adapted from Roberts, (2003a).

The aim of this exploration program was to find the source of the Umkondo Placer diamonds and, along the way, a number of kimberlites were discovered to the west of the Umkondo Basin (Figs. 1.3 and 1.4) and none within the basin itself. The marked absence of kimberlites within the basin may be an indication that the remnants of the kimberlites are buried beneath the Umkondo sedimentary pile.



<b>Kimberlite ID</b>	<b>Longitude (X<sup>o</sup>)</b>	<b>Latitude (Y<sup>o</sup>)</b>
Chikara-01	32.4884	-19.5311
Chikara-02	32.4992	-19.5435
Chikara-03	32.5007	-19.5428
Chikara-04	32.5250	-19.5151
Chikara-05	32.5270	-19.5178
Marange-01	32.2824	-19.4070
Marange-01	32.3021	-19.3900
Marange-01	32.3399	-19.3730
Marange-01	32.3273	-19.4190
Mutsetsi-01	32.4336	-19.4032
Mutsetsi-01	32.4478	-19.4025
Psungwesi	32.2739	-19.6315
Nyashanu-01-03	31.4887	-19.4579
Nyika-01-03	31.4263	-19.8738
Mungezi-01	31.3862	-19.6691
Save-01-14	32.2506	-19.6733
Mkwesine-01-03	31.8564	-20.7892

Fig. 1.5: Some of the kimberlite clusters discovered to the west of the Umkondo Sedimentary Basin. From: Pybus, and Hwata, (2002).

#### 1.4 Summary of mineral chemistry of discovered indicator minerals and kimberlites, west of the Umkondo Basin

Area	Plot	Mineral	Mineral Chemistry	Kimberlites discovered	Classification
EPO 1059 (Marange)	Cr <sub>2</sub> O <sub>3</sub> wt % v MgOwt%	Ilmenite	Cr <sub>2</sub> O <sub>3</sub> < 1.0wt%  MgO < 1.0wt%	Marange 01 Marange 02 Marange 03	Non-Diamondiferous
	Cr <sub>2</sub> O <sub>3</sub> v MgOwt%	Spinel	TiO <sub>2</sub> < 2wt%  Cr <sub>2</sub> O <sub>3</sub> = 55-67wt%  MgO > 8wt%	Marange 04	
EPO 1062 (Mutowona)	Cr <sub>2</sub> O <sub>3</sub> v MgOwt%	Spinel (Mantle root)	Cr <sub>2</sub> O <sub>3</sub> > 65wt%  TiO <sub>2</sub> = 0.00wt%	Chikara 01 Chikara 02 Chikara 03 Chikara 04	Very Low Grade
	Cr <sub>2</sub> O <sub>3</sub> v MgOwt%	Spinel (Phenocrystic)	Cr <sub>2</sub> O <sub>3</sub> = 64wt%  TiO <sub>2</sub> < 2wt%	Chikara 05	
EPO 1063 (Chitora)	Cr <sub>2</sub> O <sub>3</sub> v MgOwt%	Spinel	MgO very high		Moderate to High Interest
	Cr <sub>2</sub> O <sub>3</sub> v TiO <sub>2</sub> wt%	Spinel	TiO <sub>2</sub> > 0.7wt%  Cr <sub>2</sub> O <sub>3</sub> < 53wt%		
EPO 1166 (Hot Springs)	Cr <sub>2</sub> O <sub>3</sub> v TiO <sub>2</sub> wt%	Spinel	Cr <sub>2</sub> O <sub>3</sub> > 57wt%  TiO <sub>2</sub> > 0.7wt%		Moderate Interest

Area	Plot	Mineral	Mineral Chemistry	Kimberlites discovered	Classification
	Cr <sub>2</sub> O <sub>3</sub> wt % v MgOwt%	Ilmenite	TiO <sub>2</sub> > 0.7wt%		
EPO 1167 (Chimanimani)	Cr <sub>2</sub> O <sub>3</sub> v TiO <sub>2</sub> wt%	Spinel	TiO <sub>2</sub> < 2wt% Cr <sub>2</sub> O <sub>3</sub> = 55-67wt% MgO > 8wt%		Umkondo Conglomerate Source
	Cr <sub>2</sub> O <sub>3</sub> wt % v MgOwt%	Ilmenite	TiO <sub>2</sub> > 0.7wt%		
		Micro-diamond			
EPO 1520 (Mutowona)	Cr <sub>2</sub> O <sub>3</sub> wt % v MgOwt%	Ilmenite	Cr <sub>2</sub> O <sub>3</sub> < 1.0wt% MgO < 1.0wt%	Mutsetsi 01-05	Non-diamondiferous
	Cr <sub>2</sub> O <sub>3</sub> v TiO <sub>2</sub> wt%	Spinel	TiO <sub>2</sub> < 2wt% Cr <sub>2</sub> O <sub>3</sub> = 55-67wt% MgO > 8wt%		
EPO 1523 (Marange)	Na <sub>2</sub> Owt % v TiO <sub>2</sub> wt%	Garnet	Na <sub>2</sub> O > 0.07wt% Cr <sub>2</sub> O <sub>3</sub> < 0.75wt%	Tsongwesi	Umkondo Conglomerate Source
	Cr <sub>2</sub> O <sub>3</sub> v TiO <sub>2</sub> wt%	Spinel	TiO <sub>2</sub> < 2wt% Cr <sub>2</sub> O <sub>3</sub> = 55-		

Area	Plot	Mineral	Mineral Chemistry	Kimberlites discovered	Classification
			67wt% MgO > 8wt%		
	Cr+Al v Na+Ti	Chrome Diopside	Cr <sub>2</sub> O <sub>3</sub> >4.5wt % Al <sub>2</sub> O <sub>3</sub> > 4wt%		
		Diamonds			

Fig. 1.6: The mineral chemistry of kimberlites discovered around and to the west of the Umkondo Basin. Data extracted from: Reports on EPOs by Kimberlitic Searches (Pvt) Ltd, (1998–2006) De Beers, © Geological Survey of Zimbabwe

Kimberlite clusters so far discovered along the western edge of the Umkondo Basin (Fig. 1.6) are barren or partially diamondiferous according to the mineral chemistry. The diamonds and a diamondiferous kimberlite garnet were concluded to have come from the Umkondo diamondiferous conglomerates. If the kimberlites in the periphery of the Umkondo Basin are said to be barren, then the question remains as to where the diamonds hosted within the Umkondo sedimentary system originated from.

### 1.5 Justification for the study

Recently, alluvial diamonds have been discovered on the western edge of the Umkondo Basin at Chiadzwa (Fig. 2.1), just to the south of the Marange kimberlites (Roberts, 2003b). The geological setting of the diamonds is a dispersal alluvial deposit, with the diamonds having been reworked from the 1106 to 1112 Ma old local basal conglomerate of the Umkondo Group (Hanson et al., 2004).

Moore et al., (2009) noted that:

. . . the diamonds are characterized by a black coating, (Fig. 1.4), indicative of radioactive damage followed by metamorphic heating, and have characteristic nitrogen and infra-red signatures.

Roberts, (2006) also noted that:

. . . another singular characteristic of the Marange alluvial diamonds is the high proportion of rounded and fractured stones that have the appearance of having been mechanically abraded.

These two characteristics imply that the Marange diamonds have undergone extensive travel to their present location and have also undergone burial and metamorphism. The primary source of the Marange alluvial stones remains a mystery, but is inferred to be located to the west (Roberts, 2006). This is broadly consistent with Umkondo paleo-current directions (Button, 1978), which indicate a southwesterly to southerly provenance area for the sediments.



Fig. 1.7: Rounded alluvial diamonds from Chiadzwa, Save Valley with black coating indicative of radioactive damage, followed by metamorphism. From: Roberts, (2006)

The approximately 1.1 Ga age for the host Umkondo Group sediments and their diamonds required the existence of kimberlites older than any in Zimbabwe for which reliable dates are available.

### **1.6 Objectives of the study**

The objectives of this study are:

1. To understand the evolution of the Umkondo Basin, which knowledge might indicate the possible provenance of the Umkondo Basin diamond placer,
2. To evoke renewed interest in diamond exploration and the economic evaluation of the Umkondo Basin alluvial diamond potential, and
3. To study the diamonds themselves to extract geological information to enable a better understanding of the Umkondo Basin.

## **2.0 CHAPTER TWO**

### **INTRODUCTION AND GENERAL OVERVIEW OF SEDIMENTARY-HOSTED DIAMOND DEPOSITS IN ZIMBABWE**

#### **2.1 Introduction**

The Umkondo Sedimentary Basin consists mainly of the rocks of the Umkondo System, which lie east of the Save River and form the mountainous region along the border between Zimbabwe and Mozambique, from Mount Himalaya in the north to Mount Selinda in the south, including the Chimanimani Mountains (Watson, 1969). The basin covers an area in excess of two million hectares of generally unexplored diamondiferous sediments. Its northern and southern limits are at latitudes 19° 22' and 20° 36' S, respectively (Fig. 2.1).

Watson, (1969) further states that:

. . . the later Precambrian rocks of the Umkondo System are gently dipping quartzites, siltstones, shales, calc-hornfels, crystalline limestones and pelitic schists which in the Chimanimani Mountains are steeply folded and overthrust and unconformably lie on a granitic basement which contains small areas of Basement Schists. In the lower beds outcropping along the western margin are numerous small and scattered copper occurrences and crystalline siliceous limestones of no economic value but give rise to several deposits of high-grade calcareous tufa.

#### **2.2 An overview of sedimentary-hosted diamond deposits in Zimbabwe**

In Zimbabwe, placer diamond occurrences have been known at Somabula and Featherstone, but the recent discovery of basal conglomerate diamonds in the Umkondo Basin (Fig. 2.1) is the most important economically, although it remains effectively unexplored. Diamond placer deposits are a significant accumulation of kimberlites residue, after their erosion and deposition, and potentially carry the record of diamond emplacement on the cratons. Bluck, et al., (2005, pp 213) states that: “the three types of diamond placer deposits; retained, transient, or terminal (Fig. 2.3) have to be colossal to have an impact on total diamond production and should be of high value per carat. Retained placers remain on the craton in karst in diamond-

rich gravels trapped in caves, highly irregular karst surfaces, and cavities in post-Archaean carbonates subjected to climatic and base level changes, and intra-cratonic basins”.

As is evident in the Umkondo System, the placer sediments begin with coarse basal conglomerates and grits and terminate in limestones and mudstones overlapping onto the Zimbabwe craton. In the Somabula placer diamond deposit, the diamondiferous, yellowish-grey, and coarse gravel sits directly on Archean granite and terminates in sandstone and mudstone. The diamonds within the Umkondo Basin could have been derived from the erosion of kimberlites on the basin floor during the initial stages of basin opening, and later from the surrounding drainages or from kimberlites having been intruded into the sediment fill.

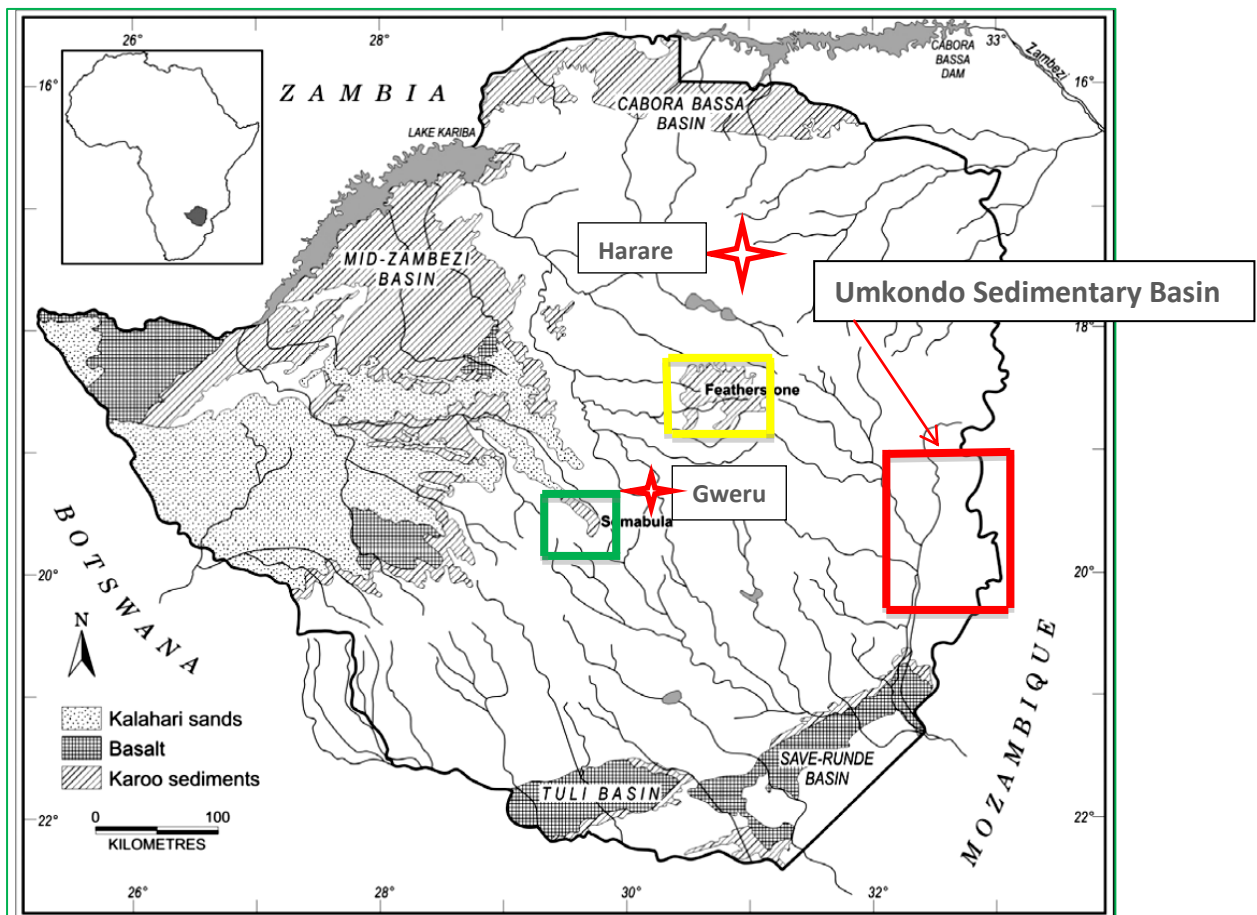


Fig. 2.1: Distribution of diamondiferous Karoo sediments in Zimbabwe, Somabula (Green box) and Featherstone (Yellow box), and Precambrian Umkondo Basin (Red box). Map adapted from: Moore, et al., (2009)

Of critical importance to the development of diamond mega-placers is the evolution of major drainage systems.

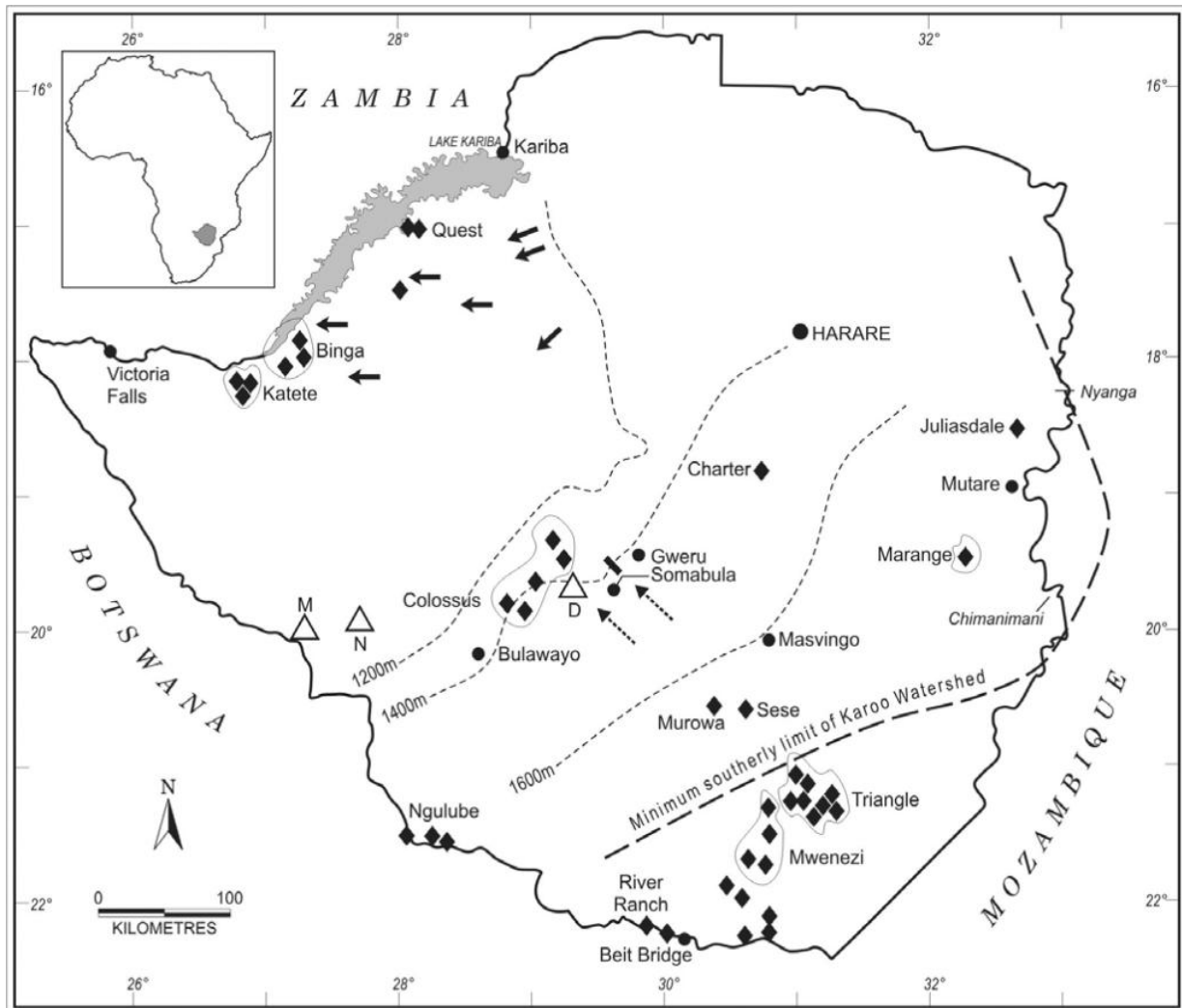


Fig. 2.2: Distribution of known kimberlites (solid diamonds) in Zimbabwe. Triangles: Major unexplained kimberlitic heavy mineral anomalies; D = Daisyfield; M = Maitengwe; N= Nanda. From: Moore et al., (2009)

In Fig. 2.2, the dotted lines represent contours on the pre-Karoo floor, with heights in metres above present day sea level. The solid arrows represent Permian ice movement directions, while the dashed arrows are inferred Permian ice movements. Moore, et al., (2009) state that:

. . . the present major drainage system of Zimbabwe has existed since pre-Karoo times, during the late-Triassic when the system was disrupted by rifting during the breakup of Gondwana, and the headwaters of the tributaries of the Zambezi were further south, (Fig. 1.2) of the present day Zambezi-Limpopo river systems divide and draining across the granite-greenstone basement.

A palaeo-drainage reconstruction has important implications for the dispersion of diamonds and associated pathfinder minerals from primary kimberlite sources. The Sese–Murowa kimberlites are inferred to be the primary source of hitherto unexplained alluvial diamonds in basal gravels of the Somabula Karoo outlier, located on the central Zimbabwe watershed, some 120 kilometers to the northwest.

The linear, southeast–northwest aligned Somabula Karoo outlier has discontinuous basal diamond-bearing gravel overlain by Upper Karoo sediments. Moore et al., (2009), citing Moore, and Moore, (2006), interpreted the basal braided river system lag gravel as “fluviially winnowed Permian tillites formed by erosion before the deposition of the Somabula upper Karoo sequence”. The paleo-current and isopach evidence (Fig. 2.2) indicate that the flow of the upper Karoo Somabula river system was to the northwest (Moore, and Moore, 2006) and that the clast assemblage of vein quartz and quartzites and exotic lithologies (Zealley, 1918), matching rocks in the vicinity of Shurugwi, 50 kilometers to the south of the present watershed and heavy mineral-suite of staurolite (~98%), with subordinate kyanite and garnet, beryl, chrysoberyl, corundum, topaz, tourmaline, zircon, chromite, gold and PGM alloys in the Somabula gravels, offered a potential “fingerprint” of the provenance area, and thus evidence for the location of the primary kimberlite source of the associated diamonds. This statement points to a northwesterly glacial flow having deposited the basal Somabula sediments.

Moore et al., (2009) further state that “staurolite is also the dominant heavy mineral phase in the basal Featherstone gravels”, some 50 km to the south of Harare (Fig. 2.1). Moore et al., citing Spence, (2000) described two linear trains of kimberlitic heavy mineral (ilmenite and G10 garnet) on Archaean basement granite and parallel to the Somabula outcrops at Daisyfield and Mambo, some 25 to 30 kilometers to the southwest of the Somabula outlier. They also suggested that the linear Mambo and Daisyfield kimberlitic mineral anomalies could reflect the occurrence of local thin kimberlite stringers, and that it would be expected

that the associated halo would become progressively more diffuse away from the source. In contrast, mineral counts drop off sharply at the anomaly margins.

Moore, et al., (2009) also emphasize that:

. . . the north-sloping Somabula Karoo surface, exotic clast lithologies in the Somabula gravels, and palaeo-current indicators point to a southerly provenance for the Somabula diamonds in contrast to the Mwami mica field provenance 300km to the north . . . ,

Furthermore, Moore, et al., (2009) comment that:

. . . the Nyanga staurolite schists and the Chimanimani kyanite schists are most likely to be the sources of the heavy mineral suite of the basal Somabula gravels, and thus the eastern highlands of Zimbabwe has persisted from pre-Karoo times to the present.

The linear Somabula Karoo outlier is a transient placer that extended to the south of the present watershed.

### **2.3 Factors influencing mega diamond placer deposit formation**

Transient placers are diamond-rich sediments deposited along the dispersal route or within the active drainage basin, especially when the drainage density in the drainage basin is low and inefficient in removing sediments, and therefore results in sediment load remaining in river terraces and trap sites for extended periods of time. The transient placer relies on uplift–incision episodes to rejuvenate tributaries, which is required to increase the slope and energy in the channels (Bluck, et al., 2005). The coarse sediment and increase in velocity of flow results in hydraulic selection and retention of diamonds in transient placers. The Umkondo Placer is not a transient placer but most likely a retained placer.

A terminal placer occurs at the extreme end of the drainage system, where successive low-diamond and sediment loads are further segregated into a viable placer. Bluck, et al., (2005) state the factors necessary for the formation and magnitude of a terminal placer as:

1. The availability of both primary and secondary diamond deposits that can generate enough diamonds for transportation into the terminal placer.
2. A large-scale exit drainage system to drain large areas of the craton, in order to bring substantial quantities of diamonds and low sediment of grain size capable of trapping diamonds.

3. An energetic terminal environment to separate and concentrate diamonds and gravels from the other sediments.
4. Very long periods of time from successive sediment inputs to allow diamond fractionation in a terminal placer while the above three conditions always remain united in time.

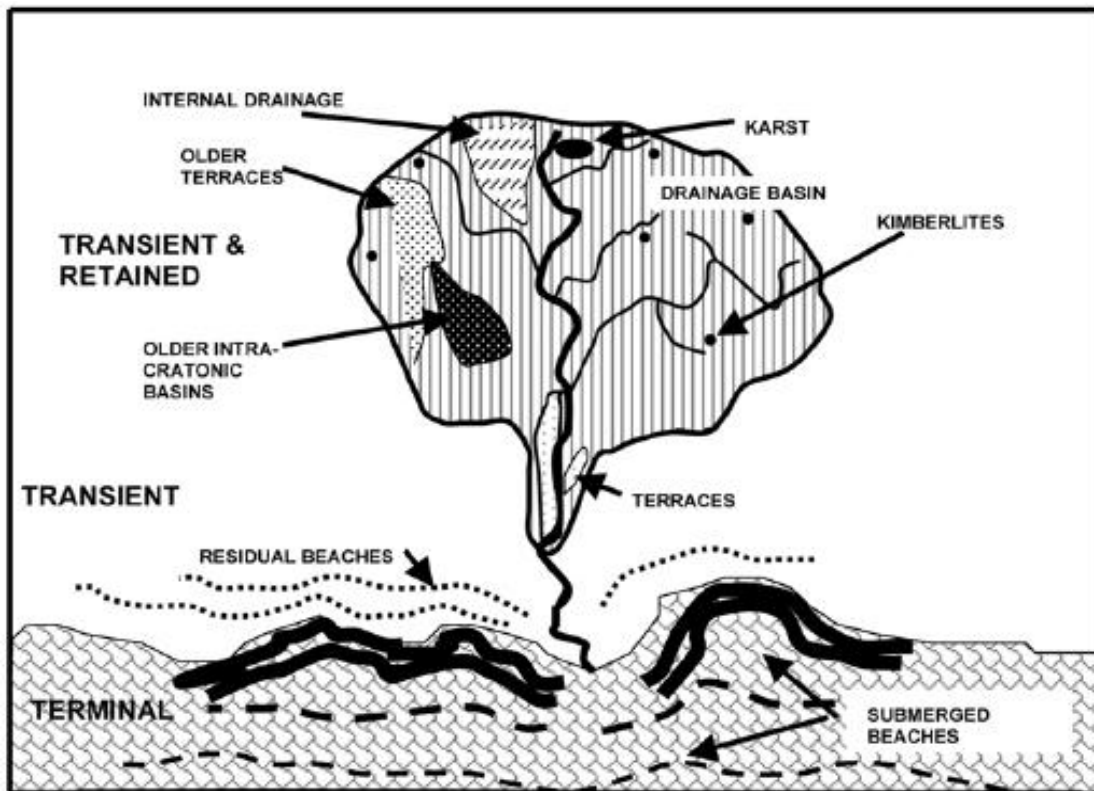


Fig. 2.3 Types of diamond placers. From: McDonald, et al., (2005).

The timing of the whole dispersal and terminal development is important as the diamonds are to be recovered from loose sediment and not cemented rock. Recoverable diamond placers are found in deposits that have escaped burial, orogenesis, or unlithified sediments. Bluck, et al., (2005) follow Clifford's, (1966) assertion that:

. . . most diamondiferous kimberlites are found in crustal blocks over 2Ga old, with low geothermal gradients and relatively thick crust, which enable for high pressure at low temperature resulting in the formation of diamonds within the diamond stability field in the lower portions of the cratonic lithosphere. Diamondiferous kimberlites and lamproites have been found in Proterozoic belts of which the belts may have been cover to older cratons beneath them at the time of kimberlite emplacement.

The combination of craton extent, fertility, and geological history are therefore, in part, major controls on the development and richness of a mega placer that might be generated. The global availability of diamonds is therefore to a large extent related to the global area of Archaean crust, and thus continents with large Archaean blocks have greater potential for diamond yields and greater likelihood of producing placers. It is the interactive part of the craton that is the key influence on volumes of diamonds generated.

The diamond fertility of cratons is a function of the time range over which diamond-bearing kimberlites intruded, the abundance of kimberlite intrusions at any one time, and the grade and purity of the diamonds in the kimberlites. Diamond formation episodes beneath cratonic blocks extend from the Archaean through the Permian, Jurassic and Cretaceous. Current evidence suggests that the Kaapvaal craton is the most fertile, with some of the world's richest pipes, which intruded during the Cretaceous. The degree of diamond retention, loss, and concentration through down-weathering over time determines the quantity of diamonds available for final release. The two cratonic factors related to diamond loss–retention are the seismically fast roots extending to depths greater than 200–250 kilometers, and buoyancy and root or tectosphere which control the post-formation history of the craton. Carlson, (2000) states that:

. . . the 200 km deep Archaean lithospheric mantle, which are peridotites depleted in Ca, Al and Fe and the resultant low garnet, is lighter than younger lithospheric mantle, thus Archaean cratons have a long history of buoyancy, which is consistent with the fact that stratigraphically younger formations commonly overlap onto cratons from thicker deposits in deeper basins off their margins.

Some important drainage prerequisites for the development of a mega-placer are: the accessibility to the final drainage network of diamond-bearing deposits on the craton or its borders, whether primary, transient or retained; the percentage of the drainage basin area which is on-craton; the degree of efficiency to which older drainage networks have robbed the craton of accumulated diamonds; and the sediment loads and efficiency of the drainage network to release diamonds.

The accessibility of large quantities of diamonds to the drainage network, due to the nature of diamond retention on-craton, whether primary or secondary, should be available to the

drainage network at specific time intervals. Source areas releasing small quantities of diamonds over a long time-span may fail to yield sufficient diamonds for mega-placer development. The range of settings in which diamonds may be retained on the craton and their corresponding ease of access to the drainage are illustrated in Fig. 2.3. Three situations are taken to illustrate this point: primary deposits in cover, pre-assembled placers and down-wasting on planation surfaces.

### **3.0 CHAPTER THREE**

#### **THE GEOTECTONIC EVOLUTION OF THE UMKONDO FORELAND BASIN**

##### **3.1 The tectonostratigraphic evolution**

The observed sequence of basin events that occurred during the formation of the Umkondo foreland basin in eastern Zimbabwe is part of a regional tectonic model for the period of the formation of Gondwanaland at about 1100 Ma (Fig.3.1). Master, (2006) explains that:

“...the accretion of a volcanic arc terrain associated with the possible docking of Antarctica during the Rhodanian assembly may have resulted in the loading of the Zimbabwe Craton margin and in turn producing a foreland basin in which the majority of the Umkondo sediments were deposited”.

De Celles, and Giles, (1996) defined a foreland basin system as:

. . . an elongate region of potential sediment accommodation that forms on continental crust between a contracting orogenic belt and the adjacent craton, mainly in response to geodynamic processes related to subduction and the resulting peripheral or retroarc fold-thrust belt.

The Umkondo Group outcropping in eastern Zimbabwe and adjacent parts of southern Mozambique is a sedimentary and volcanic succession linked with the Ritscherflya Supergroup of Antarctica (Master, 2006; 2010), and both are interpreted as the products of a foreland basin developed in response to arc collisions in the late Mesoproterozoic, during the formation of the Rodinia supercontinent (Fig. 3.1).

The western domain of the Umkondo Group, the Calcareous and Argillaceous Series, comprises weakly to non-metamorphic strata of pebbly basal arkoses that are succeeded by shallow-marine stromatolitic limestones, cherts and cross-bedded arkoses that are interbedded with basalts and mafic and felsic tuffs (Mukwakwami, 2012) nonconformably overlying the Archaean granites and gneisses of the Zimbabwe Craton, while the eastern domain, the Frontier Series, which is a fold-thrust belt, along the Mozambique border, consists of highly deformed and strongly metamorphosed facies grade psammmites and metapelitic schists that were thrust westwards onto the craton during the Mozambique orogeny about 550 Ma. Manhica, et al., (2001) interpreted the less than 2.3 Ga Frontier Series as:

. . . a typical passive craton margin succession in which initial marginal marine orthoquartzites are overlain by deeper shelf pelites, formed in an overall deepening,

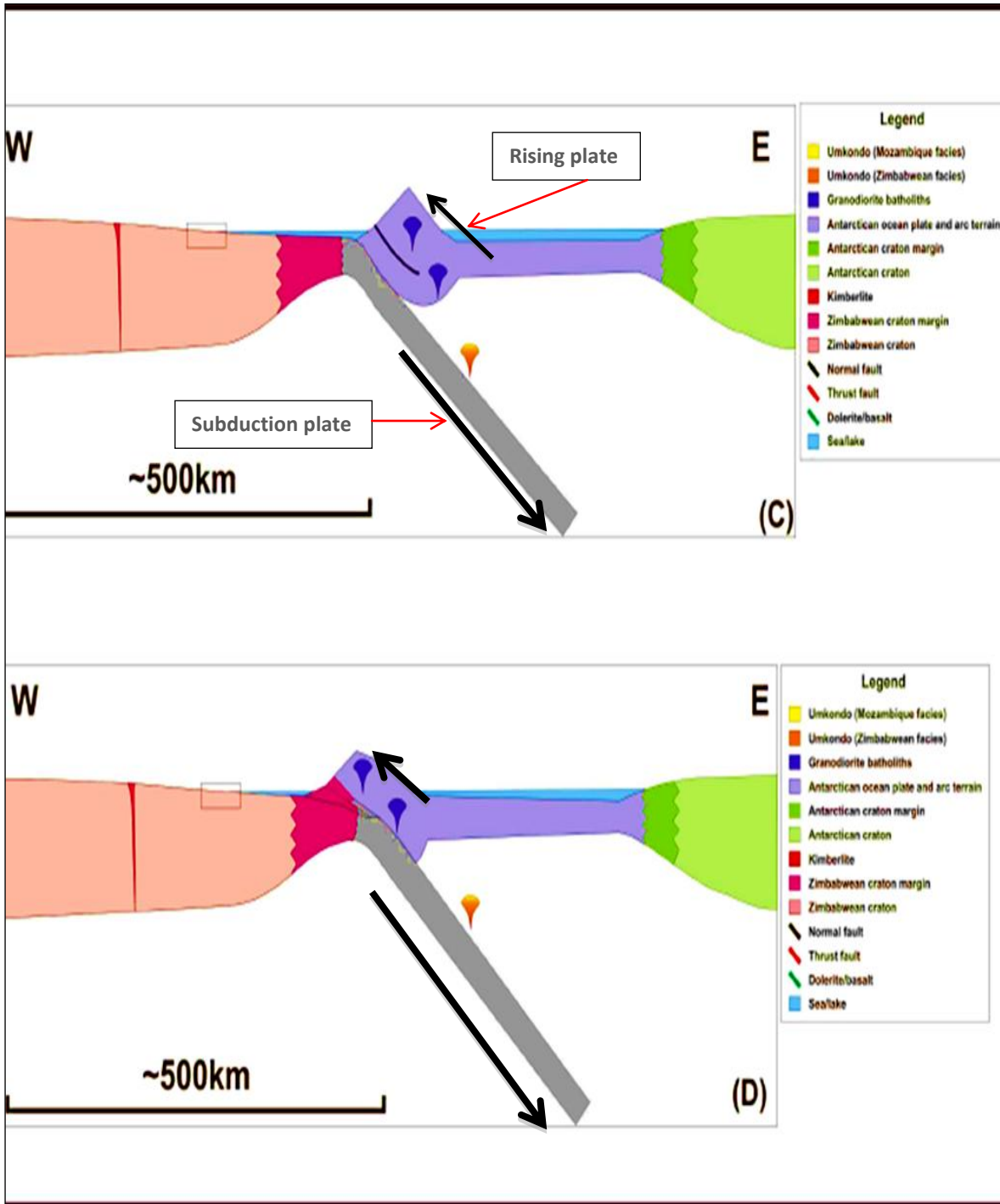


Fig. 3.1: The initial collision of arc terrain.

Illustration adapted from Roberts, (2003a)

transgressive sedimentary regime, while the overlying Calcareous and Argillaceous Series represent a regressive, shallowing upward sedimentary regime.

In the early stages of foreland basin sedimentation on the eastern margin of the Zimbabwe Craton (Fig. 3.2), a shallow shelf succession of stromatolitic carbonates, formed in subtidal to intertidal environments, was succeeded by deeper water siltstones and shales, as the basin initially deepened, in response to loading by the Maud Belt arc to the east. The northern continuation of the Maud Belt is found in southern Mozambique, where the Vhanduzi Migmatite Gneiss, and ca. 1112 ±18 Ma Nhansipfwe Gneiss and other gneisses adjoin the reworked Zimbabwe Craton, 40 kilometers east of the Zimbabwe–Mozambique border.

Further, Master, (2010), citing Button, (1977), explains that:

. . . a forebulge rose to the west of the Maud Belt, and its erosion led to the regressive outbuilding of a braided fan delta, comprising arkosic sandstones, over the shallow marine shelf argillites, with palaeocurrents towards the east. The upper part of the arenite succession shows reworking into clean quartzites by northerly directed longshore currents. As the forebulge was eroded and gradients were reduced (Fig. 3.2), the arenites were overlain by a sandy argillite succession, representing a meandering river floodplain.

The reduction in gradients was in turn succeeded by more arkose, marking a renewed pulse of sedimentation, perhaps caused by doming, just prior to the eruption of mafic pyroclastics and tholeiitic lavas (Master, 2010), together with intrusion of voluminous sills (Fig. 3.3), of the ca. 1106 ± 2 Ma Umkondo Large Igneous Province (Hanson et al., 2004), while the Umkondo sediments were still unconsolidated.

The decompression melting of this anomalously buoyant mantle produced widespread asthenospheric melting in the spinel zone, suggesting lithospheric thickening of about 90–100 kilometers at 1.1 Ga (Roberts, 2003a). Melts migrated towards the surface to form dolerite sills and dykes, and more rarely preserved basaltic flows that cap the Umkondo sediments (Fig. 3.3).

The Umkondo Basin termination was marked by extensive faulting, folding, rifting, erosion, and burial and metamorphism, resulting in the present rugged terrain and lithological suites of the Eastern Highlands of Zimbabwe (Fig. 3.3). The basal conglomerates and the limestones at the base of the Umkondo Sedimentary sequence represent a transgressive environment, whilst the overlying argillaceous and arenaceous sequences represent a regressive sedimentary environment. The 1.1Ga Umkondo sediments are older than the overlying dolerite sheets.

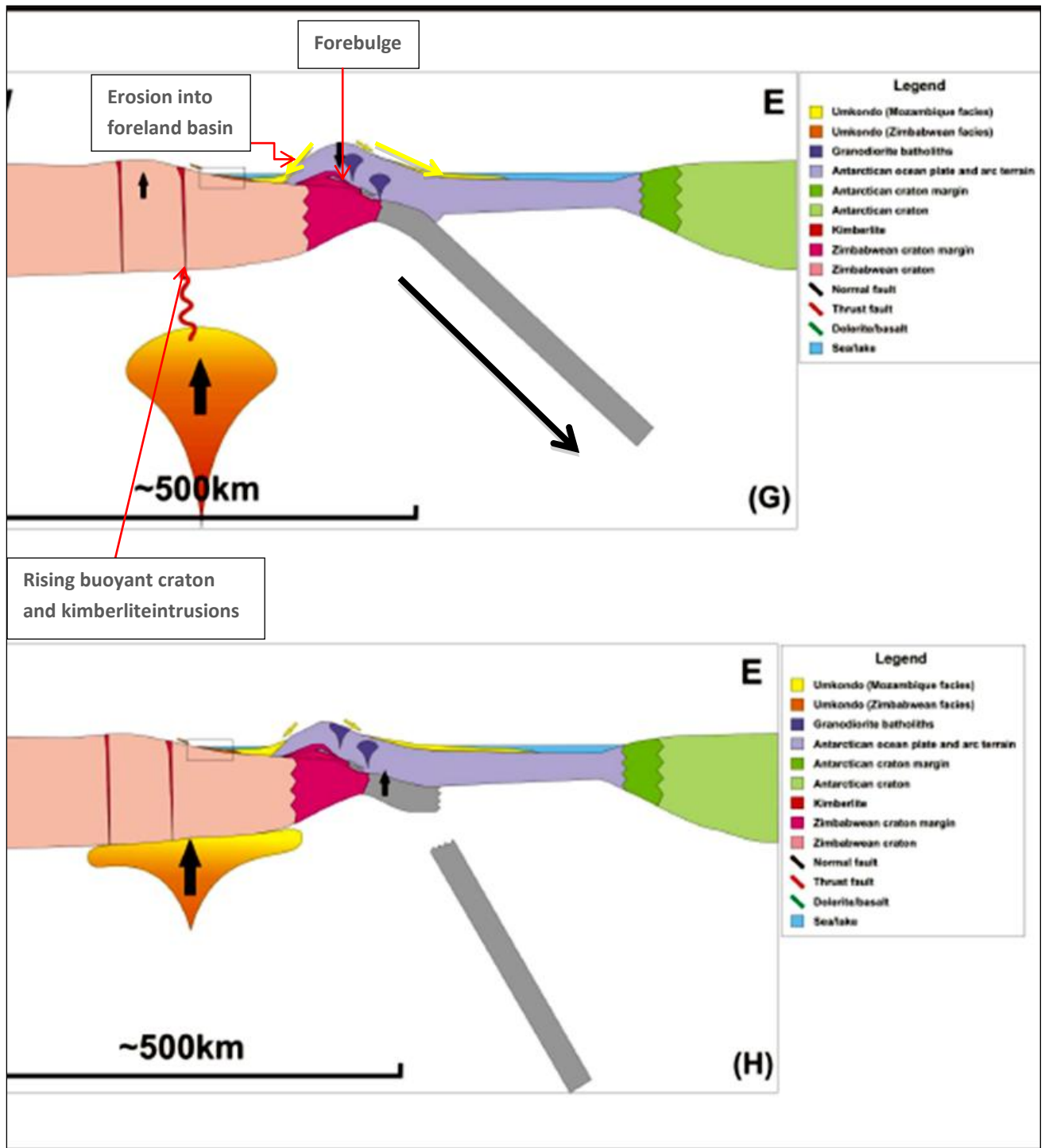


Fig. 3.2: Loading, and development of a forebulge, increased erosion into the basin and also mantle melting.

Illustration adapted from Roberts, (2003a)

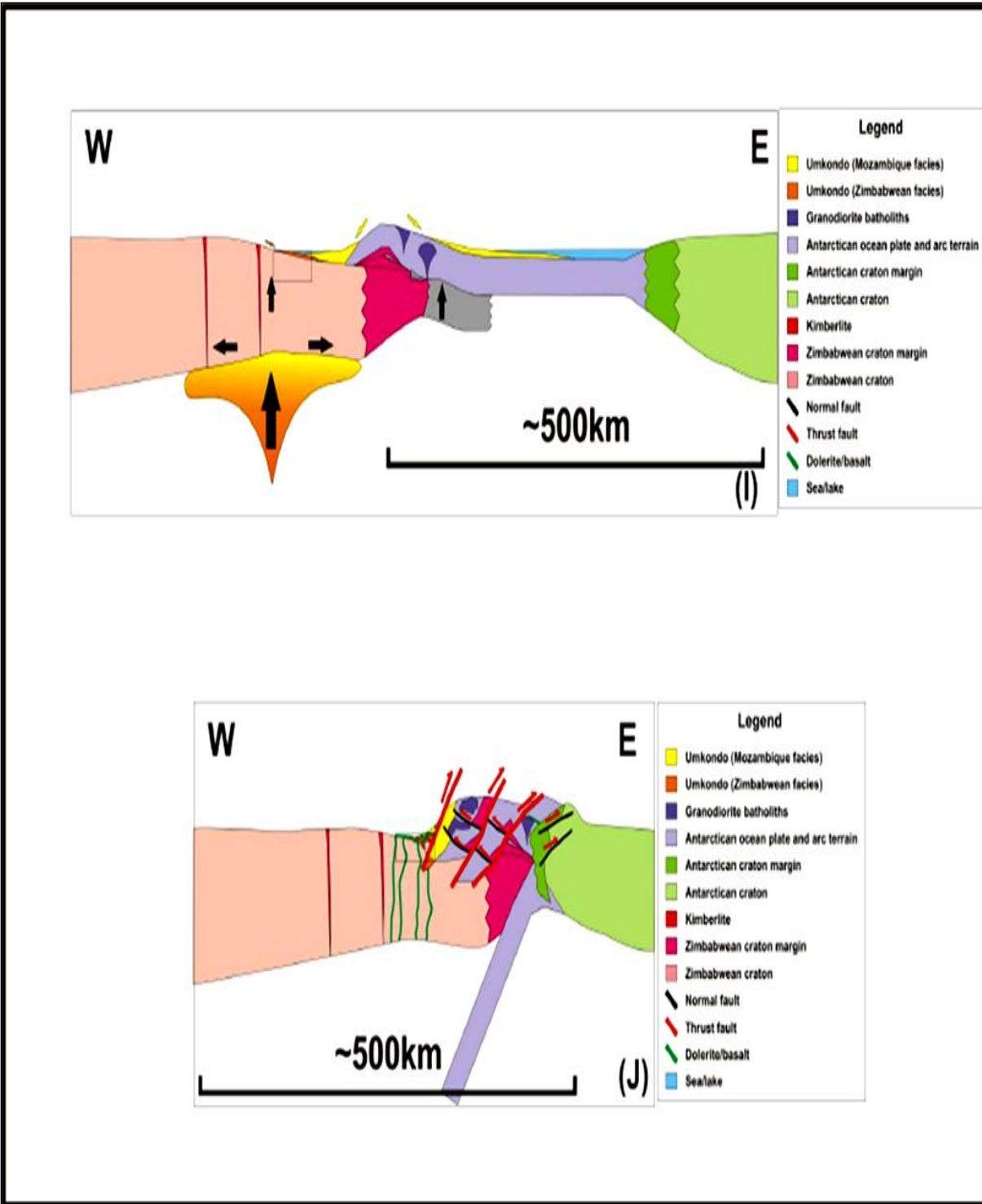


Fig. 3.3: The Umkondo Basin termination and Post African collision.

Illustration adapted from Roberts, (2003a)

### 3.2 Similarities between the Umkondo Group and Ritscherflya Supergroup

From the discussions above, Master, (2006), citing various authors, noted a number of similarities between the Umkondo Group and Ritscherflya Supergroup of Antarctica, indicating that they may have been part of the same large basin:

1. Mafic sills and lava flows in the two areas have the same chemical composition (Krynauw et al., 1991; Munyanyiwa, 1999);
2. The mafic sills intruded into the sediments while they were still unconsolidated (Krynauw et al., 1988, 1994; Master, 2006), indicating similar ages of sedimentation in both basins;
3. The contacts of mafic sills in both areas are contaminated, and converted into granophyres (Button, 1977; Krynauw et al., 1988; 1994, Master, 2006);
4. The Umkondo volcanics and sills have the same palaeopole as the sills in Ahlmannryggen (Jones et al., 2003), in a tightly reconstructed Gondwana configuration (Roeser et al., 1996);
5. The U-Pb baddeleyite ages of mafic rocks from Umkondo Group and Ahlmannryggen are the same, at  $1106 \pm 2$  Ma (Wingate 2001; Hanson et al., 2004);
6. The Rb-Sr age, recording a metamorphic overprint, of mafic rocks from both areas is the same at, ca. 1,080 Ma; and
7. This initially-deepening, then upward-shoaling, Umkondo–Ritscherflya succession represents a basinal response to lithospheric depression by crustal loading, followed by migration and erosion of the forebulge, with regressional infilling of the foreland basin from both the colliding arc and foreland (craton) sides.

## **4.0 CHAPTER FOUR**

### **THE PARAGENESIS OF THE DIAMONDIFEROUS BASAL CONGLOMERATES OF THE UMKONDO BASIN**

#### **4.1 Introduction**

Cratons may break by extension forming rift valleys, some eventually to become passive margins on craton dispersal. Orogens have been thrust and also converge onto cratons: for example, in southern Africa, the Kheis, Namaqua-Natal, Damara, and Cape fold belts all converge on the Kaapvaal craton. Converging fold belts result in sediment return and are accompanied by foreland basins, like the Umkondo, that migrate towards the interior of the cratons as the fold belts advance.

The foreland basin margin, distal from the fold belt (i.e. interfacing with the craton), receives sediment and diamonds from the craton, resulting in a potential on-craton diamond loss. The sediment in the foreland basin also offers a host to kimberlite intrusions, as in some Karoo basins of southern Africa. Foreland basin sediment can extend over the larger part of the craton. Many foreland basins are marine, so placer deposits may develop along the migrating shorelines at the craton–basin margin during both advance and retreat of the basin edge. As cratons, away from the zone of convergence, passively receive sediment rather than actively subside to accommodate it, much of the foreland basin sediment is lost when the converging mountain mass is eroded down and the basin inverts. At this point, any newly-intruded kimberlites are subject to erosion and, if the time of inversion is optimum for both large-scale drainage development and conditions at the river terminus, the potential for mega-placer development is then enhanced. The timing of kimberlite intrusion in relation to foreland basin development is thus significant.

#### **4.2 Conditions that enhance diamond placer development**

The timing of the whole dispersal and terminal development is important, as the diamonds are to be recovered from loose sediments that have not undergone burial or orogenesis, and not from cemented rock.

##### **4.2.1 The craton**

Bluck et al., (2005) follow Clifford's, (1966) assertion that:

...most diamondiferous kimberlites are found in extensive Archaean crustal blocks over 2Ga old, which have low geothermal gradients and relatively thick crust, thus enabling for high pressure at low temperature and, consequently the formation of diamonds within the diamond stability field in the lower portions of the cratonic lithosphere, although diamondiferous kimberlites and lamproites have been found in Proterozoic belts. Proterozoic belts may be cover to older cratons beneath them at the time of kimberlite emplacement.

The combination of craton extent, fertility, and geological history are, in part, major controls on the development and richness of any mega placer that the craton might generate. The diamond fertility of cratons is a function of the time range over which diamond-bearing kimberlites intruded (from the Archaean through the Permian, Jurassic and Cretaceous); the abundance of kimberlite intrusions at any one time; and the grade and purity of the diamonds in the kimberlites. The post-formation history of the craton seismic roots (thermal shield), which resist delamination and fail to compress in the same way as younger crust at 200–250 kilometer depths and buoyancy, relates to diamond retention, loss, and concentration through down-weathering in determining the quantity of diamonds available for final release into basins. Bluck et al., (2005), citing various authors (e.g. Carlson et al., 2000) state that:

. . . the 200km deep, less dense kimberlite xenoliths are low garnet, Ca, Al and Fe-depleted peridotites lighter than the younger lithospheric peridotites, and thus Archaean peridotites have a history of buoyancy, which is consistent with the fact that stratigraphically younger formations commonly overlap onto cratons from thicker deposits in deeper basins off their margins.

#### **4.2.2 Drainage**

Important prerequisites for the development of a mega-placer are: the accessibility to the final drainage network of diamond-bearing deposits on the craton or its borders, whether primary, transient or retained (Fig. 4.1); the area of drainage basin whose proportion is on-craton; the degree to which older drainage networks have robbed the craton of accumulated diamonds; and the sediment loads and efficiency of the drainage network to release diamonds. At a specific time interval, the availability of on-craton abundant diamonds' delivery to the basin must be synchronous with their availability to the drainage network and optimum conditions

for their concentration.

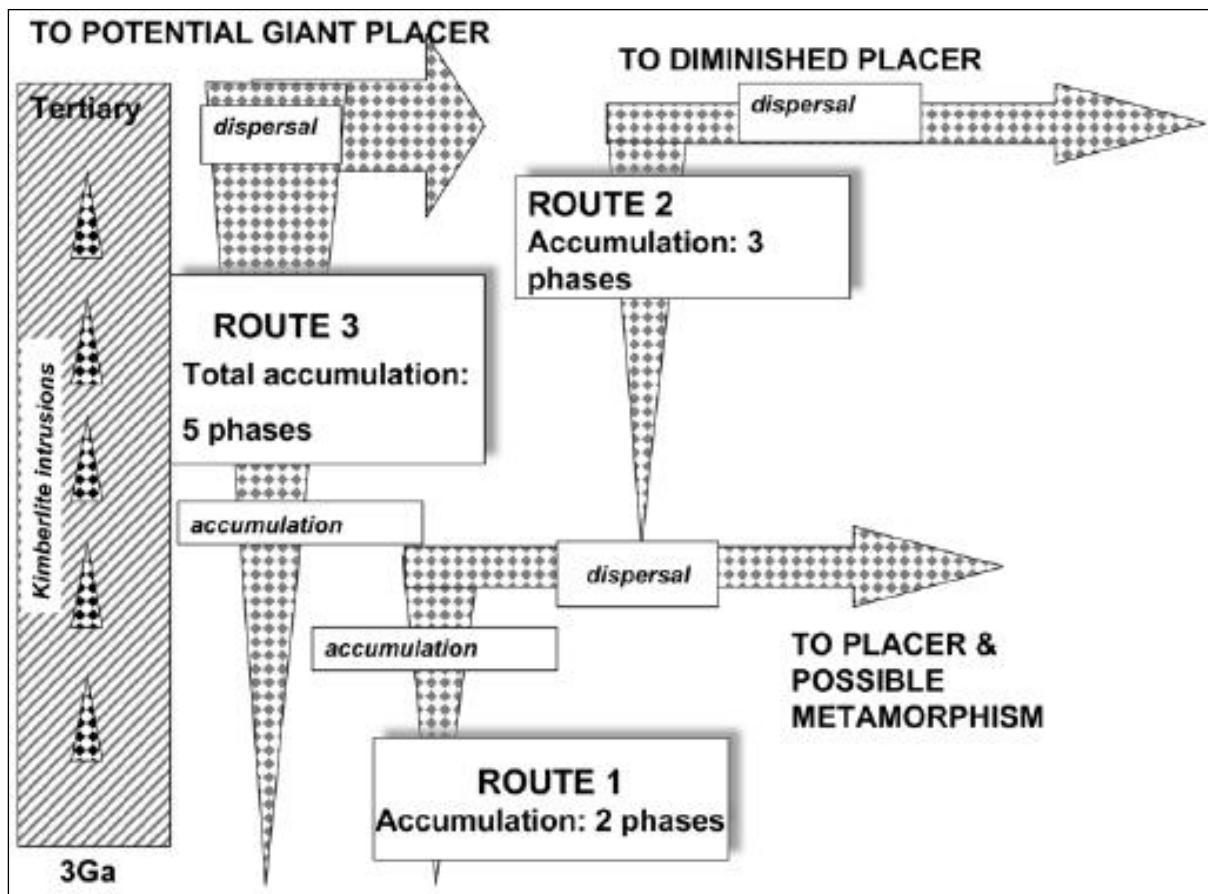


Fig. 4.1: The importance of retaining diamonds on the craton in order to yield a mega-placer. The left-hand column has five phases of diamond-bearing intrusions. In Route 1, large-scale drainage removes the accumulated diamonds from two phases of intrusion, and then a subsequent drainage removes the other three in Route 2. In Route 3, large-scale drainage affects the total diamond-bearing phases and is likely to result in a mega-placer. From Bluck et al., (2005)

Source areas releasing small quantities of diamonds over a long time-span may fail to yield sufficient diamonds for mega-placer development. The range of settings in which diamonds may be retained on the craton, and their corresponding ease of access to drainage, are illustrated in Fig.4.2. Many kimberlites have intruded a cover (often provided by a foreland basin).

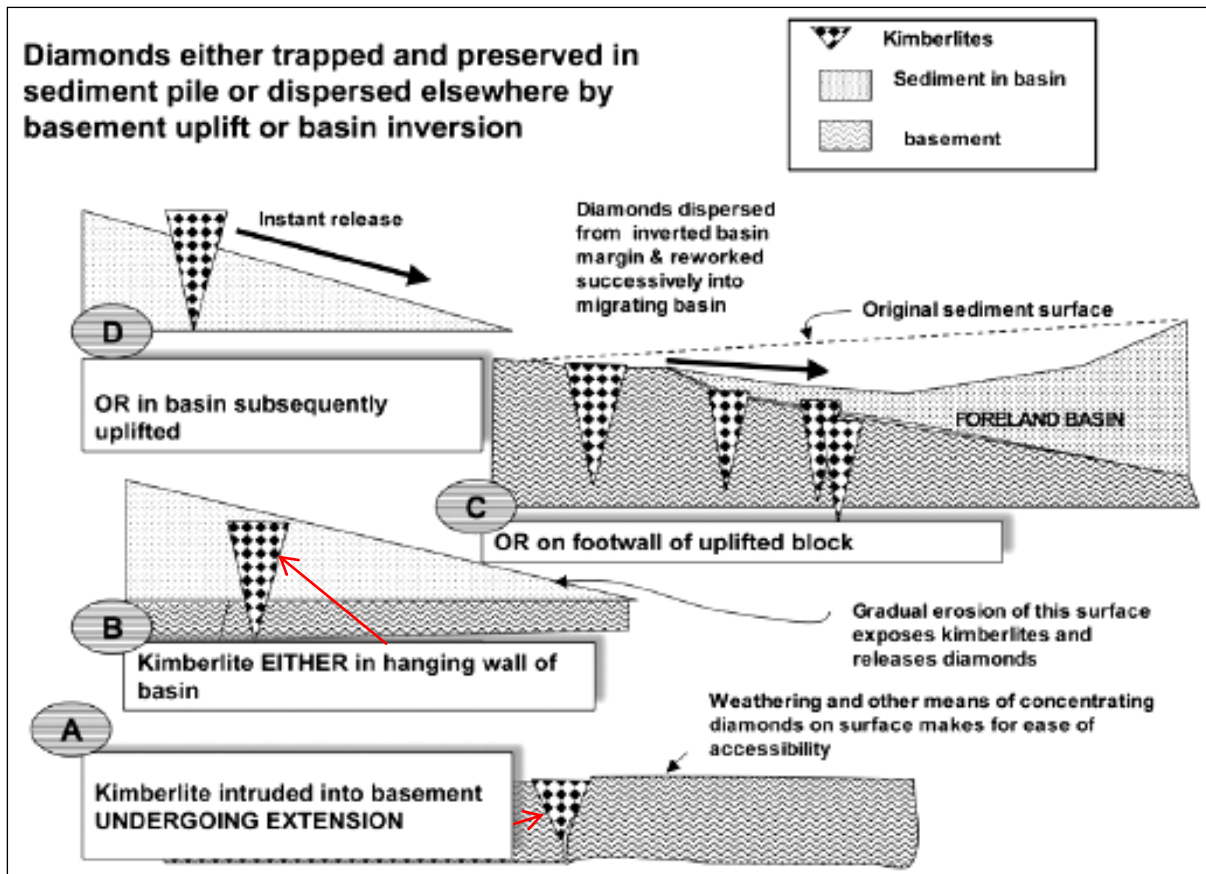


Fig. 4.2: Means of concentrating and retaining diamonds on cratons. (A) Gradual downwasting of the craton surface intruded by kimberlites, (B) Kimberlite being intruded into sedimentary cover, (C) Diamonds being eroded from uplifted craton for reworking on the margin of a migrating foreland basin, and (D) Basin sediment uplifted and diamonds dispersed over the craton to find residence elsewhere.

Adapted from Bluck et al., (2005)

The rate of erosion and removal of kimberlite cover to expose diamond-bearing rocks is important to the delivery time of diamonds to the placers. Exposed kimberlite pipes may continue two kilometers below the current level of erosion to yield significant quantities of diamonds as the cover continues to be stripped off (Fig. 4.2 A, B), or may be totally buried by sediments.

The accessibility of diamonds to the final drainage network of the river, generating the terminal mega-placer, is greatly enhanced during rejuvenation if several discrete retained and transient placer deposits that would possibly yield larger, concentrated and commercially viable deposits are already gathered within or near to the final large drainage network (for example, the present Orange–Vaal drainage basin, which has existed since at least Cretaceous times (de Wit, 2004). Down-wasting during planation on positive cratonic relief significantly increases the diamond concentration of weathered products by more than ten times the grades of the host gravel (Bluck et al., 2005). Many pre-1 Ga kimberlites may have been eroded and the diamonds held in palaeosols, or upgraded and dispersed into intra-cratonic basins or basins peripheral to the craton.

Depending on climate and relief, large rivers have proportionally large drainage basins with high sediment discharges, and any part of the drainage basin not on the craton is potentially contributing sediment but no diamonds to the final placer. A high proportion of the placer drainage basins should be on the craton or on those fringes that may have diamond-bearing rocks. In order to release the greatest abundance of diamonds, repeated additions of newer kimberlites should be added to the craton; wide craton area coverage by a high-energy regional drainage network must develop at the optimum time; and down-wasting must be continuous. Early large-scale drainage networks will potentially take away those accumulated diamonds. Lower elevations and low relief due to lack of substantial marginal active mountain chains result in large rivers with large drainage basins in high precipitation areas carrying low sediment loads.

The resultant steeper slopes during rejuvenation increase drainage density and river energy, causing residual placers and buried kimberlites to be reached by the drainage network cutting into soft cover; increase sediment transport efficiency and potential for diamond sorting in rivers; and yield clasts which form diamond trap sites. The conditions that enhance diamond placer development, discussed above, were at play during the formation of the Umkondo diamondiferous conglomerates and grits. A pattern of sedimentation events can be deduced from the different rock types in the Umkondo sedimentary basin.

### 4.3 Sedimentation model of the Umkondo Basin

The area to be discussed in this section lies on the western margin of the Umkondo basin (Fig. 4.3) where the diamondiferous Umkondo conglomerates are better developed and where mining activities are currently concentrated.

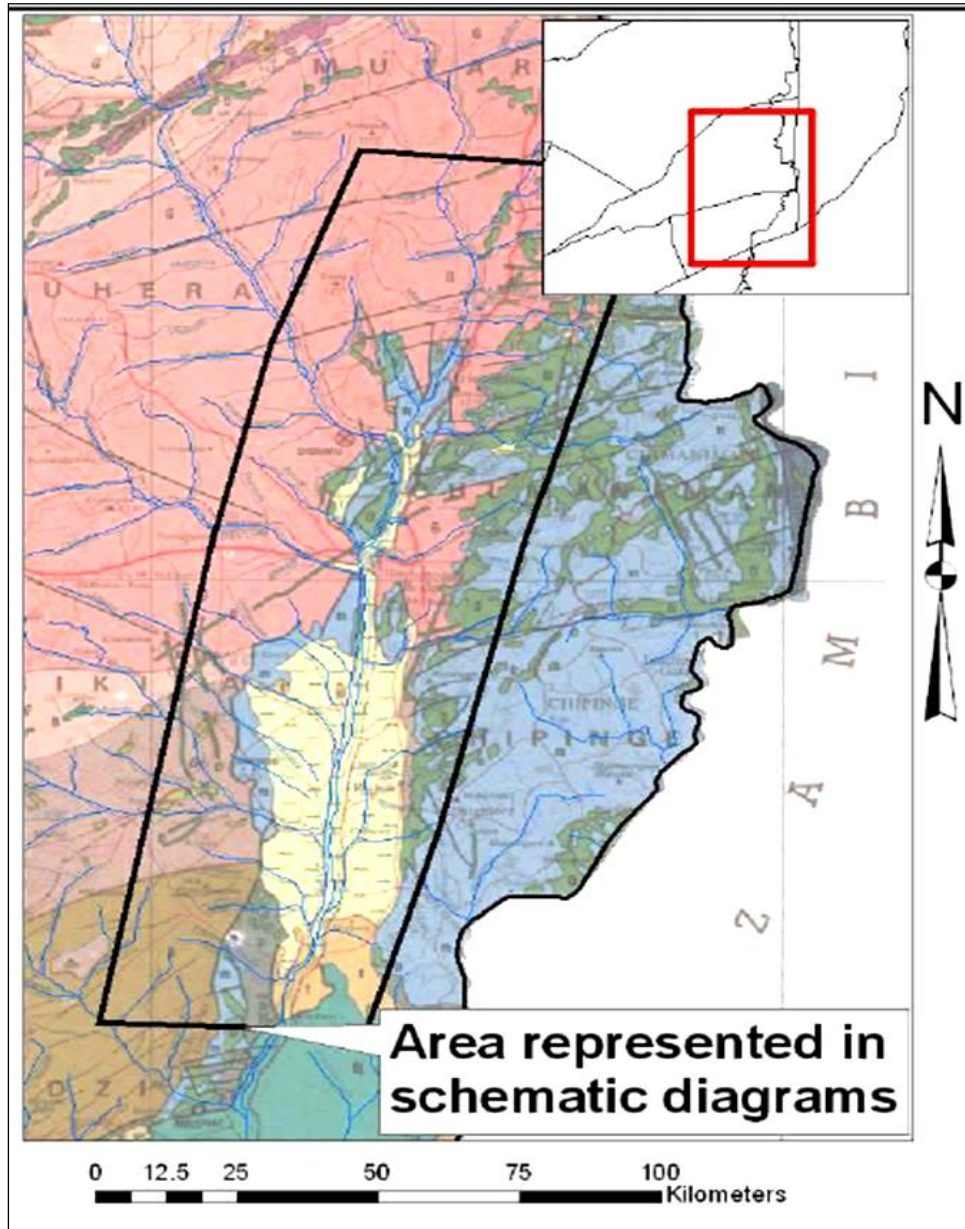


Fig. 4.3: The area represented in schematic diagrams for the western Umkondo model for basin formation and sedimentation. Map from: Roberts, (2003a)

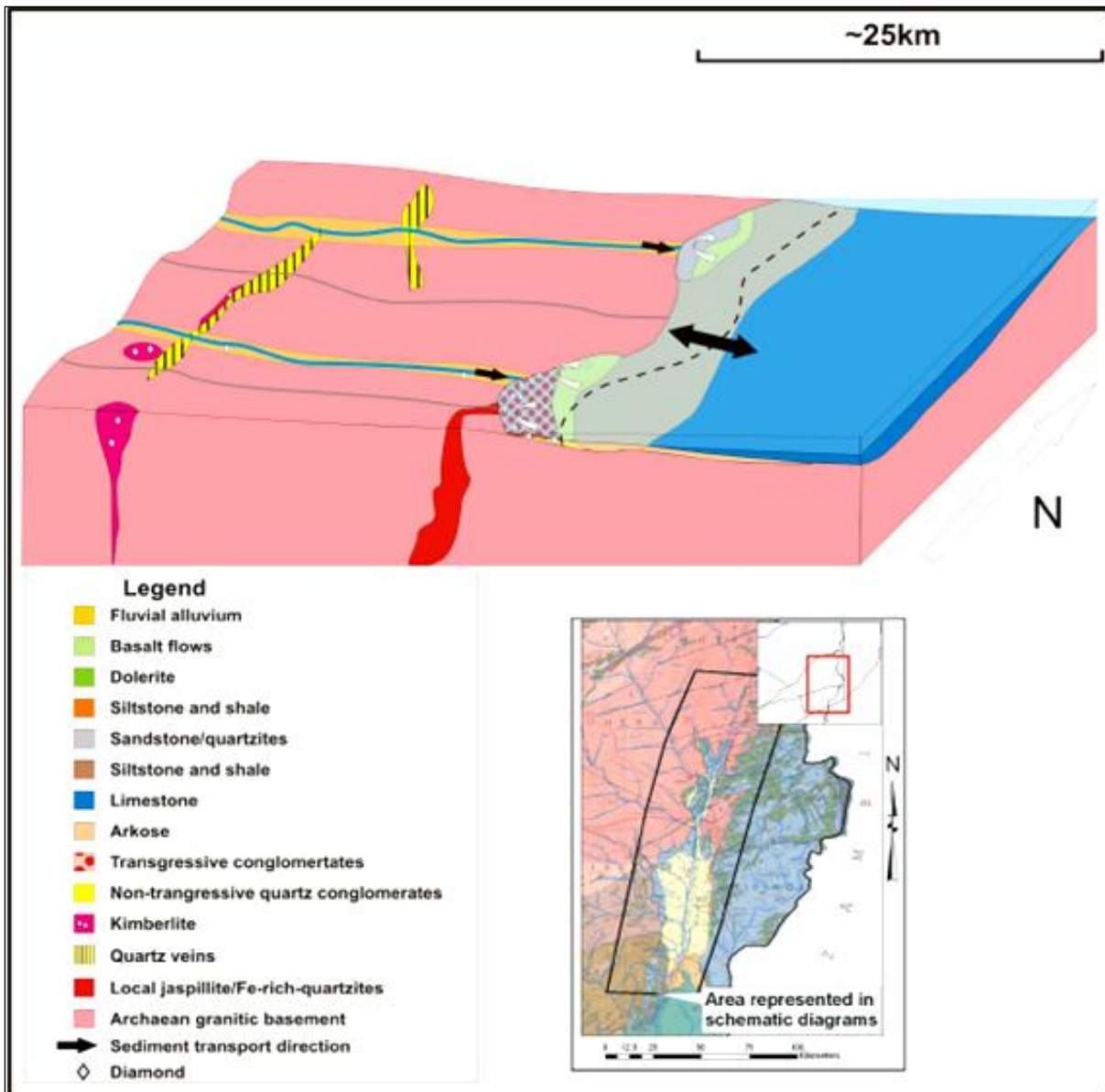


Fig. 4.4: The basal conglomerate deposition on a stable Zimbabwe Craton basin margin. Illustration taken from: Roberts, (2003a)

Roberts, (2003a) suggests that “the initial Umkondo basin transgression was associated with the subsidence of a foreland basin.” The initial transgression eroded the basement and kimberlites into the basin margin, where the conglomerate was reworked and the diamonds concentrated by wave action and by alternating high and low tidal wave energy variations.

It has been suggested that the subsequent increase in sediment input from the Zimbabwe Craton may have been a result of the development of a forebulge on the Zimbabwe Craton (Master, 2006) in response to the loading of the craton margin.

The basal conglomerates are modelled as having been formed at the basin margin on an initially stable Zimbabwe craton margin (Fig. 4.4). Diamond input appears to be discrete, and related to direct, low-sediment content fluvial inputs into the basin margin, with little or no longshore dispersion. For the concentration of the diamonds within the conglomerate, Roberts, (2003a) further suggested that “over a long duration wave action winnowed the conglomerates and resulted in significant rounding of the clasts including the highly concentrated diamonds”.

The diamonds appear to have been concentrated in the basal-most portions of the conglomerate due to the jiggling action in the shore environment. An initial transgression is believed to have remobilised the conglomerates as a transgressive lag that eroded local basement lithologies and incorporated the more angular quartz vein clasts (Fig. 4.4).

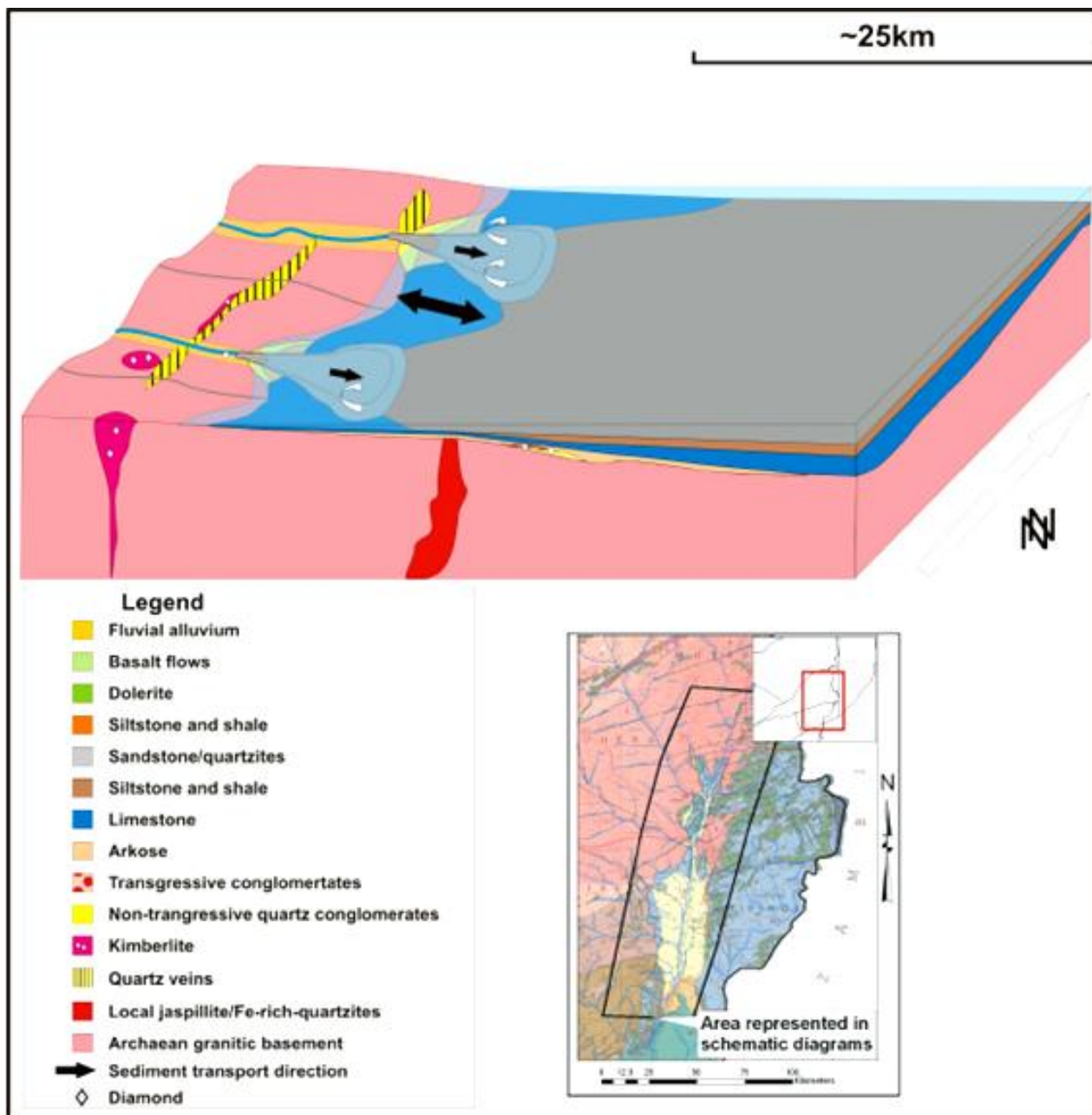


Fig. 4.5: Major regression to produce the argillaceous and arenaceous sediments of the Umkondo Group.

Illustration taken from: Roberts, (2003a)

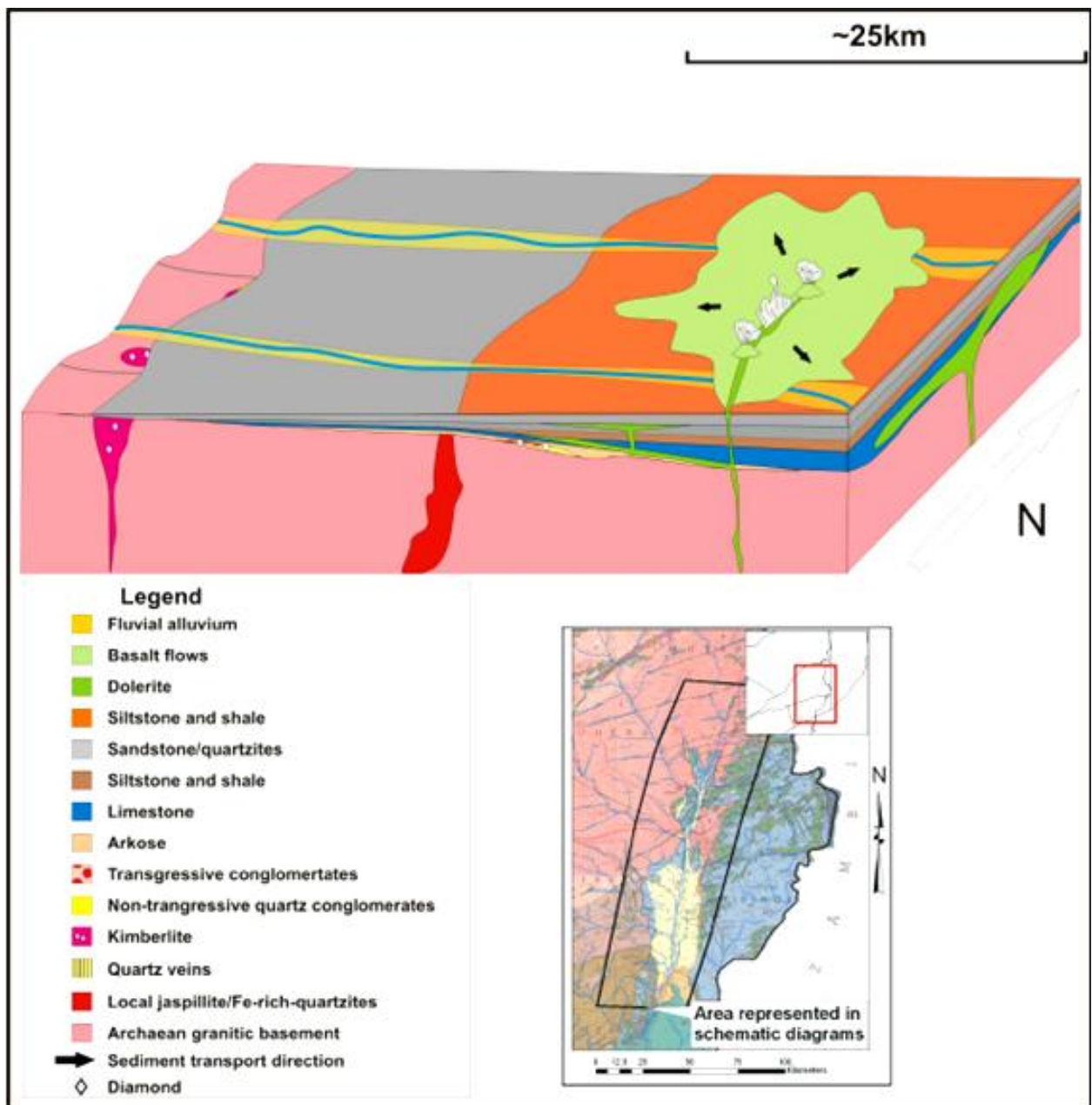


Fig. 4.6: Regression and magmatic emplacement produced dykes and sills that capped the Umkondo sediments at about 1.1 Ga.

Illustration taken from: Roberts, (2003a)

As the initial transgression developed into a major transgression, with the low sediment input being maintained, the limestones also developed, overlying the basal arkoses. Sediment input subsequently increased either as a result of the loading of the basin floor, or of the rise of the

buoyant Zimbabwe craton, to produce the argillaceous and arenaceous sediments which dominate the Umkondo Group (Fig. 4.5). The Umkondo Group sedimentation was concluded with a major regression and possibly an uplift of the basin associated with the impact of the buoyant mantle material (Roberts, 2003b).

As the accretion of the arc terrain associated with the possible docking of Antarctica during Rhodanian assembly stalled (Master, 2010), the rising of buoyant mantle material along the Zimbabwe Craton margin resulted in widespread melting and injection of basaltic melt (Fig. 4.6), which today caps the Umkondo sediments. After the termination of sedimentation, the Umkondo sediments underwent faulting and rifting, which resulted in the present topography of the Eastern Highlands of Zimbabwe.

## **5.0 CHAPTER FIVE**

### **DIAMOND SURFACE STRUCTURES AS EVIDENCE OF DISTAL TRANSPORTATION AND UNUSUAL CHEMISTRY FOR THE UMKONDO DIAMONDS**

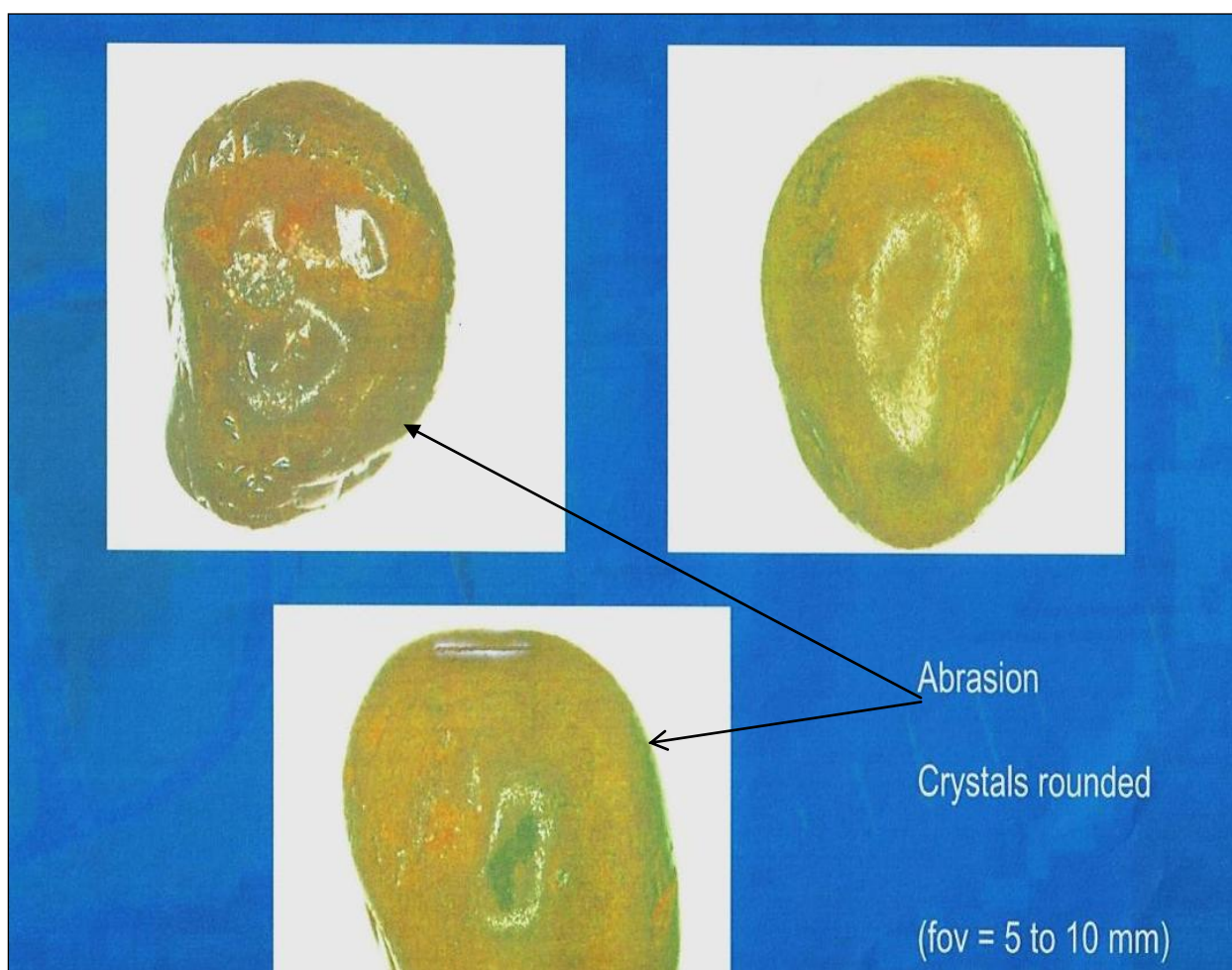
#### **5.1 Introduction**

It has been indicated in Chapter 1 that numerous non-diamondiferous to very low grade kimberlites were discovered in and around the western edge of the Umkondo Basin where alluvial diamond mining activities are taking place. Therefore, the sedimentary-hosted diamonds within the Umkondo conglomerates are not in any way related to these kimberlites, and thus the diamonds must have been transported from somewhere into the basin. Furthermore, it has been shown in Chapter 2 that the diamonds within the 1.1 Ga Umkondo conglomerates are older than these conglomerates and also much older than the rest of the kimberlites on the western edge of the Umkondo Basin. Roberts, (2003 b) showed that there are surface structures on the diamonds that support the idea that the Umkondo alluvial diamonds were transported from distal regions into the Umkondo Basin.

#### **5.2 Surface structures**

There is ample evidence of distal travel and most likely multiple burial and heating as deduced from the diamond surface textures morphology and the unusual chemistry of the recovered diamonds from the vicinity of the Makodzi Anomaly (Chapter 9, Fig.9.1), around which most of the mining activities are taking place. Roberts, (2003b) explains the extreme abrasion on the surfaces of the diamonds as having resulted from “long travel distance from sources” (Fig. 5.1), and the brown spots on the diamonds as indicating a “heating event experienced by originally irradiated diamonds” (Fig. 5.2).

The brown spots are due to burial and heating, and the green spots with matched brown spots are thought to be due to irradiation again after temperature decline. The majority of the once octahedral-shaped diamonds have rounded edges and points at present, rather than the normally sharp edges and pointed apexes; also due to abrasion during transportation (Fig. 5.3). The fragility of the diamonds is due to a combination of in-situ breakage or the diamond pieces of larger stones which were abraded during long distance transportation.



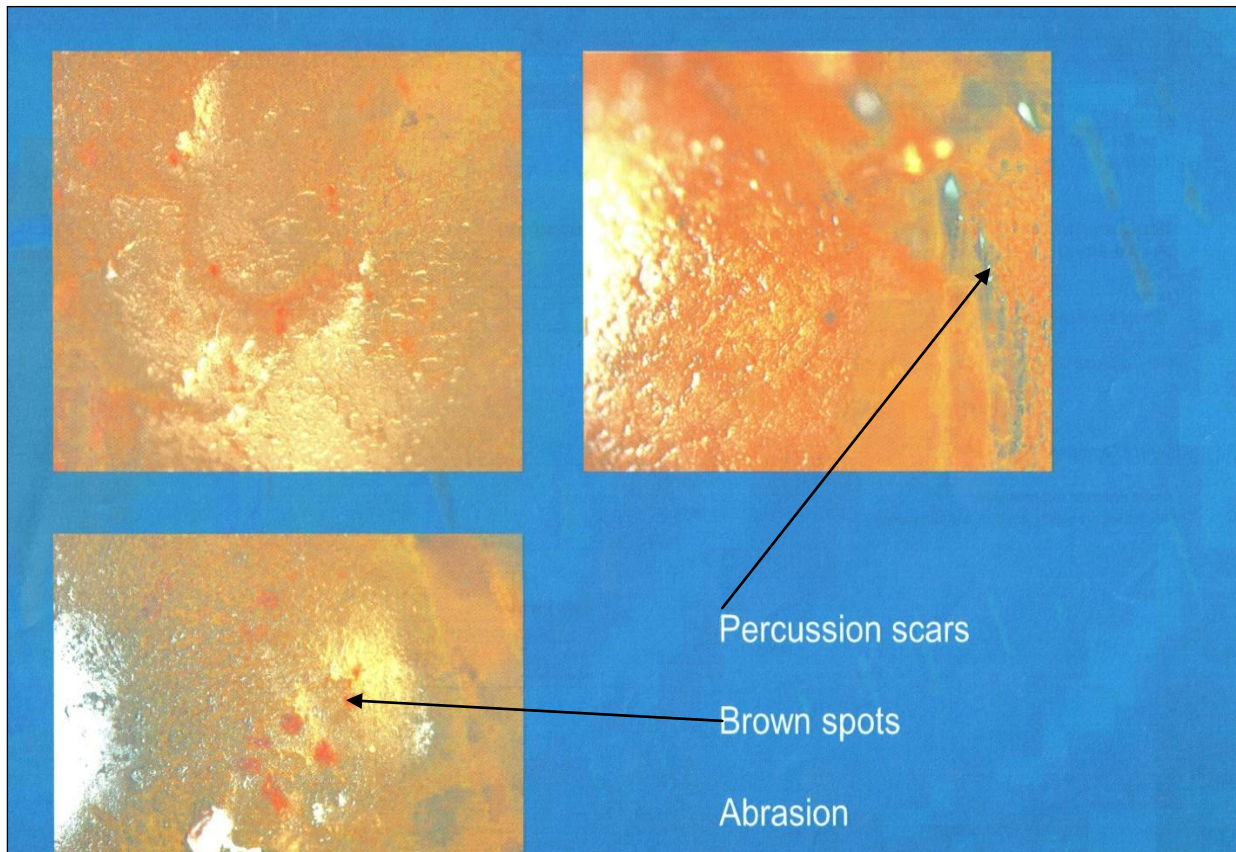
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Fig. 5.1: Rounded diamond crystals due to extreme abrasion during transportation. Figure adapted from Roberts, (2003b).

The diamonds from the basal conglomerate at Makodzi, on the western edge of the Umkondo Basin, are often fractured and broken (Fig. 5.4), with the eroded breakage surfaces suggesting that diamond breakage took place during transportation and within the conglomerate during burial and subsequent exhumation (Roberts, 2003b).

Roberts, (2003b) suggests that the heating of the diamonds was typically pegged at approximately 500°C, although encasing sediments suggest a lower temperature of metamorphism or recrystallisation, as seen by greenschist facies overprint. The age of the conglomerate is probably slightly greater than 1.1Ga (date of syn/post Umkondo Dolerites),

and this long period of time may have been sufficient for green spots to revert to brown (Fig. 5.2) under burial conditions. Nitrogen contents and Infra-Red characteristics of the Makodzi diamonds define an almost unique population by global standards, suggesting that they are derived from the same high-nitrogen, possibly eclogitic, mantle source.

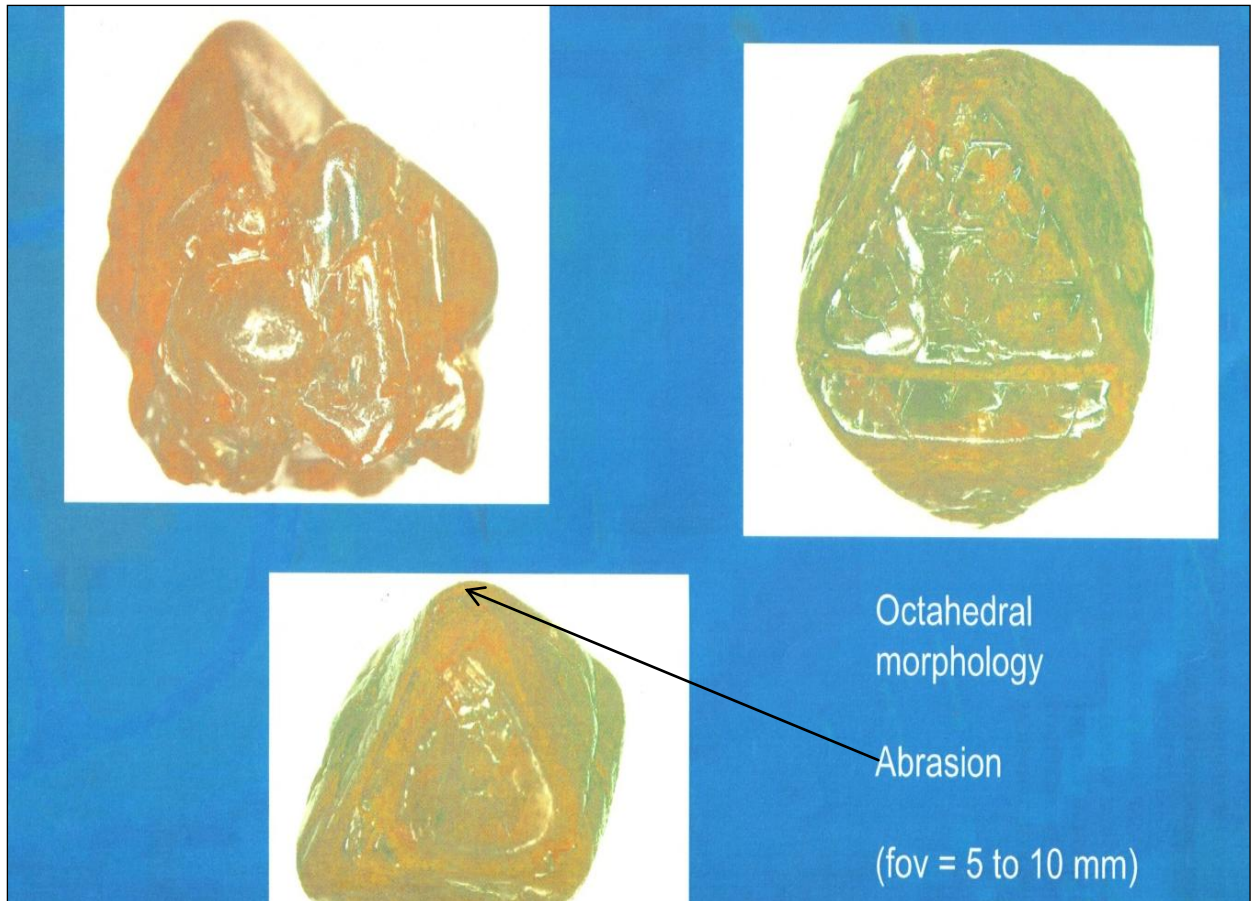


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Fig. 5.2: The brown spots are due to burial and heating while percussion scars are due to abrasion on the diamonds during transportation.

Figure adapted from Roberts, (2003b).

As the diamonds are transported by water in river channels, they are continuously knocked against other pebbles and rock surfaces, and also roll along the stream bed. The mode of transportation results in sharp diamond edges and apexes being continuously abraded, resulting in rounded pebbly diamonds and some broken diamond pieces.

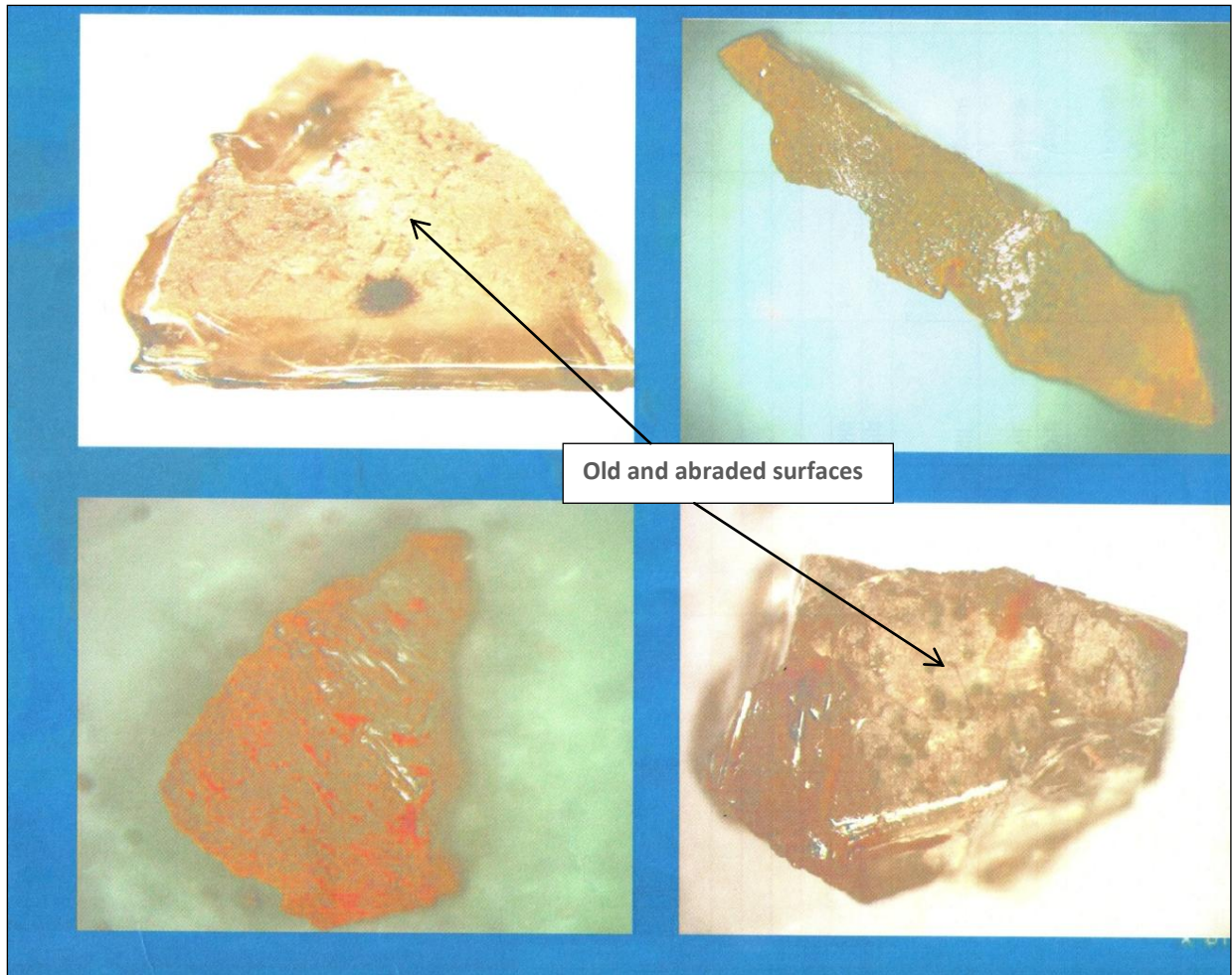


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Fig. 5.3: The octahedral morphology of the diamond crystals with sharp edges and points is more rounded due to abrasion during transportation.

Figure adapted from Roberts, (2003b).

Some of the diamonds still exhibit the smoothed-out octahedral morphology due to their relative resistance to abrasion, as opposed to the totally rounded pebbly diamonds.



Scale: 1:2

Fig. 5.4: The old and abraded surfaces are an indication of long-distance transportation from source. Figure adapted from Roberts, (2003b).

### 5.3 The unusual Chemistry of the Umkondo Diamonds

Diamonds are broadly divided into two types (I and II) based on the presence or absence of nitrogen impurities, and further subdivided according to the arrangement of nitrogen atoms (isolated or aggregated) and the occurrence of boron impurities. Diamond type is directly related to colour and the lattice defects that are modified by treatments to change colour. Irradiation on all types of diamonds produces green or blue colours, and if irradiation is followed by heating to temperatures of 800–1000°C it produces a yellow or pink colour which is common with the Marange diamonds.

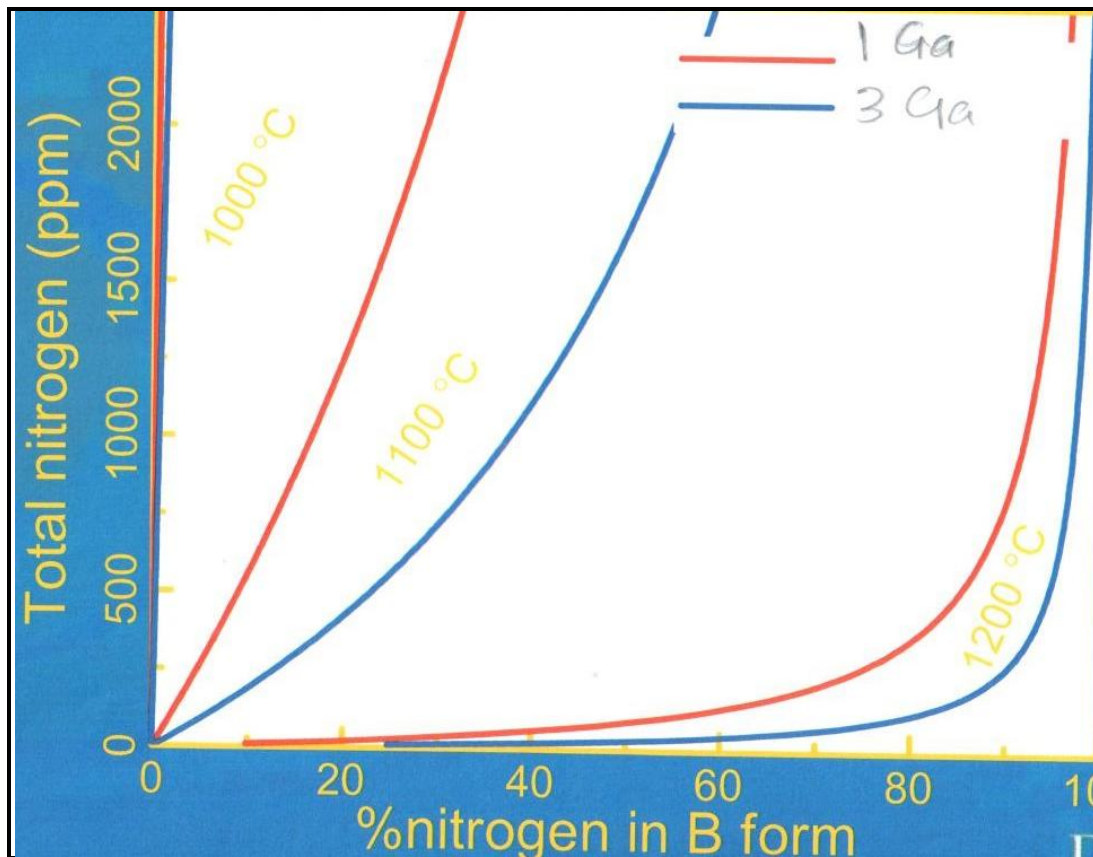


Fig. 5.5: The variations of B form nitrogen with temperature of formation and age of the diamonds as a percentage of total nitrogen. Figure adapted from Roberts, (2003b).

In some cases, certain diamond types have become associated with specific geographic occurrences. Type Ia stones occur in all major diamond deposits, but they are perhaps best known from the mines of South Africa. As a result, yellow type Ia diamonds are often termed “cape” diamonds (Christopher M, Breeding and James Shingley, 2009). Pink type Ia diamonds are typically a product of the Argyle mine in Australia. Type Ib diamonds can occur in all major deposits, but they are well known from mines in India, Brazil, and South Africa (Christopher M, Breeding and James Shingley, 2009 citing King et al., 2005). Type IIa diamonds likewise occur in all deposits, but the Golconda region of India has historically been known as one important source. Many type IIa pink diamonds are thought to originate from Brazil, Africa, and India. Type IIb diamonds are less widely distributed; most come from India and the Cullinan (formerly Premier) mine in South Africa (Christopher M, Breeding and James Shingley, 2009 citing King et al., 1998).

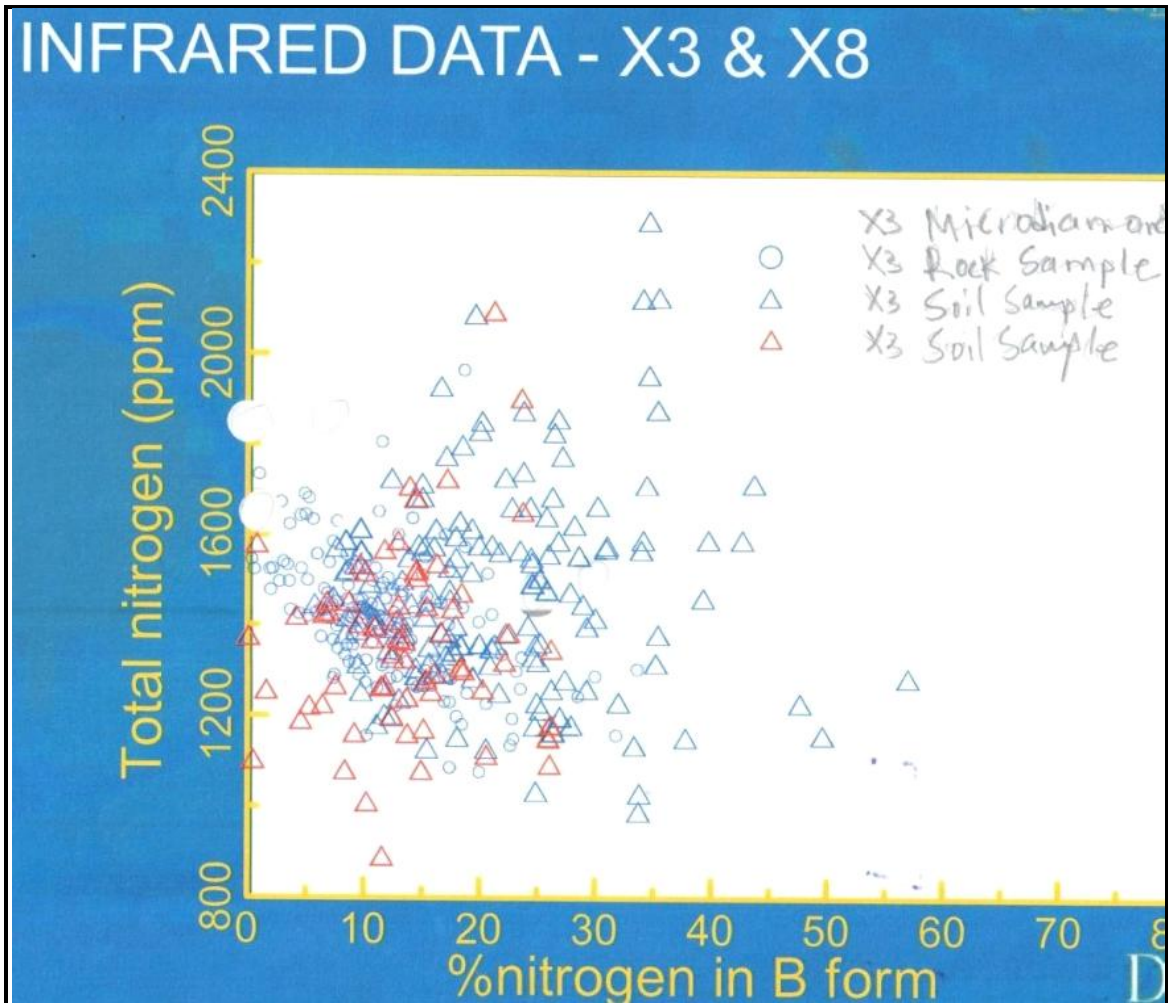


Fig. 5.6: The B form nitrogen plots through infrared method for soil, rock, and microdiamonds from the Makodzi Anomaly, Marange diamond fields.

Figure adapted from Roberts, (2003b).

Both Somabula and Venetia diamonds (Fig. 5.7 and 5.8 respectively) show concentrations of B form nitrogen that ranges from 0% to 100% of the total nitrogen concentrations of around 500ppm. On the other hand the Marange diamonds show a unique concentration of B form nitrogen of between 0% and 40% of the total nitrogen of around 1500 ppm. Thus the concentration of B form nitrogen in the Marange diamonds is unique and unrelated to diamonds from many regions around the world.

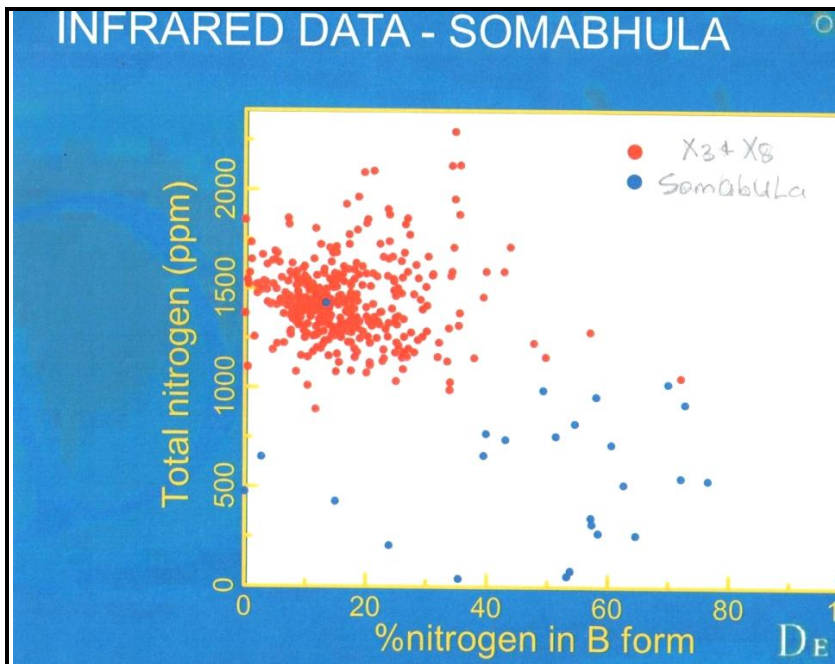


Fig. 5.7: A comparison of the B form nitrogen concentration in samples X3 and X8 from the Makodzi Anomaly to that of the diamonds of the Somabula gravels.  
Figure adapted from Roberts, (2003b).

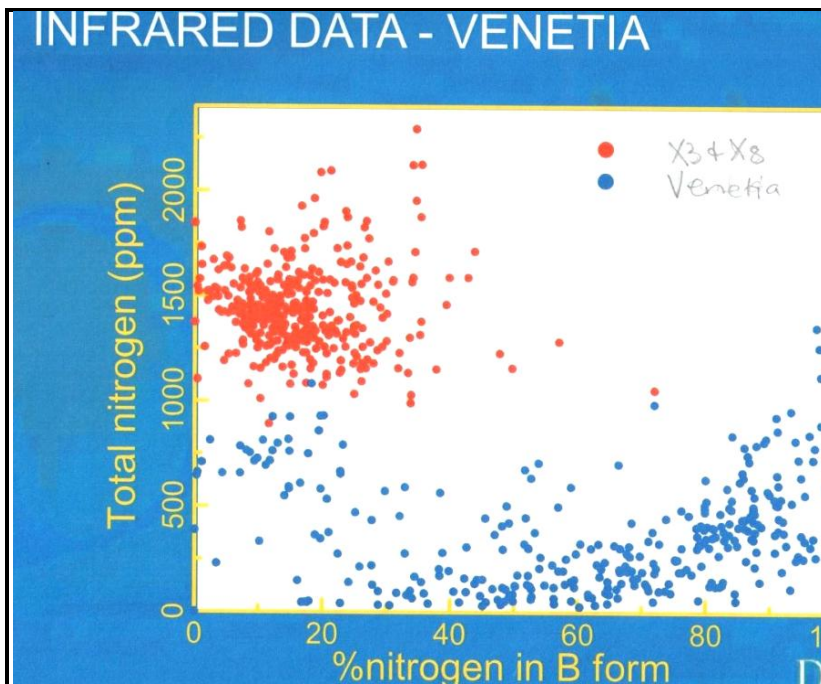


Fig. 5.8: A comparison of the B form nitrogen concentration in samples X3 and X8 from the Makodzi Anomaly gravels to that of the diamonds from Venetia kimberlite in South Africa.  
Figure adapted from Roberts, (2003b).

#### **5.4: Possible sources of the diamonds**

The source of the diamonds within the grits and conglomerate of the Umkondo System at the contact between the Frontier Series and the Lower Calcareous Series is not known. There are, however, indications of possible provenance which require intense and extensive study to unravel the mysterious source. The indications of provenance are that:

1. The diamonds may have been eroded from the upper portions of the Frontier Series before the series was thrust over the Zimbabwe Craton. This accession comes from the presence of lithic fragments of the Frontier Series within the eastern diamondiferous Umkondo conglomerate below the Chimanimani Mountains, suggesting that the diamonds may have originated from a secondary sedimentary source, the Frontier Series.
2. The diamonds may have come from one huge kimberlite or a cluster of kimberlites extruded onto the floor of the Umkondo Basin after the over-thrusting of the Frontier Series onto the Zimbabwe Craton but before the deposition of the Calcareous Series. This accession is unlikely since no evidence of the presence of indicator minerals or diamonds themselves has yet been found in the interior of the basin. Diamonds have only been found on the eastern and western margins of the Umkondo Basin, suggesting a source from outside the basin.
3. The kimberlites on the western edge of the Umkondo Basin have not been dated and the kimberlites are said to be barren or partially diamondiferous, according to the mineral chemistry analyses. Could they be remnants of once much larger and extremely rich kimberlite clusters that have since been eroded down to their root zones? The paleo-directions of the channels into the Umkondo Basin are from the west and north-west. The location of these kimberlites relative to the paleo-direction seems to suggest that the kimberlite clusters may be part of the kimberlites that contributed diamonds into the Umkondo Basin.
4. The age of the diamond-hosting conglomerate is estimated at more than 1.1Ga, and therefore, the contributing kimberlites must have been much older. The general age of the kimberlites known today is much younger, probably about half the age or less of the contributing kimberlites. This therefore suggests that some kimberlites older than the ones known today may have contributed diamonds into the Umkondo Basin. These kimberlites

have since been dissipated by denudation, and what remains now is their diamond component hosted within placers, of which the Umkondo is one.

5. The brown and red spots on the diamonds, the surface textures, and the unusual chemistry of the diamonds seem to suggest that the diamonds may have come from a distal source rock not yet known to mankind but definitely not kimberlitic. The unusual chemistry does not exist in the known kimberlites nearer to the Umkondo Basin, thus further emphasizing that these kimberlites are not related to the contributing kimberlites.

6. As will be discussed in Chapter 9, the conglomerate average pebble size, diamond grades, and average stone size (carats per stone) progressively decrease from north to south. The decreases seem to suggest that the contributing streams' paleo-direction was from generally the north to the north-west, and thus the provenance of the Umkondo diamonds was to the north to north-west of the present location of the alluvial deposit.

## **6.0 CHAPTER SIX**

### **THE REGIONAL GEOLOGY OF THE UMKONDO SEDIMENTARY SYSTEM**

#### **6.1 Stratigraphy**

As has been alluded to in the preceding chapters, the Umkondo Sedimentary Basin is a foreland basin thought to have formed during extensional–compressional cycle at the margin of the Zimbabwe craton. Many foreland basins are marine or lacustrine. In the Umkondo sedimentary sequence, the diamond-bearing conglomerate grades upwards rapidly into bedded grits and sandstones capped by carbonates, and the sequence suggests a shallow marine environment of deposition.

##### **6.1.1 The Basement Complex**

Following his 1962 article, Watson, (1969) reinforces his earlier assertion that:

. . . the Umkondo System rests on a floor of the Archaean crystalline intrusive granites of the Mutare Batholith which contain a small remnant of Basement named the Cronley Schist Belt. The Schist Belt consists of a northern Greenstone Series and southern highly metamorphosed calc-hornfels quartz-chloritized biotite schists Sedimentary Series with a wedge of banded ironstone between the two series in the south-west. On either sides of the schist belt along strike occurs east-north-east foliated gneissic and contaminated granites.

In the south of Birchenough Bridge, the Umkondo System rests directly on even-grained, Archaean gneissic rocks of the Limpopo Mobile Belt and continues eastwards into Mozambique underneath the Frontier Series. On the west side of the Umkondo highlands, the reddened and epidotized intrusive granites are often cut by quartz and pegmatite bodies with some occurrences of beryl.

The base of the reddened zone is evenly linear, representing a flattening due to weathering of fresh granite to patchy concentrations of granitic rock debris in small depressions or peneplanation of the granitic floor prior to Umkondo sedimentation. The phenomenon is widespread in the top 150 centimeters of the granitic floor. It then rapidly dies out with depth into the shades of grey more normal in the Basement Complex granites.

System	Age	Series	Contact	Lithology	Thickness (m)	
Umkondo	Precambrian		Major Unconformity			
				Umkondo Dolerites	Total over 1,700	
				Intensive contact		
		Upper Argillaceous Series		Red/purple shales and siltstones	500–900	
		Quartzite		Black quartz-magnetite ironstone	+450	
		Lower Argillaceous Series		Black/grey Shales and siltstones	300–450 in west, 2,500 in east.	
		Calcareous Series		cherty calc-hornfels and limestone	240–300 thinning to 0 eastwards	
		Frontier Series	Unconformity	<b>Diamondiferous conglomerates</b>	0.1–2	
				Upper Chlorite Schists (UCS)	0–330+ in south	
				Upper Quartzite (UQ)	150 to over 450 in north	
				Lower Chlorite Schist (LCS)	150–450	
	Lower Quartzite (LQ)		210–300			
	Major unconformity	<b>Diamondiferous conglomerates</b>				
Basement Complex	Archaean			Granite, gneiss, and greenstones	?	

Fig. 6.1: Stratigraphy of the Umkondo System. Table reconstructed from: Watson, (1969).

The red contact zone at the top of the granitic floor to the Umkondo System is, therefore, partially igneous and partially sedimentary. The granite shows the microtexture to be sedimentary bedding in arkose consisting of quite well sorted, interlocking, turbid

plagioclase grains of variable sizes, and of subsidiary rounded to sub-angular quartz grains (Watson, 1969).

In Mozambique, east of Chimanimani, granitic gneiss underlies the rocks of the Frontier Series, and, away from the contact, the gneiss has a strong ENE foliation and contains parallel streaks and inclusions of chlorite and hornblende schists. It appears to be Basement Complex granite that has been affected by the shearing and metamorphism of the Limpopo Mobile Zone. In a zone up to about 3.50 meters thick, the gneiss underlying the Frontier Series has been converted by tectonic movements and deformation to sheared, cataclastic, quartz-sericite schist, or, more rarely, quartz-chlorite schist.

The earliest rocks of the Umkondo System, the Frontier Series, were deposited in a basin (not the Umkondo Basin) lying mainly to the east of Zimbabwe in Mozambique, and only a small portion of the total sediments of the Series remains today. The rocks form a 50 kilometers long and up to 10 kilometers wide strip, partly forming the Chimanimani Mountains. The northern 30 kilometers of the Frontier Series have been overfolded and piled up in recumbent folds and slices against the younger rocks, but in the south they dip disconformably westwards under the younger Lower Argillaceous Series, and end.

### **6.1.2 The diamond-bearing Umkondo System.**

The 400 kilometre long Precambrian Umkondo Sedimentary System outcrops discontinuously along the eastern border of Zimbabwe and the western part of Mozambique from the Lower Save River northwards to Inyanga. The western portion of the Umkondo System, outcropping in Zimbabwe, has been very gently folded and slightly metamorphosed, while the eastern portion, mainly in Mozambique and only slightly impinging into Zimbabwe, has been intensely deformed and metamorphosed. The Umkondo System consists of the north-trending Frontier Series, which is overlain by the Calcareous and Argillaceous Series (Fig. 6.1). The exact age of the Umkondo System is not known. Watson, (1969), citing McElhinny, and Opdyke, (1964), points out that:

. . . the Umkondo Dolerites show that they are well over 1,136 Ga, and the Umkondo Sedimentary rocks must be older. The Umkondo Dolerites may be older than the Mashonaland Dolerites, which have been dated at 1,433 to 1,638Ga.

The supposition that the deformed Frontier System rocks are older than the other flat-lying Umkondo rocks to the west is largely based on marked lithological differences between the two types along a sharp, and apparently faulted, contact coupled with the much higher degree of folding and metamorphism exhibited by the Frontier rocks. The thousands of metres of younger Umkondo sediments are found to the west and end sharply against the Frontier Series, and none has been found capping the Frontier Series (Watson, 1969).

#### **6.1.2.1 The Frontier Series**

The 42 kilometer long Frontier Series outcrops as the Chimanimani Mountains along the Mozambique border and on the south is terminated and down-thrown by the easterly-trending Zunguni Fault. The northern half of the Chimanimani Mountains is composed of the Lower and Upper Quartzites, with the sandy, ferruginous and micaceous Lower Chlorite Schists sandwiched between them. These rocks are folded into a north-trending synclinal structure, which is complicated by over-folding, multiple thrusting and facies changes. In the southern half, the Frontier Series appears to pass disconformably westwards under the Lower Argillaceous Series.

##### **6.1.2.1a The Lower Quartzites**

The base of the white, east dipping, well-foliated, micro-sheared, fine- to medium-grained Lower Quartzites in Mozambique rests unconformably on the reddened Mozambique gneiss, with occasional lenses of slightly chloritic quartz-mica schist (Watson, 1969). The bedding dips westwards. There are also narrow bands and micro-augen of white quartzite, which trend from east to west. The Lower Quartzites weather to a soft, white, friable, and rather sugary rock, with a well-developed system of joints and fractures which trend either north or east. Coupled with the east-dipping foliation, the Lower Quartzites give rise to a curious weathering phenomenon, *roches penetantes*, which resemble huge graveyards of easterly-inclined and roughly-aligned white tombstones.

In the South of Ben Nevis Peak, the Lower Quartzites are overfolded on to the Lower Chlorite Schists, with shearing along the apex of the fold, while the folding and thrusting increases southwards until south of Skeleton Pass. Here the Lower Quartzites are piled up in a repetitive succession to form the highest range of mountains, and Binga, the highest peak in

the range. Here micaceous shear zones are common.

### **6.1.2.1b The Lower Chlorite Schists**

The frequently-overfolded Lower Chlorite Schists, a zone of sandy, chloritic and micaceous metasediments, overlie the Lower Quartzites. The Lower Chlorite Schists mostly form a well-marked zone of low-lying, undulating, grassy slopes underlain by reddish-brown soils at the foot of a westerly-inclined, Lower Quartzite dip-slope. The Lower Chlorite Schists can be sub-divided into three horizons from bottom to top, as follows:

1. Ferruginous quartz-mica schists, 2. chlorite schists, and 3. ferruginous quartz schists.



Fig. 6.2: Westerly steeply-dipping Lower Quartzites, Frontier Series, Chimanimani National Park. Figure from: Watson, (1969).

The lowest, horizontally wavy foliated (Fig. 6.3), ferruginous quartz-mica schists form a sharp contact with the underlying Lower Quartzites, and are penetrated by stringers and macro-augen lenses of quartz and quartzite, all elongated in an east to west direction. The sheared, ferruginous transitional basal quartz-mica schist horizon is overlain by the coarsely crystalline, micaceous and schistose quartz-chlorite and the slightly micaceous, very fine-

grained and siliceous chlorite schists, with a combined thickness of between 60 and 90 meters. They weather to green or red rocks. The quartz-chlorite and chlorite schists are capped by the 1.5 meter greenish-black, highly schistose, fine-grained ferruginous (magnetite) quartz schist horizon. It forms the top most horizon of the Lower Chlorite Schists with a sharp contact between it and the overlying Upper Quartzites.

Watson, (1969) explains two phenomena common at this contact:

(a) First, the normal easterly foliation dips of the overlying Upper Quartzites tend to steepen on approaching their contact with this ferruginous quartz schists horizon, actually curling under and reversing westwards along the contact, and

(b) Secondly, the Lower Chlorite Schists normally dip westwards beneath the Upper Quartzites along a sharp contact but, in several places, the top of the schists seems to be torn or ripped backwards against the overlying Upper Quartzites, lipping up against the latter as if the quartzites had bulldozed themselves into the schists from a westerly direction.

Watson, (1969) explained both phenomena as suggesting:

a sharp, west to east movement of the Upper Quartzites over the Lower Chlorite Schists . . . as the Frontier Series as a whole was thrust into its present position from the east, the more solid, homogeneous, Upper Quartzites ground to a halt first against the more stable block of the Umkondo highlands, whilst westerly movement still continued in the more mobile, underlying schists . . . set up differential movements between the two zones. The essence would be a faster, further movement westwards of the Chlorite Schists relative to the Upper Quartzites.

### **6.1.2.1c The Upper Quartzites**

The Upper Quartzites are white, fine-grained pure quartzites with a foliation that generally dips eastwards, although there is a tendency along their contact with the Lower Chlorite Schists for the foliation to turn under and dip westwards.

Further north, the Upper Quartzites are overfolded and thrust and eventually become a synclinal structure. Like the Lower Quartzites, they form large areas of *roches penatantes* but do not develop a red colour like the Lower Quartzites.

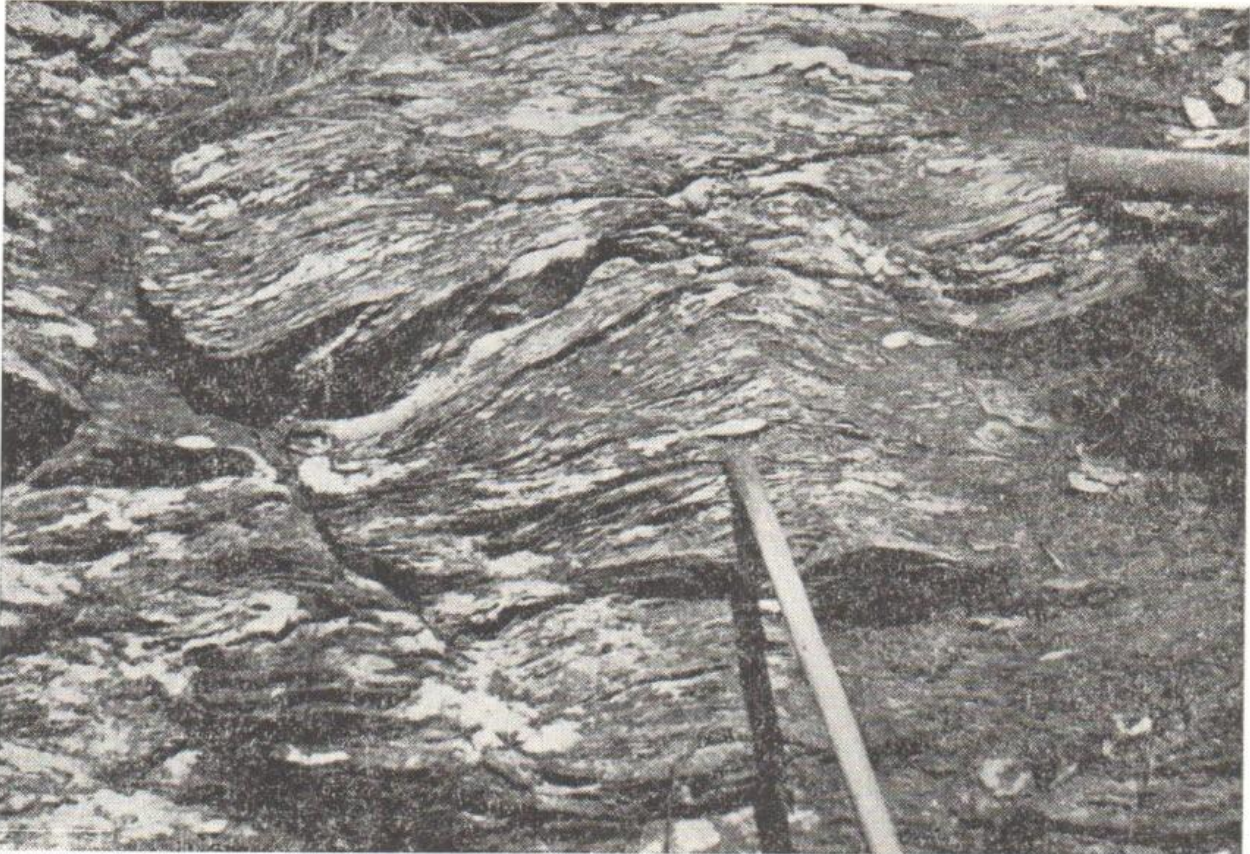


Fig. 6.3: Chlorite Schists with quartz augen, Frontier Series, Chimanimani National Park.  
Figure from: Watson, (1969)

#### **6.1.2.1d The Upper Chlorite Schists**

The less ferruginous Upper Chlorite Schists are fine-grained, greenish-grey rocks with occasional zones that are more arenaceous and less schistose. Southwards, the Upper Chlorite Schists lie on top of the Upper Quartzites and under the thrust fault contact with the Upper Argillaceous Series. A narrow band of chlorite schist, which divides the Upper Quartzites into upper and lower portions, occurs in a recumbent fold in the middle of the

quartzites.

### **6.1.2.2 The Calcareous Series**

The siliceous limestone and finely-banded, grey, cherty calc-hornfels Calcareous Series, resting on the granitic floor, forms the lowest horizon of the Umkondo System along the western part, and underlies the Lower Argillaceous Series. The chert bands resist weathering and give the limestone outcrops a characteristic fluted appearance. Watson, (1969) interprets the finely-bedded, very fine-grained, cherty nature of the calc-silicate rocks and the limestone rocks of the Calcareous Series as having been deposited in a:

. . . shallow, still-water environment. The presence of magnetite in the iron-stones indicates that they were precipitates rather than detrital sediments. . . . The various facies changes seem to lens in and out of each other as if dependent on localized changes in sedimentary conditions or supply of source material rather than breaks in sedimentation.

The calcareous beds do not outcrop in the east of the Umkondo succession: probably they are being hidden by the thrusting of the Frontier Series against the main mass of the Umkondo Highlands.

### **6.1.2.3 The Lower Argillaceous Series**

The Lower Argillaceous Series disconformably overlies the Frontier Series eastwards, and conformably overlies the Calcareous Series to the west, whilst both unconformably lie on the granitic floor. Both are overlain by the Lower Argillaceous Series. Westwards there is no break in deposition between the Calcareous Series and the Lower Argillaceous Series, and the Calcareous Series appears to pass eastwards, by lateral facies change, into the lower portion of the thickened, eastern part of the Lower Argillaceous Series.

A thin, black magnetite, coarse arenaceous bed, 600 metres above the contact between the Lower Argillaceous Series and the Frontier Series, contains scattered angular to sub-angular aelion quartz grains and streaks of green chlorite, as well as a few sub-rounded to well-rounded grains of Frontier Series lithic quartzite fragments. The presence of Frontier Series lithic quartzite fragments indicates that the Frontier Series is not only much older than the Lower Argillaceous Series and the western Umkondo rocks, but that it is also sufficiently

older to have undergone deformation, metamorphism and erosion before the deposition of the Lower Argillaceous Series.

The arenaceous and pelitic metasediments of the Frontier Series reflect a turbulent, high-energy environment, and the chlorite schists reflect calmer, deeper water and a migrating shoreline, while the Calcareous Series reflects a low-energy, still-water and possibly lagoonal environment, which enabled the colloidal precipitation of calcium, silica and iron. According to Watson, (1969), the evidence indicates that:

. . . the Calcareous and Lower Argillaceous Series are younger than, and belong to a different sedimentary deposition environment from, the Frontier Series and not a westerly facies equivalent.

The Lower Argillaceous Series outcrops as a strip of low-lying country extending southwards down the western side of the Chimanimani Mountains, and westwards is overlain by the hilly country composed of rocks of the Quartzite Series. It is bounded on the east by the Frontier Series and dips westwards to outcrop on the western margin. The reversal of the normal easterly dip of the western Umkondo rocks reflects their general structure, that of an open, gently-asymmetrical syncline with a steeper eastern limb.

The finely-bedded phyllitic shales and siltstones of the Lower Argillaceous Series are considerably thicker and of higher metamorphic grade to the east than in the west. The phyllites at the base of the Lower Argillaceous Series contiguous with the Frontier Series reflect localised slight rises in metamorphic grade as a result of the emplacement of the Chimanimani Mountains.

#### **6.1.2.4 The Quartzite Series**

The Umkondo Highlands Quartzite Series conformably overlies the Lower Argillaceous Series with a sharp clear contact. Swift, (1962) interpreted the Series as “a continuation of the shallow water sedimentary environment of the foreland basin and not a geosynclinal deposit. The increase in grain-size and feldspar content reflects a rise in elevation of the source area relative to the sinking basin floor following the deposition of the great thickness of the Lower

Argillaceous Series sediments especially in the east.” The feldspar content of the Quartzite Series decreases from the base of the series and is deficient in the uppermost coarser-grained, white quartzites horizons.

#### **6.1.2.5 The Upper Argillaceous Series**

The red- to purple-coloured Upper Argillaceous Series makes up the highest beds in the Umkondo sedimentary sequence and overlies the grey to black Quartzite Series. The rocks are mainly variegated phyllites, slates and cleaved mudstones, interbedded with siltstones and fine-to medium-grained, massive, feldspathic sandstones. They have been folded into a flat-dipping synclinal structure that pitches north-north-east. The red to purple phyllites are composed of scattered quartz grains and iron-ore in a matrix of minute parallel flakes of sericite and chlorite in varying proportions.

## 7.0 CHAPTER SEVEN

### THE GENERAL CHARACTERISTICS OF THE BASAL DIAMOND-HOSTING CONGLOMERATES AND GRITS OF THE UMKONDO SYSTEM

#### 7.1 Introduction

The basal sediments are dominated by thin arkose and rare conglomerate that are overlain by limestone

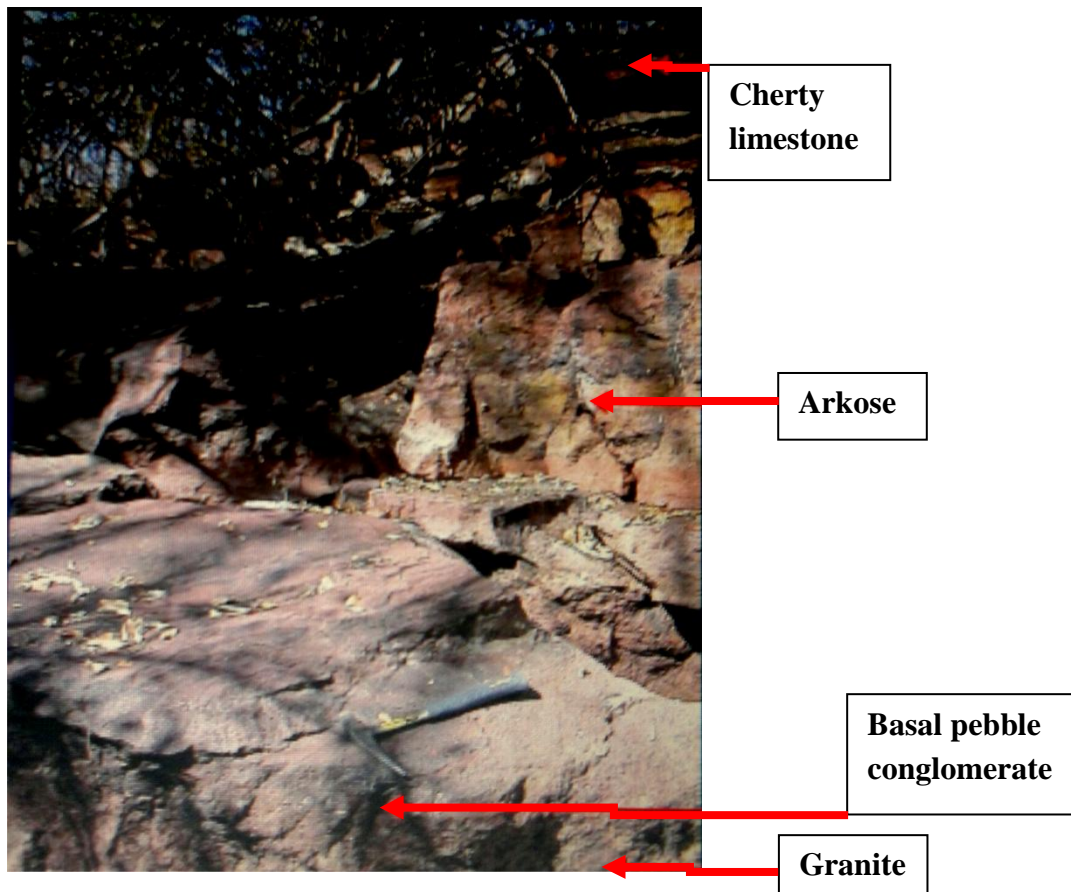


Fig. 7.1: The thin basal pebble conglomerate non-conformably overlying the red granite basement. Photo adapted from: Roberts, M, (2003a).

The conglomerate is rare because it does not occur in the majority of the basin especially in the interior.

#### 7.2 Conglomerate characteristics

The conglomerate fines both upwards and laterally into arkosic grits, which in turn are overlain by cherty limestone (Fig. 7.1). The grits are predominantly sandy to gritty with occasional local pebbly conglomerates. The conglomerate thins out laterally to a one-pebble thick lag. Within the arkosic grits of the conglomeratic unit are multiple intercalations of fine conglomerate up to 10 centimeters thick and a maximum pebble-size of up to 1 centimeter. The conglomerate pebbles are matrix-supported, the matrix being mainly derived from the underlying basement granite on the western margin and Frontier Series on the eastern margin. The coarse conglomerate units are located in zones 300–1,000 meters along strike (Roberts, 2003a). The conglomerate units form north–south trending folds, with the thickest conglomerate (up to 2 meters), on the fold-crests and thinner, highly-faulted conglomerate in the lows or troughs. The faulted lows are oriented east–west and are occupied by streams draining off the high lands. The conglomerate within the lows has been crushed by faulting and is friable, whilst that on the crests is very hard. Because of the friability of the conglomerate within the lows, these lows have become the favorite sites for illegal mining using simple tools. The east–west fault-guided streams have eroded the friable conglomerate off the high lands, and thus high diamond grades are localized within these streams below the hills.

Clasts are generally sub-rounded to well-rounded and are dominated by vein quartz pebbles (Fig. 7.2). Typically rare, but locally common, basement lithic clasts tend to be more angular (Ward, 2009), due to the lesser distance travelled, and in places tend to have been very locally derived (Figures 9.3 and 9.4). The red contact zone at the top of the granitic floor to the Umkondo System is partially igneous in the west and partially sedimentary in the east. The granite shows the microtexture to be sedimentary bedding in arkose consisting of quite well sorted, interlocking, turbid plagioclase grains of variable sizes, and of subsidiary rounded to sub-angular quartz grains. The clast shapes include both prolates and discs, with discs becoming more common upwards through the conglomerate (Fig. 7.2).

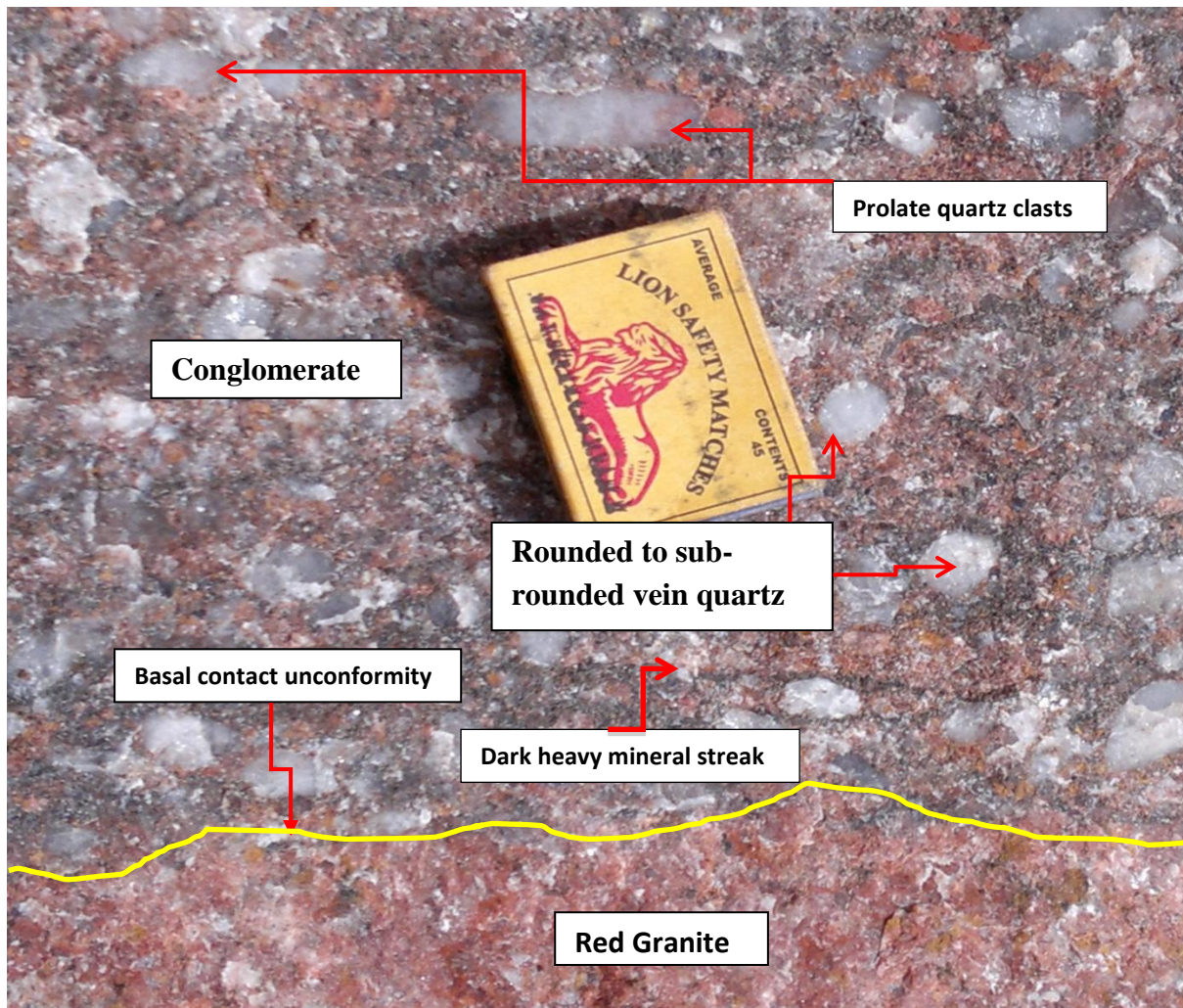


Fig. 7.2: The diamondiferous basal conglomerate, Umkondo, eastern Zimbabwe.

Photo by: the author, (2013).

The sub-rounded to rounded vein quartz pebbles have their long axes parallel to bedding, while the bedding is marked by streaks of dark heavy mineral laminations (Fig. 7.2). In the east, the conglomerate progressively changes from reddish to a darker colour (Fig. 7.4) as the conglomerate approaches the contact with the Upper Chlorite Schist of the Frontier Series. The colour of the conglomerate is due to the incorporation of the local lithologies and minerals. The predominant local lithologies incorporated into the eastern conglomerates of the Umkondo Sedimentary System are the ferruginous Lower Quartzite and the Lower Chlorite Schist.

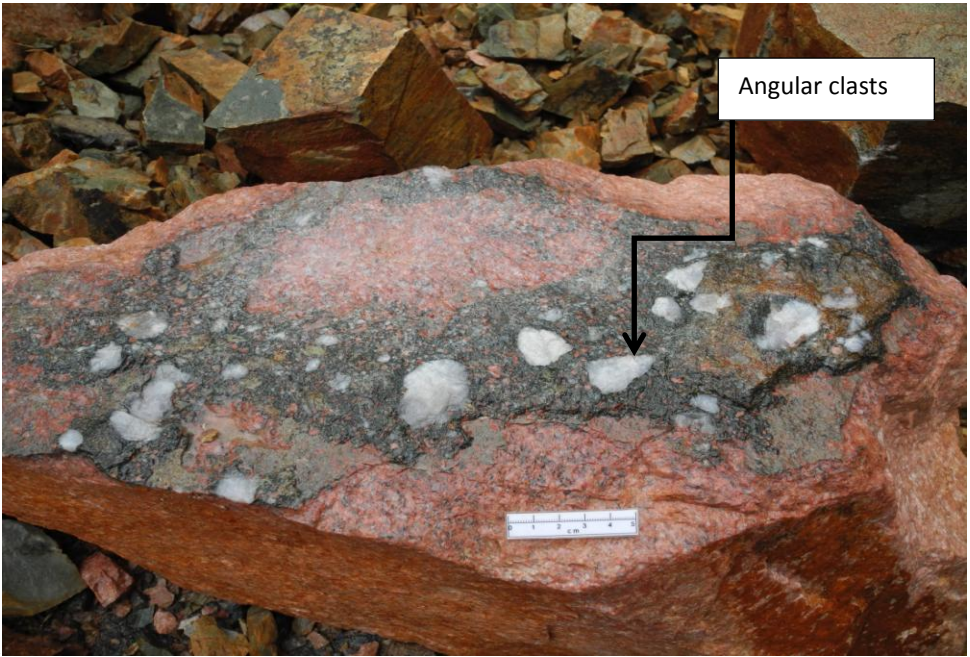


Fig. 7.3: Angular pink granitic clasts in conglomerate. Adapted from: Ward, (2009).

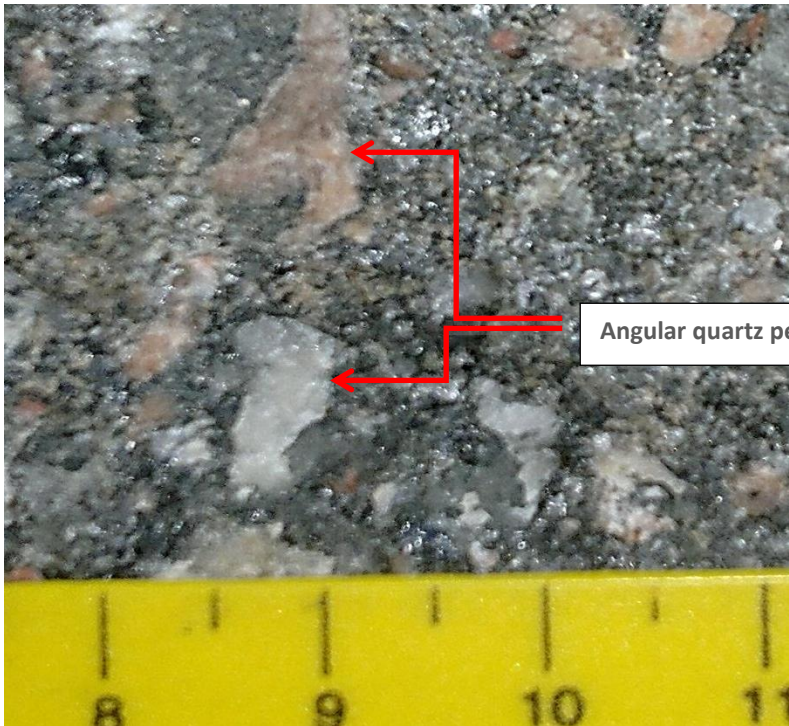


Fig. 7.4: The quartz vein and quartzite pebbles become more angular and the whole rock appears darker in the east.

Photo by: the author, (2013)

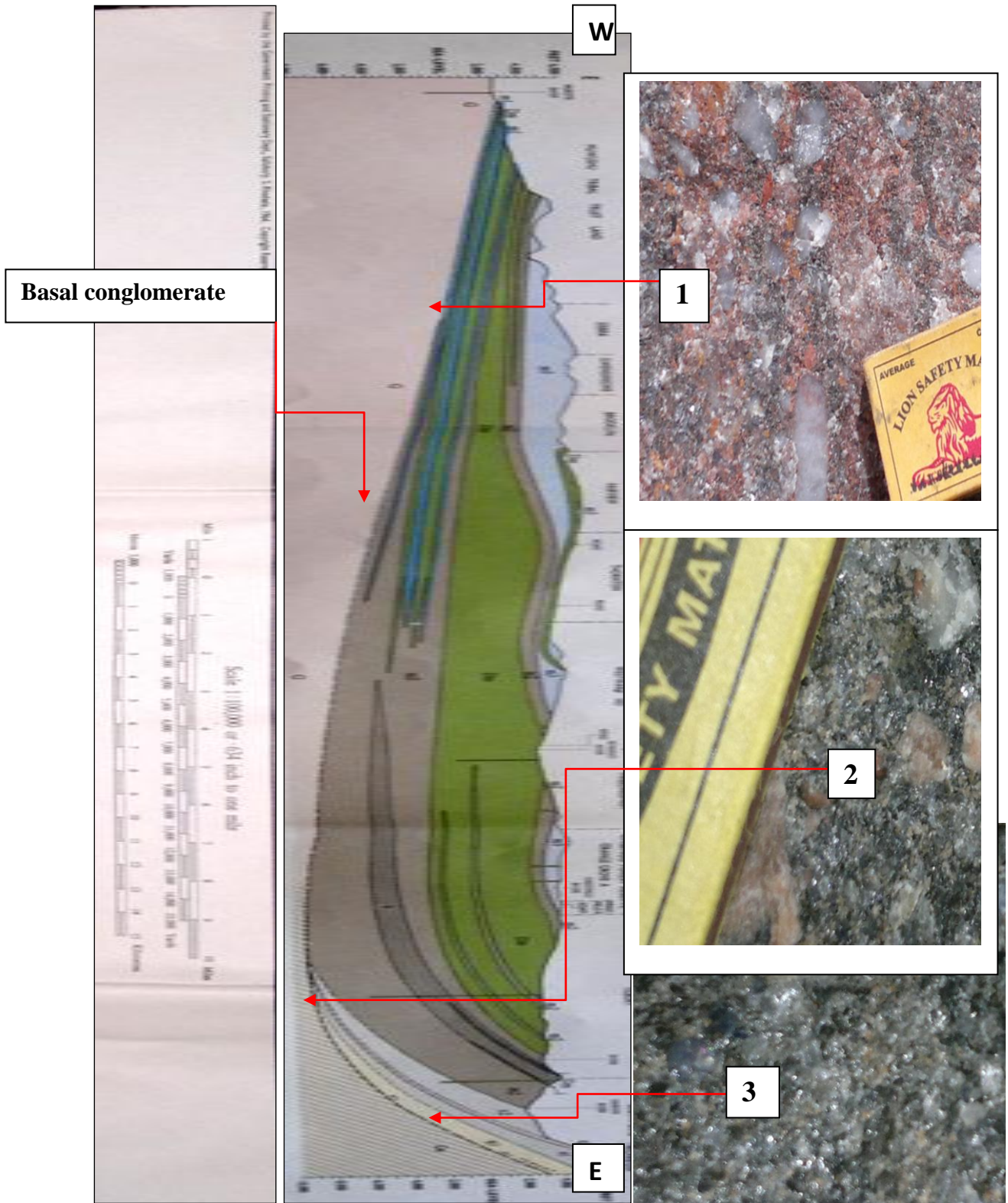


Fig. 7.5: The conglomerate matrix composition changes from purely reddish granitic in the west to dark iron-rich from west to east. (1) The western pinkish-red conglomerate, (2) Mixed

granitic and Frontier Series matrix conglomerate, (3) The eastern dark gray conglomerate overlying the Frontier Series.

Adapted from: Watson, (1969)

The conglomerate matrix composition and colour are therefore a function of the local underlying lithologies. In the west, the conglomerate is pinkish-red due to the incorporation of the underlying granitic red feldspars, some of which form part of the population of angular pebbles. In the eastern part of the basin, the conglomerate is dark grey due to the incorporation of the chlorite and magnetite-rich rocks of the Frontier Series.

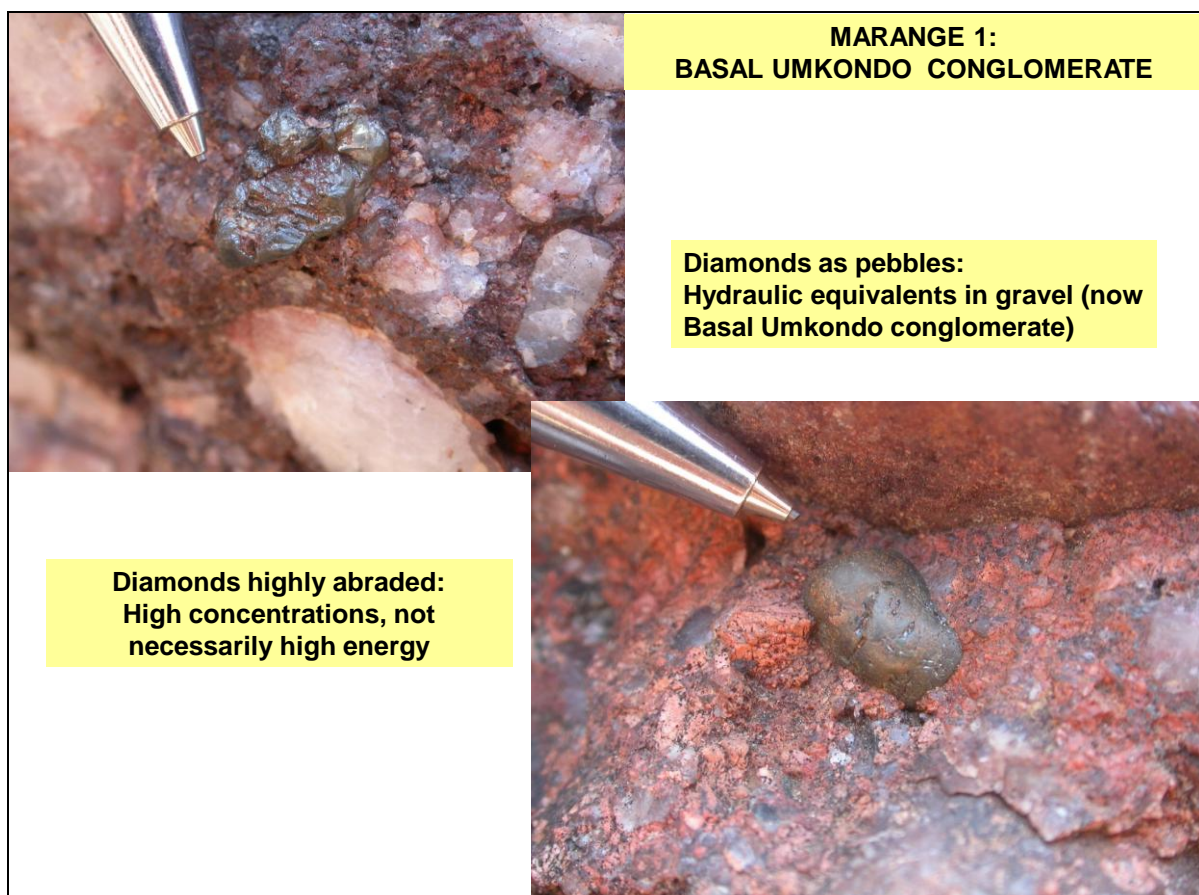


Fig. 7.6: Highly abraded diamonds sitting as hydraulic equivalents in gravel/conglomerate.

From: Ward, (2009)

Where the diamonds occur both in the east and west of the basin, they appear to be sitting within the conglomerate as true hydraulic equivalents (Roberts, 2003b) of the other pebbles in the population (Fig. 7.6). The diamond sizes also decrease upwards as the conglomerate fines upwards. The fining upwards is a function of the decrease in energy of the transportation agent, water in this particular case.

### **7.3 Mineral resources**

The Umkondo Basin has traditionally been known to be poorly endowed with mineral wealth, and the only production has been in small amounts of beryl, and lime and limestone. All copper prospects proved to be small, lowly mineralized and uneconomic to mine.

The beryl occurs on a small pegmatite body in granite which also contains small amounts of lithium minerals. Copper staining is widespread in the Calcareous and Lower Argillaceous Series of the Umkondo System (Watson, 1969) as well as in some of the intrusive dolerite sheets. The origin of the copper mineralization could be primary, such as vertical lodes in the large pre-Karoo faults, while others may be syngenetic. Copper staining is also found in bodies of ironstone in the Calcareous Series.

Numerous small lenses of ironstone and ferruginous sandstone, which are too low grade to be of economic importance, occur in the Calcareous, Lower Argillaceous and, to a lesser extent, the Quartzite Series. The ironstones are composed of magnetite, haematite, some ilmenite, quartz, and chlorite, and are thought to be metamorphosed ferruginous precipitates. They are hard, black, massive rocks, which show bedding and appear to dip conformably with the adjacent sedimentary rocks. Limestone and burnt lime have been the chief mineral products. Much purer calcareous tufa and travertine have also been the main sources for limestone.

The Umkondo Basin alluvial diamonds were discovered in early 2000. The diamond resource is the most important mineral resource of the Umkondo Sedimentary Basin. The diamonds occur in conglomerates and grits lying unconformably on the Upper Argillaceous Series of the Frontier Series in the east of the basin, and nonconformably between the granites and the Calcareous Series to the west. The discovery of diamonds found within the basal sediments

of the Umkondo Group, (1.1Ga), when following-up on a reconnaissance for garnet in eastern Zimbabwe (Roberts 2003b), has provoked considerable interest. It is hoped that the understanding of these basal sediments could assist in understanding the primary source of the diamonds, and the understanding of the diamonds and the host conglomerate could provide insight into the development of the Umkondo Basin.

Depending on the dollar per carat value of the Marange diamonds, it has been suggested in media reports that the value of the deposits “could be worth up to US\$800 billion . . .” In December 2010, an industry expert told the Telegraph (UK) that the deposit was “the richest diamond field ever seen by several orders of magnitude.” According to one article in the Belfast Telegraph, (2009) it was estimated that the fields could meet a quarter of the world’s demand for diamonds. Former Zimbabwe Finance minister Tendai Biti has described the 60,000 hectare Marange diamond field as “the biggest find of alluvial diamonds in the history of mankind”. “Potential revenue is estimated at US\$1 billion–US\$1.7 billion a year, about half the crisis-ridden country’s total forecast GDP [in 2010] and enough to end its economic woes almost at a stroke,” the Economist (UK) reported. One industry insider who has visited the area, and who spoke to Partnership Africa Canada (PAC) 7 on condition of anonymity, confirmed that “the caratage of Marange is virtually unheard of and bigger by order of magnitude than anything mined anywhere in the world. It’s a complete freak”.

These sentiments by various groups and individuals have resonated throughout the world to the extent where it appeared that the Marange alluvial diamond field resource had been proven. What really appears to be coming out now is that, though the Umkondo Basin is large, its alluvial diamond resource is mainly confined to some portions on the western and eastern margins of the basin and not throughout its interior. The larger part of the diamonds on the western margin has since been eroded away, and most likely the host gravels lay some hundreds of meters beneath the deep sediments of the Save Basin. At those depths, the Save basin hosts billions of cubic meters of underground water which is difficult if not impossible to pump out and mine the resource. Above the mineralised gravels and hundreds of meters of loose sands which make underground or even open pit mining operations difficult. Besides these two factors, the Save Basin is an international conservancy for the black rhino, and is

highly productive in terms of agriculture using the underground water. It remains to be seen if the potential Save Basin resource is ever going to be economically exploited.

Thus, after much has been said by individuals, international diamond interest groups and the Zimbabwe government, proper exploratory work needs to be carried out to prove any of the sentiments.

## **8.0 CHAPTER EIGHT**

### **THE STRUCTURES, MAGMATISM AND METAMORPHISM OF THE UMKONDO SEDIMENTARY SYSTEM**

#### **8.1 Introduction**

During the formation and sedimentation of foreland basins the margins of cratonic blocks pass through periods of extension, when sediments and some diamonds eroded from kimberlites and retained placers are dispersed from raised buoyant cratons into adjacent basins (Bluck et al., 2005). The extensional periods are normally followed by craton margin compression, which is resisted by the main craton and results in fold belts thrust and riding onto the craton to return sediment that was previously lost. As the fold belts advance and return the sediments, the foreland basins are pushed towards the interior of the craton. The older Umkondo sediments, the Frontier Series, were thrust westwards onto the Zimbabwe craton from the Mozambique side, resulting in the formation of the Chimanimani Mountains and the Umkondo Basin to the west, in which the younger western Umkondo rocks were deposited.

Watson, (1969), citing Phaup, (1969), postulated that the Umkondo Basin and its granitic floor were subjected to:

. . . potassium metasomatism at around 1.9 to 2 Ga and the rocks underwent intense folding, shearing and faulting which produced a marked east-north-east grain, as is seen in the Mozambique gneisses and in the post-Umkondo and post-Karoo fault directions.

After the Frontier Series had been deposited, it was folded, metamorphosed, and uplifted, and the rocks were being eroded at the time the Lower Argillaceous Series was being deposited further west. The western Umkondo rocks have only undergone slight deformation, whereas the Frontier Series has been overfolded and thrust. The Umkondo rocks therefore fall into two distinct tectonic areas, which are the Frontier Series of the east, and the western area of Umkondo rocks. Watson, (1969) points to three tectonic events that might have affected the Umkondo Basin as:

1. Renewal of older structures of the Limpopo Zone,
2. Karoo and post-Karoo tectonic events, and
3. Tectonic and metamorphic events that occurred in Mozambique at 1,000 Ma and again in the lower Palaeozoic between 450 and 650 Ma.

## **8.2 The Frontier Series structures**

The Frontier Series structures are a result of the tectonic events that took place throughout the history of the Umkondo Basin. The oldest rocks of the Umkondo System, the Frontier Series, were overfolded and thrust (Watson, 1969, citing Mennell, 1920) after the intrusion of the Umkondo Dolerites. The Frontier Series is cut into tectonic slices by four major thrust planes, T1 to T4 (Fig. 8.1). Unlike the western area rocks, the Frontier Series is not broken into blocks by large east-north-easterly faults except by the Zunguni Fault.

T1 is the lowest and possibly the oldest thrust, dipping at about 55°E to ENE, separating the Frontier Series from the younger Lower Argillaceous Series and disappearing under T2. Its eastern outcrop is a zone of marked shearing. T1 also separates the Frontier Series from the much older gneisses. The erosional relics of the Frontier Series rocks overlying T1 consist of a recumbent fold with an axial plane that dips very flatly eastwards, and the fold plunges at a very low angle to the south.

The thrust fault T2 has two upward trending branches, T2A and T2B, which outcrop to the east of it. In places, the thrusts are marked by the development of breccia and the mineral kyanite. The third thrust plane, T3, underlying the Lower Quartzites and dipping at 20–30° E, passes under T4. The highest thrust, T4, dipping at 25–30°E, also underlies the Lower Quartzites.

There is a very marked difference in tectonic intensity and style between the deformation of the western area of Umkondo rocks and that of the Frontier Series.

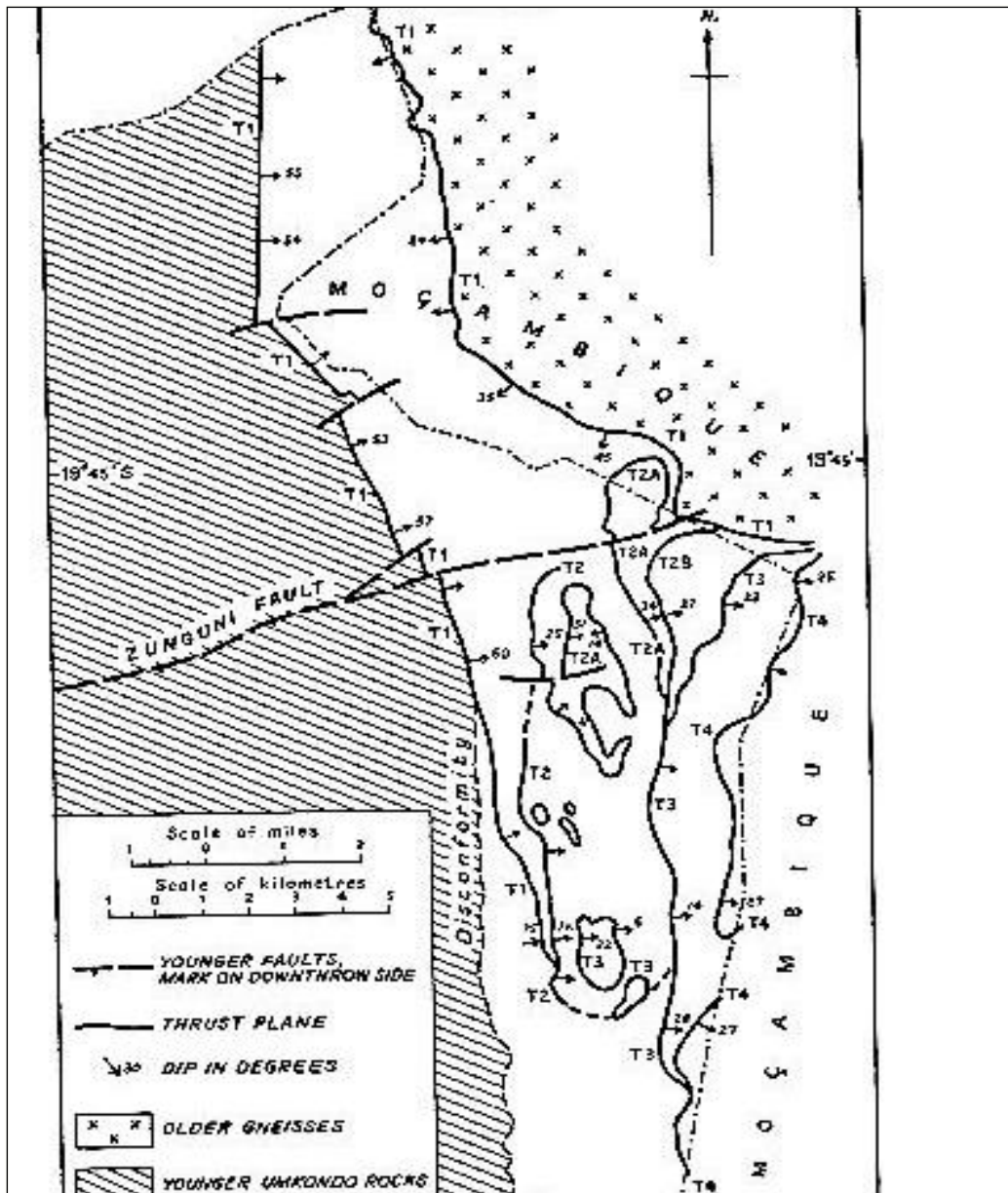


Fig. 8.1: The Frontier Series thrust planes (Phaup, 1969). Map from Watson, (1969).

The western area rocks, dipping at an average of 4–5°, have been very gently folded into wide synclines and broken into blocks by sets of normal, south steep-dipping east-northeasterly and north-north-west striking faults (Fig. 8.1). Their strikes are generally slightly curved, concave to the north in the area north of Chimanimani, and almost straight or convex to the north in the area to the south. Similar faults occur in the rocks of the Limpopo Metamorphic Zone to the south-west and in the Karoo rocks of the Lower Save Valley, so

that the post-Umkondo faults in this area may be either a renewal or extension of much older faults with some post-Karoo movement, of post-Umkondo age. Only the Zunguni Fault and a few minor east-north-east faults extend into the Frontier Series, where they displace the folds and thrust faults.

The faults of the smaller north-north-west group have steep dips and smaller vertical displacements, usually around 30 to 60 meters, and are downthrown to either the east or the west. Their strike is rarely curved and extends for 1–5 kilometers only, and many terminate against the east-north-east faults. Quite a number have been filled with dolerite of unknown age. Similar faults are abundant in the Karoo rocks of the Lower Save Valley, but this does not imply a post-Karoo age for those in the Umkondo rocks.

### **8.3 Magmatism in the Umkondo System**

The sedimentary rocks of the Umkondo System have been extensively intruded by thick sheets of dolerite, which were together folded and metamorphosed with their enclosing sedimentary beds. The sediments are thought to have been intruded at the end of the period of sedimentation and before the earliest deformation of the Umkondo rocks. McElhinny and Opdyke, (1964) studied the magnetic properties of the Umkondo dolerites and concluded that the rocks are made up of a:

. . . homogeneous palaeomagnetic group and K-Ar age determinations method have shown that they had been affected to a greater or lesser degree by the Lower Palaeozoic thermal event centered to the east in Mozambique.

The determined ages of the dolerites range from 640 to 1,136 million years old (Munyanyiwa, 1999), so the Umkondo Dolerites must be older than 1,136 Ga and the sedimentary rocks still older.

Munyanyiwa, (1999) also noted that the dolerite has been intruded as:

. . . coalescence and transgressive sheets into the Umkondo sediments with the bulk of the dolerite being intruded into the Calcareous and Lower Argillaceous Series, and fewer and smaller sheets in the Quartzite and Frontier Series.

Most of the sedimentary inclusions in the dolerite sill intrusive into these eastern outcrops of

the Lower Argillaceous Series seem to be solely of finely-laminated, ferruginous siltstones. The Lower Argillaceous Series particularly has been invaded by scattered north-trending veins of quartz identical to those found in the Save and Odzi Valleys to the west of the Umkondo highlands. The dolerites to the north are on a granite floor, whilst in other areas they are on both a granitic and a calcareous floor and in sheets separated by rocks of the Calcareous and Lower Argillaceous Series. To the south, there is generally a layer of calcareous rocks between the floor of the dolerite and the granite, and the roof is either the upper part of the Lower Argillaceous Series or the basal part of the Quartzite Series.

The dolerite outcrops intruded into rocks of the Lower Chlorite Schists, and the Upper Quartzites of the Frontier Series form the central and northern parts of the Chimanimani Mountains, as three comparatively small sheets (Watson, 1969) that have been affected by the folding and thrusting. Long striking dolerite dykes up to 15 kilometers are comparatively rare in the sedimentary rocks of the Umkondo System and occur mainly in the granite country in the north-west. These steep-dipping dykes belong to four sets, which strike N30W, N20E, N65E and N85E.

#### **8.4 Metamorphism**

All the rocks within the Umkondo Basin have undergone low-grade metamorphism to within the Greenschist Facies, while the Basement Schists were metamorphosed to the biotite-chlorite subfacies before the intrusion of the granite (Munyanyiwa, 1999). The granite in turn was metamorphosed with the production of sericite and a slight clouding in its feldspars whilst biotite was chloritized. The micro-brecciation and reddening of the granite, accompanied by veinlets of epidote, took place in post-Karoo times (Swift, 1962). The gneisses which outcrop in Mozambique were metamorphosed in the Limpopo Zone, at the time of deformation of the Frontier Series. Along their thrust plane contact with the Frontier Series, the gneiss has been sheared into a white, quartz-mica schist or, more rarely, quartz-chlorite schist.

The Frontier Series has been metamorphosed twice, first before the deposition of the Lower Argillaceous Series, and again after the intrusion of the Umkondo Dolerites. The first metamorphism converted the arenaceous sediments into quartzites, and the second produced

rocks of the biotite-chlorite and muscovite-chlorite subfacies of the Greenschist Facies (Munyanyiwa, 1999). Locally, in the vicinity of the thrust faults, kyanite has been found. The large sheets of the Umkondo Dolerites produced up to the pyroxene hornfels facies thermal or contact metamorphism of their immediate wall rocks in many places, but mainly in the Calcareous and Lower Argillaceous Series.

Sometime later, the rocks of the Umkondo System underwent regional deformation and metamorphism. The carbonate- and chert-rich Calcareous Series now contains a variety of minerals, mainly in the muscovite-chlorite subfacies of the Greenschist Facies, whilst the Lower Argillaceous and Quartzite Series generally belong to the muscovite-chlorite subfacies. The argillaceous varieties show slaty or phyllitic cleavages. The Umkondo Dolerites have undergone fairly extensive and widespread saussuritization and uralitization. The lower Palaeozoic metamorphism of around 450 to 650 Ma (Watson, 1969) seems to have had little effect on the rocks within the Umkondo area.

## 9.0 CHAPTER NINE

### DIAMOND PRODUCTION STATISTICS, WESTERN MARGIN OF THE UMKONDO BASIN (2007–2015)

#### 9.1 Introduction

The mining activities within the Umkondo Basin are based on conglomerate and other secondary depositional environment ores, such as scree on the slopes of hills, lag material on the peneplains, and paleo-basal gravels in old river channels like the Makodzi River gravels.

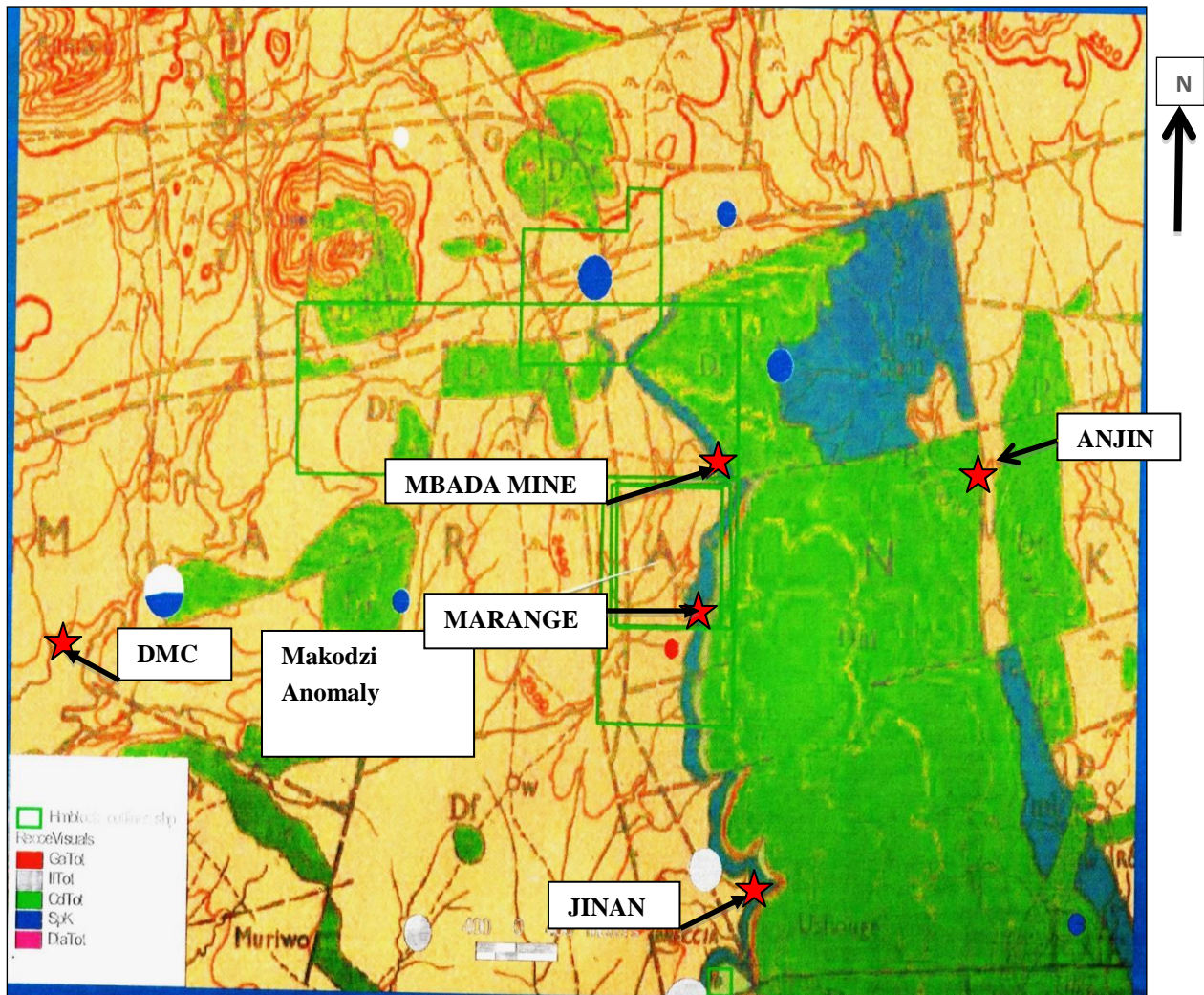


Fig. 9.1: Diamond producing mines on conglomerate and alluvial deposits around the Makodzi Anomaly, western Umkondo Basin, at Chiadzwa, Marange Communal Land. Base map adapted from: Roberts, (2003b).

## 9.2 Summary of production statistics

SUMMARY OF MBADA HILL PRODUCTION STATISTICS 2007–2009							
DATE	ORE PROCESSED (TONS)	DIAMONDS PRODUCED			YIELD		
		(COUNT)	(GRAMS)	(CARATS)	GRAMS/TON	CARATS/TON	CARATS/STONE
Oct07	315.00	2684.00	2549.20	12746.00	8.10	40.49	4.74
Nov07	164.00	1376.00	1357.40	6787.00	8.27	41.33	4.93
Feb08	559.00	4121.00	3967.60	19838.00	7.30	36.49	4.81
Mar 08	537.00	3133.00	3207.80	16039.00	5.98	29.90	5.12
Apr08	1195.00	6110.00	6133.75	30672.25	5.13	25.66	4.99
May08	2073.00	10576.00	9793.20	48966.00	4.81	24.07	4.61
Jun08	1912.00	8642.00	7767.30	38836.50	4.11	20.57	4.47
Jul08	2253.00	9184.00	8444.90	42224.00	3.52	17.61	4.55
Aug08	388.00	1259.00	1169.00	5845.00	2.90	14.51	4.65
Sept 08	814.20	1702.00	1618.90	8094.50	2.01	10.07	4.67
Oct08	608.00	1482.00	1238.80	6194.00	2.31	11.55	4.18
Nov08	251.00	866.00	803.50	4017.50	3.18	15.90	4.66
Jan09	1062.00	4432.00	3723.20	18616.50	3.50	17.49	4.26
Feb09	1855.00	9739.00	8691.00	43455.00	4.83	23.71	4.33
Mar09	1461.00	7125.00	5721.22	28604.10	3.98	19.91	4.04
Apr09	981.00	4488.00	4435.10	22175.50	4.73	23.65	4.94
May09	619.00	2738.00	2617.10	13085.50	4.25	21.21	4.81
Jun09	999.00	4102.00	4075.10	20375.50	4.05	20.27	4.95
<b>TOTAL</b>	<b>18046.20</b>	<b>83759.00</b>	<b>77314.07</b>	<b>386571.85</b>	<b>4.61</b>	<b>23.02</b>	<b>4.65</b>

Fig. 9.2: An excerpt of Marange Resources (Pvt) Ltd production statistics based on Mbada Hill Mine. Data extracted from: Marange Resources (Pvt) Ltd, Mbada Hill Mine, Zimbabwe Mining Development Corporation (ZMDC) and compiled by Jaravani, (2009).

SUMMARY OF MARANGE MINE PRODUCTION STATISTICS JAN 2012–DEC 2013							
DATE	ORE PROCESSED	DIAMONDS PRODUCED			YIELD		
	(TONS)	(COUNT)	(GRAMS)	(CARATS)	GRAMS/ TON	CARATS/ TON	CARATS/ STONE
Jan 12	59816.00	13215.00	10230.64	51153.20	0.18	0.89	3.87
Feb 12	43223.00	12988.00	4297.00	21485.00	0.12	0.58	1.65
Mar 12	41326.00	5352.00	6800.00	34000.00	0.17	0.83	6.35
Apr 12	71018.00	18700.00	14054.00	70270.00	0.21	1.06	3.76
May 12	85784.00	18568.00	14326.00	71630.00	0.17	0.84	3.86
Jun 12	91974.00	17908.00	17312.00	86560.00	0.19	0.97	4.83
Jul 12	79162.00	22640.00	8468.00	42340.00	0.11	0.56	1.87
Aug 12	81950.75	11585.00	9869.00	49345.00	0.13	0.65	4.26
Sept 12	71873.50	23153.00	17722.00	88610.00	0.30	1.48	3.83
Oct 12	59514.81	24860.00	19728.00	98640.00	0.35	1.74	3.97
Nov 12	52626.24	17418.00	16077.00	80385.00	0.31	1.56	4.62
Dec 12	34001.62	10160.00	7098.00	35490.00	0.22	1.11	3.49
Jan 13	6400.92	14569.00	7960.00	39800.00	0.25	1.24	2.73
Feb 13	48957.32	13702.00	8008.00	40040.00	0.18	0.88	2.92
Mar 13	46841.22	11777.00	9667.00	48335.00	0.21	1.03	4.10
Apr 13	27717.55	14317.00	16910.92	84554.60	0.59	2.97	5.91
May 13	18941.08	24889.00	9602.00	48010.00	0.55	2.76	1.93
Jun 13	34400.47	14421.00	10911.16	54555.80	0.31	1.54	3.78
Jul 13	58035.11	15118.00	9600.00	48000.00	0.16	0.82	3.18
Aug 13	39709.84	13556.00	9897.85	49489.25	0.26	1.30	3.65
Sept 13	27205.26	7516.00	4906.24	24531.20	0.20	0.98	3.26
Oct 13	43585.25	12483.00	7604.06	38020.30	0.18	0.88	3.05
Nov 13	50474.39	15754.00	9896.60	49483.00	0.20	0.99	3.14
Dec 13	55044.00	13591.00	7861.00	39305.00	0.14	0.71	2.89
<b>TOTAL</b>	<b>1229582.34</b>	<b>110723.00</b>	<b>251642.47</b>	<b>1258212.35</b>	<b>0.20</b>	<b>1.02</b>	<b>4.05</b>

Fig. 9.3: Table of the current production statistics at Marange Mine. Data extracted from: Marange Resources (Pvt) Ltd Production 2012 to 2013. © Marange Resources (Pvt) Ltd.

The diamond yields from the Makodzi River basal gravels averaged 23 carats per ton for Mbada Hill Mine, an average of 5 carats per stone (Fig. 9.1) from October 2007 to June 2009.

On a month by month basis, a very low tonnage of ore was processed through a 10 ton pan plant during the period represented in Fig. 9.1 for Mbada Hill Mine but the recoveries were very high.

SUMMARY OF MARANGE MINE PRODUCTION STATISTICS JAN 2014–DEC 2015							
DATE	ORE PROCESSED	DIAMONDS PRODUCED			YIELD		
	(TONS)	(COUNT)	(GRAMS)	(CARATS)	GRAMS/ TON	CARATS/ TON	CARATS/ STONE
Jan 14	48784	12279	3983.00	19915	0.16	0.78	1.62
Feb 14	61116	11230	4785.80	23929	0.08	0.41	2.13
Mar 14	57756	12961	5419.00	27095	0.08	0.39	2.09
Apr 14	40932	14740	6221.96	31110	0.09	0.47	2.11
May 14	69583	16527	6963.68	34818	0.15	0.76	2.11
Jun 14	86681	13558	4598.00	22990	0.10	0.50	1.70
Jul 14	80853	14810	14129.00	70645	0.05	0.27	4.77
Aug 14	119426	10374	10748.04	53740	0.17	0.87	5.18
Sept 14	144986	19495	12599.80	62799	0.09	0.45	3.22
Oct 14	117972	14139	7780.00	38900	0.09	0.43	2.75
Nov 14	135913	15607	10992.56	54963	0.07	0.33	3.52
Dec 14	114014	13012	5391.00	26955	0.08	0.40	2.07
Jan 15	110055	11715	3163.00	15815	0.05	0.24	1.35
Feb 15	108937	14305	12990.10	64951	0.03	0.14	4.54
Mar 15	117685	13600	13706.00	68530	0.12	0.60	5.04
Apr 15	104150	12887	5024.86	25124	0.05	0.24	1.95
May 15	95854	12779	7944.60	39723	0.08	0.41	3.11
Jun 15	87102	11749	4152.00	20760	0.05	0.24	1.77
Jul 15	157761	13014	6541.82	32709	0.04	0.21	2.51
Aug 15	111957	-	3934.00	19670	0.04	0.18	-
Sept 15	100747	-	3423.00	17115	0.03	0.17	-
Oct 15	-	-	-	-	-	-	-
Nov 15	-	-	-	-	-	-	-
Dec 15	-	-	-	-	-	-	-
<b>TOTAL</b>	<b>2121049</b>	<b>258781</b>	<b>154415.22</b>	<b>772256</b>	<b>0.08</b>	<b>0.36</b>	<b>2.98</b>

Fig. 9.4: Table of the current production statistics at Marange Mine. Data extracted from: Marange Resources (Pvt) Ltd Production 2014 to 2015. © Marange Resources (Pvt) Ltd.

The diamond grades at the two mines are markedly different, with Mbada Mine to the north recording higher grades in 2007 to 2009, at an average of 23.02 carats per ton (Fig. 9.1), while Marange Mine (Figs. 9.2 and 9.3), a few kilometers south, is presently recording lower grades, ranging from 1.02 to 0.15 carats per ton. The other surrounding mines, Anjin and DMC (Fig. 9.1), are also recording production grades in the same range as Marange Mine. Although production figures were not available for Jinan Mine, further south of Marange Mine (Fig. 9.1), much lower grades (about ten times lower than the Marange grades) have been reported. Much further south, 40 kilometers away at Birchnough Bridge, where the same conglomerate outcrops, samples processed from the area yielded no diamonds. It is therefore concluded that the conglomerate diamond mineralization on the western margin of the Umkondo Basin falls sharply over a short distance from north to south. The diamonds within the basal gravels of the Middle Save River basin just to the south and Odzi River basin to the east of the area represented (Fig. 9.1) are a result of a further southward dispersion by fluvial action along the channels of the two major drainage systems.

In contrast to the rapid southward dwindling of the conglomerate diamond grades is the conglomerate pebble size, roundness, percentage of pebbles, and packing of pebbles. All the conglomerate size pebble variations are matrix-supported, but the matrix increasingly becomes more abundant southwards as the pebbles become smaller and more sparsely distributed.

Within the diamond dispersal around the Makodzi Anomaly, the average diamond size decreases westwards, from 8 millimeters to 6.7 millimeters, perpendicular to the hill slopes and in the direction of local stream drainage. This observation seems to suggest that the diamond size within the dispersal is a function of the distance from the conglomerate outcrops on the hill slopes. With the decrease in size, there is an increase in the gem content percentage, from 20% near the slopes to 60% further west away from the hill slopes. The progressive increase in gem percentage westwards is based on the fact that the more pure and more resistant diamonds can travel much further away from source than their non-gem counterparts.

### 9.3 Marange Mine diamond size frequency distribution (DSFD), 2012 to 2015

According to the data in Figures 9.5, 9.6, 9.9, 9.11 and 9.12, and the diamond size frequency distribution (DSFD) normal curves (Fig. 9.7 and 9.8), the largest population of diamonds at Marange Mine falls within 5.6 millimeters to 8 millimeters in size. This population of the diamonds and the DSFD represents the diamond footprint for the Marange diamond field on the western margin of the Umkondo Basin. The diamond size frequency distribution (DSFD) is one of the most important factors determining the revenue of a diamond deposit (Lantuejoul, and Millad, 2008). Since the DSFD typically varies spatially in an alluvial deposit, it should be modeled locally for each one of the various mines in the Marange diamond field. In the Marange diamond fields the DSFD varies with the distance away from the source conglomerates and the sub-environments of deposition.

2012													
Number of Stones													
Seive Size (mm)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
11.20	-	-	-	-	-	-	-	-	-	-	109	161	270
8.00	-	-	-	-	-	-	-	-	-	-	1944	2923	4867
6.70	-	-	-	-	-	-	-	-	-	-	3253	4834	8087
5.60	-	-	-	-	-	-	-	-	-	-	2225	3050	5275
4.75	-	-	-	-	-	-	-	-	-	-	826	1177	2003
3.35	-	-	-	-	-	-	-	-	-	-	289	573	862
2.80	-	-	-	-	-	-	-	-	-	-	10	23	33
2.36	-	-	-	-	-	-	-	-	-	-	0	19	19
1.70	-	-	-	-	-	-	-	-	-	-	0	1	1
-1.70	-	-	-	-	-	-	-	-	-	-	0	0	0
<b>TOTAL</b>	0	0	0	0	0	0	0	0	0	0	8656	12761	<b>21,417</b>

Fig. 9.5: Marange Mine Diamond Size Frequency Distribution (DSFD) Data 2012.

Data extracted from Marange Resources (Pvt) Ltd, Production 201. © Marange Resources (Pvt) Ltd. (N.B Data not available from Jan to Dec 2012).

These environments include lag material trapped within weathered dolerite dykes ditches which run parallel to the conglomerate outcrop strike, basal gravels in west- and south-draining streams, conglomerate scree on the slopes below the conglomerate outcrops, and lag material on the granite and dolerite peneplains. The lag material is usually thicker, averaging 1m over dolerite surface and about half a meter on granite surfaces. This difference in thickness is a result of differential rates of weathering between the two surfaces with the dolerite surface weathering much faster than the granite surface.

2013													
Number of Stones													
Seive Size (mm)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
11.20	73	106	164	223	83	133	52	17	7	39	59	50	1006
8.00	939	1890	2341	3941	2154	2660	1486	842	165	980	1561	375	19334
6.70	1271	2490	3131	6051	3698	3021	2495	1914	305	2001	2628	440	29445
5.60	704	1677	1606	4006	2213	1375	1572	1614	230	1308	1450	173	17928
4.75	263	879	663	1214	682	399	568	770	79	440	313	46	6316
3.35	120	446	320	483	316	131	207	430	16	187	126	13	2795
2.80	4	21	35	24	13	6	16	43	0	7	11	1	181
2.36	0	4	2	6	5	1	0	11	0	0	0	0	29
1.70	0	0	0	0	0	1	0	0	1	0	0	0	2
-1.70	0	0	0	0	0	0	0	0	0	0	0	0	0
<b>TOTAL</b>	<b>3375</b>	<b>7513</b>	<b>8262</b>	<b>15948</b>	<b>9164</b>	<b>7727</b>	<b>6396</b>	<b>5641</b>	<b>803</b>	<b>4962</b>	<b>6148</b>	<b>1098</b>	<b>77,037</b>

Fig. 9.6: Marange Mine Diamond Size Frequency Distribution (DSFD) Data 2013.

Data extracted from Marange Resources (Pvt) Ltd, Production 2013. © Marange Resources (Pvt) Ltd.

The DSFD curve for the Marange Mine diamond population is hanging for the +11.2 millimeter stone size (Fig. 9.7, 9.8, and 9.10 ), because the diamond recovery circuits for that stone size were never installed and that process is taking place now. The largest stone ever recovered at Marange Mine was an 80 carat, 15 mm octahedral gem and the smallest has been a 1.7 carat stone. The DSFD is an important tool in establishing to the bottom and top

cut-offs when screening the diamondiferous alluvial ores, and also in establishing the DMS (Dense Media Separation) plant cyclone top and bottom apertures. At the mine level, the DSFD is applied to monitor the recovery efficiencies of the production processes, authenticity of grade variances, and possible pilferage.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	YTD Avg
<b>sieve size (mm)</b>	<b>Relative Weight (%)</b>												
11.2	4.7	5.33	6.19	5.1	4.03	6.36	3.3	3.31	3.3	3.46	3.57	15.89	5
8	44.92	45.06	44.27	42.17	39.2	46.57	39.61	29.85	35.7	35.42	39.7	46.2	41
6.7	36.28	31.79	33.95	34.94	39.21	34.38	38.01	39.7	36.32	39.86	40.2	33.44	37
5.6	11.12	12.52	11.58	13.96	14.78	11.18	15.01	21.05	18.5	17.35	14.57	7.89	14
4.75	2.38	3.99	3.1	2.94	2.74	1.99	3.44	5.74	4.51	3.59	1.89	1.3	3
3.35	0.58	1.28	0.82	0.86	0.84	0.37	0.9	2.16	2.31	1.07	0.53	0.36	1
2.8	0.03	0.04	0.07	0.02	0.05	0.08	0.07	0.16	0.1	0.11	0.05	#DIV/0!	#DIV/0!
2.36	0	0	0	0	0.02	0.02	#DIV/0!	0.03	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1.7	-	-	-	-	-	0.01	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
-1.7	-	-	-	-	-		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Fig. 9.7: Marange Mine Diamond Relative Percentage Size Frequency Distribution (DSFD) Data 2013.

Data extracted from Marange Resources (Pvt) Ltd, Production 2013. © Marange Resources (Pvt) Ltd.

In Figs. 9.5, 9.6, 9.9, 9.11 and 9.12, the predominant diamond size reflects a progressive decrease from 8 millimeters to between 7 and 6.7 millimeters over time from 2012 to date in the alluvial deposit. The decrease conforms to the direction of mining, which has been from north to south along the strike of the conglomerate outcrop, and from east to west perpendicular to the strike and in the direction of predominant drainage of the area away from the conglomerate outcrop. As has been alluded to above, the diamond size decrease

corresponds with the grade decrease and the conglomerate pebble size decrease and packing in a generally north to south direction. The alluvial deposit diamond grades beneath the conglomerate outcrop in a north to south direction directly correspond to those of the conglomerate along the slope above. The river alluvial ore grades are higher than those in the conglomerate due to subsequent secondary re-concentration by weathering, gravity, and water action, but the decreasing trend is still evidently in correspondence.

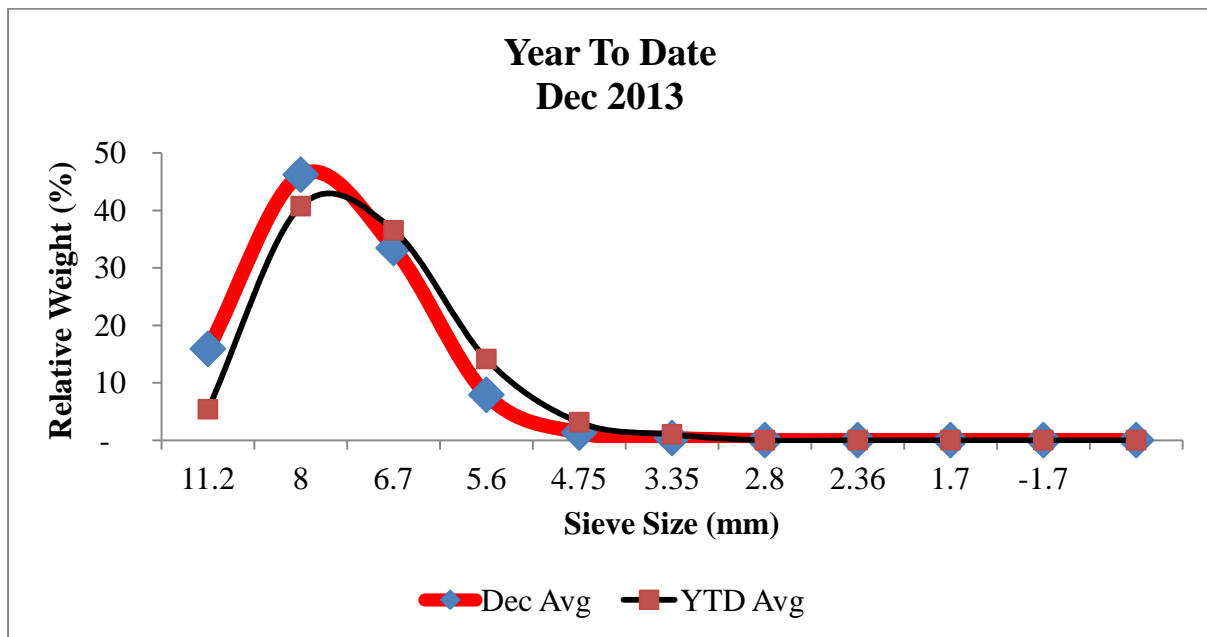


Fig. 9.8: Marange Mine Diamond Size Frequency Distribution (DSFD) Normal Distribution Graph for 2013.

Data extracted from Marange Resources (Pvt) Ltd, Production 2013. © Marange Resources (Pvt) Ltd.

The average stone size for the Mbada Hill Mine is 4.65 carats per stone for the period 2007 to 2009 (Fig. 9.1) while that for Marange Mines are 4.05 carats per stone form 2012 to 2013 and 2.98 carats per stone for the period 2014 to 2015 (Figs. 9.2 and 9.3 respectively). Therefore, the average stone size, diamond grades, and the maturity of the conglomerates decrease southwards from the Mbada Hill Mine towards Jinan Mine. The average stone size also has decreased over time which corresponds to the east to west mining trends over the period covered from 2009 to 2015. The high grade areas to the east and close to the conglomerate outcrops were exploited first and then progressively westwards into the low grade areas.

2014													
Number of Stones													
Seive Size (mm)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
11.20	31	26	35	51	91	31	178	182	138	69	79	26	937
8.00	719	332	761	1333	1891	874	1711	2680	2778	1295	1634	913	16921
6.70	944	486	1143	1899	2712	1510	1901	4743	4115	1853	2546	1391	25243
5.60	452	317	727	1141	1438	928	863	2433	1990	784	1103	546	12722
4.75	105	53	233	272	345	189	129	276	423	115	210	117	2467
3.35	22	14	57	43	49	26	27	59	51	22	34	19	423
2.80	6	2	4	1	1	0	1	1	0	1	1	0	18
2.36	0	0	1	0	0	0	0	0	0	0	0	0	1
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.70	0	0	0	0	0	0	0	0	0	0	0	0	0
<b>TOTAL</b>	<b>2279</b>	<b>1230</b>	<b>2961</b>	<b>4740</b>	<b>6527</b>	<b>3558</b>	<b>4810</b>	<b>10374</b>	<b>9495</b>	<b>4139</b>	<b>5607</b>	<b>3012</b>	<b>58,732</b>

Fig. 9.9: Marange Mine Diamond Size Frequency Distribution (DSFD) Data 2014.

Data extracted from Marange Resources (Pvt) Ltd, Production 2014. © Marange Resources (Pvt) Ltd.

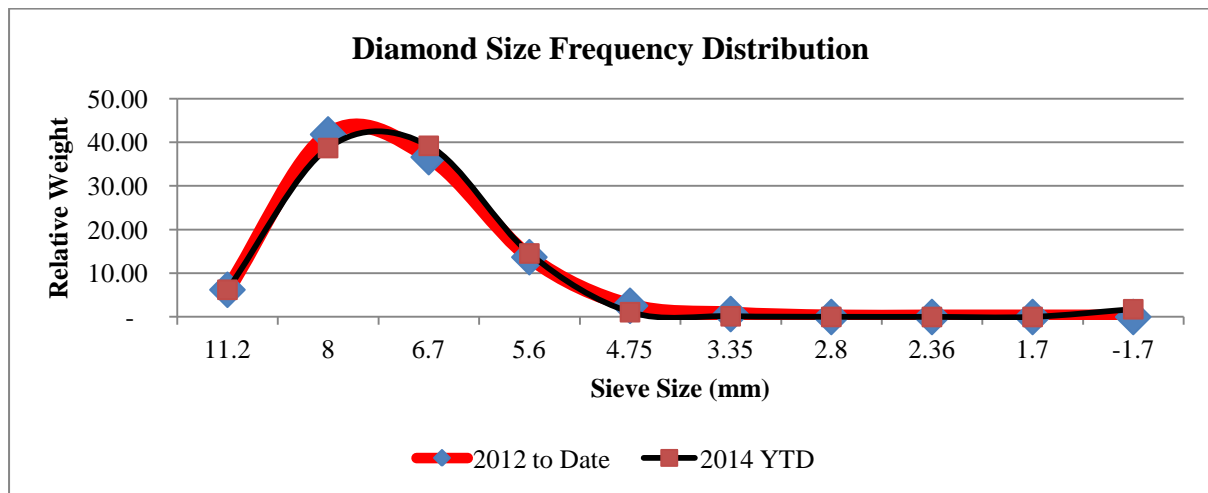


Fig. 9.10: Marange Mine diamond size frequency distribution (DSFD) curve for 2012-2014. Data extracted from: Marange Resources (Pvt) Ltd Production 2012 to 2014. © Marange Resources (Pvt) Ltd.

2015													
Number of Stones													
Seive Size (mm)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
16			0	0	0	0	0						0
15			0	0	0	0	0						0
14.00		1	0	0	1	0	0						2
13.20	1	5	0	0	0	0	0						6
12.50	1	6	4	0	1	1	0						13
12.00	1	8	2	1	1	0	1						14
11.20	19	49	3	1	5	1	2						80
8.00	446	1237	22	5	6	4	4						1724
6.70	767	1631	90	21	88	68	37						2702
5.60	369	1033	3165	457	889	569	860						7342
4.75	91	275	5322	1104	1145	691	1201						9829
3.35	20	58	3923	995	528	348	738						6610
2.80	0	1	954	261	103	58	155						1532
2.36	0	0	114	41	12	9	16						192
1.70	0	0	1	1	0	0	0						2
-1.70	0	0	0	0	0	0	0						0
<b>TOTAL</b>	<b>1715</b>	<b>4305</b>	<b>13600</b>	<b>2887</b>	<b>2779</b>	<b>1749</b>	<b>3014</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>30,050</b>

Fig 9.11: Marange Mine Diamond Size Frequency Distribution (DSFD) Data 2015.

Data extracted from Marange Resources (Pvt) Ltd, Production 2015. © Marange Resources (Pvt) Ltd.

In the summary below, there is still a possibility of recovering stones large than 15mm is size but a rare chance of finding small stones less than 1.7 carats. The population of stone size categories decreases from the 6.7mm size in both directions of increasing and decreasing stone sizes.

<b>DSFD SUMMARY 2012 TO 2015</b>					
	<b>Number of Stones</b>				
<b>Seive Size (mm)</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>TOTAL</b>
15.00	-	-	-	1	<b>1</b>
14.00	-	-	-	2	<b>2</b>
13.20	-	-	-	6	<b>6</b>
12.50	-	-	-	13	<b>13</b>
12.00	-	-	-	14	<b>14</b>
11.20	270	1006	937	80	<b>2293</b>
8.00	4867	19334	16921	1724	<b>42846</b>
6.70	8087	29445	25243	2702	<b>65478</b>
5.60	5275	17928	12722	7342	<b>43268</b>
4.75	2003	6316	2467	9829	<b>20615</b>
3.35	862	2795	423	6610	<b>10690</b>
2.80	33	181	18	1532	<b>1764</b>
2.36	19	29	1	192	<b>241</b>
1.70	1	2	0	2	<b>5</b>
-1.70	0	0	0	0	<b>0</b>
<b>TOTAL</b>	<b>21417</b>	<b>77037</b>	<b>58732</b>	<b>30051</b>	<b>187,237</b>

Fig. 9.12: DSFD Summary, 2012 to 2015

Data extracted from Marange Resources (Pvt) Ltd, Production 2012 to 2015. © Marange Resources (Pvt) Ltd.

## **10.0 CHAPTER TEN**

### **ALLUVIAL DIAMOND MINERAL RESOURCE EVALUATION TECHNIQUES, MARANGE DIAMOND FIELDS**

#### **10.1 Introduction**

There being no single, universally applicable alluvial diamond deposits method of target selection, the climatic and geomorphic history, stratigraphy, structure and tectonic history are important factors that require study and need to be understood for each alluvial diamond province prior to target selection. Because of the world wide variability of the factors above, what is appropriate in one part of the world may be entirely inappropriate in another. There are thus some basic principles which must be followed in the planning and execution of any alluvial diamond exploration program. These principles include a comprehensive knowledge of the regional geology of the drainage basin under review; the constituent lithologies of the gravel being prospected for; the geomorphic and climatic factors that may have affected the area under exploration; the type of deposit to be sought; and the post-depositional processes that may have affected the alluvial deposits being considered for exploration (Marshall, and Baxter-Brown, 1995). These are all important principles to bear in mind before starting field exploration for alluvial deposits. This overall information is necessary to buildup a short and comprehensive regional geological model upon which to base any alluvial diamond exploration program. There are various applicable remote sensing methods for information gathering, but there is no substitute for an observant, well-trained field geology expert in mapping and air-photo interpretation.

The Umkondo Sedimentary Basin diamonds are primarily hosted by a very hard, semi-continuous, 1.1 Ga conglomerate, lying disconformably on basement granite to the west of the basin and on the sedimentary Frontier Series to the east. The conglomerate released diamonds into tertiary environments, due to weathering, erosion, faulting and scarp slope retreat, to form scree on scarp slopes, lag on the intermediate peneplains next to the scarps, and basal gravels in paleochannels. Although the age of the gravels in tertiary environments is not known, they are thought to be generally Tertiary, Pleistocene or younger. Older

paleoplacers (except the Proterozoic Witwatersrand placers) are rare, due to poor long-term preservation of deposits in high-relief, subaerial environments. The Umkondo Basin conglomerate is Precambrian in age and is preserved by the Calcareous Series and the Quartzite Series of the Umkondo System.

In fluvial settings, placer concentrations occur at channel irregularities, in bedrock depressions and below natural riffles created by fractures, joints, cleavage, faults, foliation or bedding planes which dip steeply and are oriented perpendicularly or obliquely to stream flow. Coarse-grained placer concentrations occur as lag concentrations where there is a considerable likelihood of sediment reworking or flow separation, such as at the base of channel scours, around gravel bars, boulders or other bedrock irregularities, at channel confluences, in the lee of islands, and downstream of sharp meanders. It is typical for basal gravels over bedrock to contain the highest placer concentrations. Fluvial placers accumulate mainly along erosional unconformities which overlie bedrock or resistant sediments. Overlying bedded gravel sequences usually contain fewer placer minerals and reflect bar sedimentation during aggradational phases. Frequently, the generation of more economically attractive placer deposits involves multiple cycles of erosion and deposition into foreland basins. The reworking of the Umkondo conglomerates into an alluvial dispersal resulted in the reconcentration of diamonds, and hence the higher grades. The Umkondo diamond reconcentration phenomenon is equivalent to the alluvial deposits of the Orange and Vaal Rivers in South Africa, in which the reconcentration of the diamonds from the Dwyka tillite has resulted in economically mineable deposits.

## **10.2 Alluvial diamond exploration and sampling**

The methods and steps required in exploration and evaluation of a placer deposit involve photogeology at the initial stage to provide a 2D (surface) definition of the area and its geology, using air photos and satellite imagery data to unravel buried valley placers. The 3D seismic profiling, like ground penetrating radar (GPR) and shallow seismic refraction and reflection techniques, provides cross-sections of alluvial terraces with less than 5% depth error (Marshall, and Baxter-Brown, 1995), and delineates the geometry, structure and thickness of deposits with low clay contents, especially fluvial terrace, paleochannel placers and depth to bedrock, leading to target selection and the sampling program. The drilling, or

pitting, is done in strategically-selected areas to test the economic viability of the deposit. If grades are interesting, a more systematic sampling program follows this initial evaluation.

In economic terms, the main limitation to locating, evaluating and mining paleochannel placer deposits is the thick overburden, which results in high stripping ratios. Over-consolidation of sediments as a result of burial makes overburden stripping difficult and is a major limitation inhibiting exploitation of these buried deposits. The main economic limitations to mining surficial placer deposits are the result of typically low grades and the occurrence of most deposits below the water table. Environmental considerations are also an important limiting factor since these deposits often occur near, or within, present-day stream courses. A typical example of this type of surficial deposit is the Save basin, which has sand overburden in excess of 75 meters and, billions of liters of underground water, is within an international endangered animals sanctuary, and has vibrant winter agricultural activities. The bulk of the Marange diamonds are thought to have been deposited within the basin by rivers as a secondary deposit from the conglomerates.

### **10.3 Placer sampling**

One of the most difficult tasks associated with placer mining is the sampling of the deposit, where problems are associated with inaccurate assessment of the reserves more than any other reason. Within the realm of placers, those which contain valuable minerals with a high unit value, especially diamonds, are more difficult to sample than those which have a larger, bulk, lower-unit value like tin.

When sampling a placer deposit, a relatively large-size sample is required for an accurate valuation of the ground being tested. Placers are made up of varying sizes of gravel, which makes a representative sample difficult to obtain, and thus it is necessary to have knowledge of the size distribution of the mineral concerned. The right size material needs to be screened out, thereby concentrating the mineral and reducing the tonnage to be processed to save costs. When sampling placers for high unit value minerals, such as diamonds, any error in the mineral content of the sample will be magnified in the calculation of reserves. Some placers

which have a more uniform mineral value distribution may be adequately assessed with a minimum number of samples, while it may not be possible to adequately sample a deposit with a very erratic distribution of values, regardless of how many samples are taken. Thus, the investigation of a placer deposit should be made by, or be under the direction of, someone who is experienced in the art of placer sampling (Swiecki, 2011). Other items that should be observed and noted, as well as sample size and valuable mineral content, include magnitude and number of boulders, clay content, bedrock conditions, water, frozen ground, false bedrock, and any other physical characteristics that could affect mining of the deposit.

The steps to be followed in approaching a placer-sampling program commence with reconnaissance to ascertain land ownership, a check on the physical characteristics of the area, and research on the mining history of the area. This is followed by field inspections, which involve photogeology, surface grab-sampling over all exposures of gravel, a few seismic cross sections, geobotanical study, and old workings surveys. When choosing a sampling method, the disposition and density of sampling must be adapted to each placer (Swiecki, 2011).

Existing exposures can be tested for potentially valuable minerals by taking a grab sample and panning the sample. The advantages of taking samples from surface exposures are the low cost and the speed at which the samples can be taken, and the disadvantages are that the information represents what is on the surface and no quantitative information can be produced. Hand-dug pit, shaft, or trench bulk samples on dry, shallow ground can be effectively used in remote areas of the world where trained labour is not available, or the general cost of labour is relatively low. This method provides a satisfactory bulk sample and is frequently used to verify drilling results by sinking a shaft over a drill-hole. In addition, bedrock values and characteristics can be accurately determined when the excavations are sunk to bedrock.

The backhoe is a relatively inexpensive and a very adaptable, mobile, and fast piece of equipment for sampling relatively shallow, dry and stable hard ground up to about six meter deep deposits. Once a trench has been opened up, channel samples can be taken by hand or by using the backhoe, or alternatively a bulk sample can be made with all of the material from the excavation. Bulldozers are the best equipment to use in ground where trenches are to

be dug three meters deep or less and are in dry, stable ground. Prospecting placers with a large bulldozer trench is highly advantageous, in that the trenches permit a good visual inspection of the ground. Other machine-dug excavations are pits or shafts which are dug using powered equipment such as large augers, bucket drills, or clamshell excavators.

Churn drill holes are used where the ground is deep or wet and sampling by pits, trenches, or shafts is not feasible. This method utilizes a heavy casing with a drive shoe at the bottom, a chisel-shaped bit, and a vacuum-type sand pump for removing the sample from the hole. The use of connecting casings prevents contamination of samples taken at progressive depths. The advantages of using churn drills for sampling placer deposits are that the sample is very reliable, equipment is fairly portable, and few mechanical problems are encountered. The disadvantages of using churn drills are related to the very slow penetration rate, and the fact that large boulders create many problems.

A bulk sample can be between 50 and 200 tons in weight. There are some particular problems associated with placer sampling, specifically if the area contains many large rocks and boulders. The tendency would be to bypass areas containing many boulders or to sample the easily collected finer material around the boulders, which essentially is salting the sample. The most direct solution to sampling areas containing boulders involves taking samples large enough to contain a representative portion of the boulders in order to give accurate value estimates. As it is not physically possible to take large samples to include the boulders in most sampling situations, the most common solution is to visually estimate the volume and insert a correction factor into the end sample volume calculations. The methods used for estimating the value of placer ground relies on the assumption that the value found in a particular sample extends halfway to the next sample. While evaluation of ground with a generally low or fairly uniform average of values can be done using the standard reserve estimation methods, erratic high value samples in a deposit cause difficulties. Methods for adjusting erratic high values, so that an over valuation of the ground does not occur, include resampling erratic areas, using the lower value calculated, working out what the highest reasonable value should be, and then keeping all sample values within that limit.

The use of uncased drill holes in sampling ground with a high unit value mineral is inappropriate in placer sampling, because there is a tendency to unintentionally salt the

sample and get overvalued sample results due to excess material getting into the sample. Due to the large "nugget effect" associated with sampling ground containing high unit value minerals like gold and platinum deposits, the use of large diameter drill holes is recommended. When sampling deposits that have fine-grained material and contain low unit value minerals, small (50 millimeter) diameter holes may be used. Salting of samples can occur intentionally, through deliberate addition of valuable mineral to a sample, or unintentionally, through careless or improper working procedures. Once a sample has been taken from a placer deposit must be washed using riffled surface washing devices or dense media separation methods, winnowing methods, or flotation methods in order to retain the heavy valuable minerals as the lighter waste materials are washed away. The valuable mineral thus separated is then weighed to determine the value of the ground being tested.

#### **10.4 Record keeping and data processing**

Accurate and systematic records must be kept for proper placer evaluation. The major components of the data should include the following items: date, name of property and its location, drill-hole line and hole number, hole collar elevation, depth of the drive shoe for each sample interval, total hole depth, core rise in the pipe for each drive, core left in the pipe after pumping, the length of core removed, rock formation and its visible physical characteristics, depth and nature of overburden, depth of the pay gravel, depth to bedrock, nature of bedrock, thickness of pay zone, and the diameter of the drive shoe. These detailed records will be used to determine the value of the deposit as well as to determine its mineability, and to select a mining method.

#### **10.5 Reserve estimation and placer valuation**

There are many placer reserve estimation methods available: examples of these are the block, triangle, polygonal, traverses, and diamond methods. The value using the block method is calculated as the sum of the volume and value per cubic meter in each block, while the average grade is calculated as the sum above divided by the total volume. If the triangle method is applied, the value of the deposit is calculated as volume equals the average of the depth of the three drill holes times the area of the triangle. The weighted average mineral content is equal to the mineral value of each of the three holes times the depth of each of the

holes divided by the sum of the depths of the three holes. The polygonal method involves the volume sum of all the polygons multiplied by the average grade of each corresponding drill-hole to give the total mineral content. The average grade is thus the total mineral content divided by the total volume. The traverses method is very similar to that of the triangle method and may be used as a check. First, the area of a traverse is the average of the depths of the boreholes times the distance between the boreholes. The total volume of a section between two traverses is one-half the sum of the areas of all individual traverses, A and B, times the distance between the traverses. The mineral content of a section is the volume of the section times the average value between two traverses, while the total mineral content is the sum of the mineral contents of each section. The diamond method is much the same as the triangle method for regularly spaced holes where the drill holes are located at the centre of the diamond and apexes midway between drill holes on adjacent lines. The total area is equal to the sum of all diamonds that may be treated as right triangles for all practical purposes, while the total volume equals the area of each diamond times the depth of each hole through the pay zone. The total mineral value equals the sum of the mineral values in each hole times the volume of each diamond.

#### **10.6 Quality Assurance (QA) and Quality Control (QC) in sample handling and processing**

***Unless otherwise indicated, all the tables and contents included in this sub-chapter were created by the author.***

This QA/QC method for alluvial sampling and processing was developed specifically for the Umkondo dispersal, where 200 ton bulk samples are collected on a 100 meter by 100 meter sampling grid. The depth to bedrock averages about 60 centimeters but the samples are dug 20 centimeters into granite basement using an excavator. The samples are separately transported to a 10 ton dense media separation (DMS) plant for processing. It is important to decontaminate all surfaces and equipment where each sample may be off-loaded or handled and also to decontaminate the plant after each sample has been processed.

## 10.6.1 Detailed list of sample preparation activities

### Sample Extraction

Activity	Details	Data Gathered	Done
Sample extraction	Sample pit at least 5m length by 5m wide and 20cm into basement	Pit volume and in situ tonnage	
	Sampling points at regular grid 50m by 50m	Grade distribution	
Density	In situ ore x3	In situ density	
	In situ ore x3	Bulk density	
	Dry screened ore x3	Bulk density	
	Wet screened ore x3	Bulk density	
Survey	Sample pit profile	Pit dimensions and BCMs	
	Coordinates (WGS 84)		
	In situ ore stock pile	BCMs/t	
	Dry screened ore product	BCMs/t	
	Over sizes	BCMs/t	
	Under sizes	BCMs/t	
	Coarse	BCMs/t	
	Wet screen product	BCMs/t	
	In situ ore (dry analysis)	Particle size	

Activity	Details	Data Gathered	Done
Screen analysis		distribution	
	In situ ore (water analysis)	Particle size distribution	
	Dry screen product	Particle size distribution <20% fines	
	Wet screen product.	Particle size distribution <10 % fines	
Sample pad	Sterilise the sample pad at the plant		

### 10.6.2 Detailed list of sample processing procedures

#### DMS Plant decontamination certificate

The plant is purged between successive samples and/or decontaminated immediately after the project or consignment is completed, and any material spillage returned to the sample from which it came from.

Section	Element	Decontaminated (comment)
Feed preparation section	Head feed bin	
	Scrubber inlet section	
	Feed prep screen panel (deblinding)	
	Trommel screen	
	Jet wet pump (feeding feed prep)	
	Spillage	

<b>Section</b>	<b>Element</b>	<b>Decontaminated (comment)</b>
DMS	DMS floor / sump	
	Prep screen inlet section	
	Prep screen panels (deblinding)	
	Mixing box	
	Cyclone feed pump	
	Cyclone	
	Sink screen panels	
	Concentrate chute	
	Floats screen panels	
	Floats chute (screen)	
	Sputnik	
	Spillage	

<b>Section</b>	<b>Element</b>	<b>Decontaminated (comment)</b>
Slimes / Tailings	Tailings chute	
	Spillage	

### 10.6.3 Processing plant parameters

Section	Element	Average Values
Cyclone	Pressure	
	Floats density	
	Sinks density	
	Operating medium density	
Ep and cut point	Separation efficiency	
Tracer test (parameter control)	Plant efficiency	
Tracer tests during operations	Plant efficiency	

Cyclone parameters are to be measured every half hour during sample processing.

### 10.6.4 Material balance

	Mass (tonnes or kg)	%	Activity	Done
Head feed mass				
Scrubber oversize			Screen analysis	
DMS feed				
DMS tailings				
DMS grits				
Effluent/slimes			Analysis	
DMS concentrate				

### Comment

Sample ID		Consignment ID		Time		Date
Completed	Next	Completed	Next	Start		
				Finish		

DMS Attendant: \_\_\_\_\_

Security: \_\_\_\_\_

Date: \_\_\_\_\_

Date: \_\_\_\_\_

### 10.6.5 Glove box decontamination certificate

Sample ID		Consignment ID		Time		Date
Completed	Next	Completed	Next	Start		
				Finish		

Section	Element	Decontaminated
Feed preparation	Sputnik	
	Bin feed conveyer	
	Concentrate bin	
	Vibro feeder	

Section	Element	Decontaminated
Glove box	Glove box feed conveyer	
	Glove box feed chute	
	Glove box picking belt	

Section	Element	Decontaminated
Tailings	Tailings chute	
	Concentrate collection area/container	
	Spillage	

**Comments:**

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Challenges, delays, suggestions, general:

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Confirmation of decontamination and spillage and clean up:

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Glove box assistant:

Date:

---

Glove box supervisor:

Date:

Security:

Date:

#### 10.6.6 Sorting and processing efficiency monitoring

Section	Activity	Date
Perm roll tailings	Labeled and containerised	
	Re-run tailings at XRT	
Glove Box Tailings	Labeled and containerised	
	Re-run tailings at XRT	
Floats	Label the stockpile	
	Re-run floats throughout the process	
Recovered Diamonds	Sieving ( SFDs)	

Considering the recovery from the tailings, calculate the insitu grade, the sorting efficiency and the processing efficiency. The floats are to be processed for each sample before the sample is discarded.

#### 10.7 Sample density determination and screen analyses

The two processes are done before the samples are sent to the DMS plant. The insitu density= Excavated Mass/Volume of void. The void is determined by survey and the total excavated mass is determined by adding the masses of each dump truck load. The dump truck has a scale to measure the individual load masses. The bulk density= Excavated Mass/Volume of excavated ore. Here the excavated ore volume is determined by survey. The dry and wet screened ore bulk densities are determined on uniformly screened ore consisting of the +3mm to -12mm, +12mm to -30mm, and the +30mm to -50mm size envelopes. This involves small samples (one 10 liter bucket full). The bulk density= Mass of a bucketful of each size envelope/Volume of the bucket. The mass is determined on a 300kg scale.

The screen analyses are done to make sure the screened ore conforms to the bottom and top cut offs of each sample envelope as determined from the DSFD. Each envelope should contain a certain tolerable level of -3mm sand material. For the +3mm to -12mm the tolerable level is 20% sand, for the +12mm to -30mm the tolerable level is 10%, and for the +30mm to -50mm the level is 5% sand. An example of the sum screen analyses for the month of August 2015 is given below (Fig. 10.1) and its visual plot in Fig. 10.2.

	MOBILE SCREEN (DRY)	MOBILE SCREENS(WET)	STATIC SCREEN (WET)	STATIC SCREEN (DRY)
3.35	31.85	37.81	40.71	26.83
4	38.51	44.36	49.72	35.44
<b>5</b>	<b>48.25</b>	<b>53.59</b>	<b>63.72</b>	<b>51.90</b>
6.3	58.61	63.55	77.50	68.94
8	74.82	78.66	93.76	91.40
12.5	83.58	85.99	99.59	99.06
14	87.49	89.26	99.80	99.96
16	90.88	92.60	99.93	99.99
19	92.58	94.46	100.00	100.00
20	96.12	96.90	100.00	100.00
25	98.75	99.31	100.00	100.00
31.5	99.49	100.00	100.00	100.00
+31.5	100.00	100.00	100.00	100.00

Fig. 10.1: Compound screen analysis for the month of August 2015.

Data extracted from Marange Resources (Pvt) Ltd, Production August 2015. © Marange Resources.

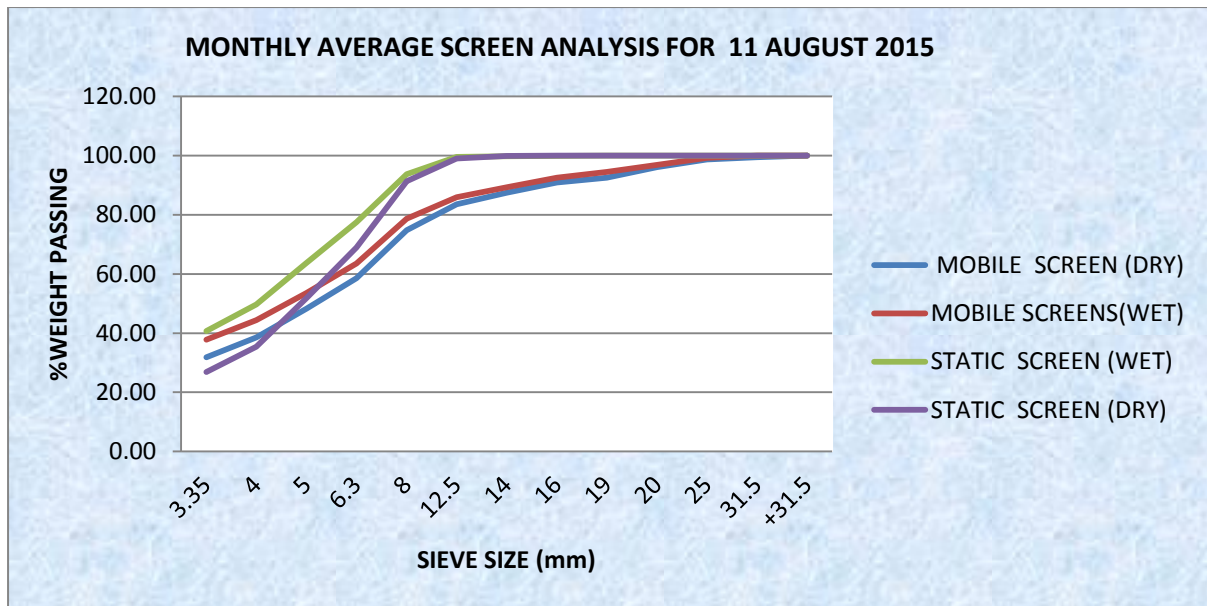


Fig. 10.2: Visual plots of the screen analysis data in Fig. 10.1.

Data extracted from Marange Resources (Pvt) Ltd, Production August 2015. © Marange Resources.

### 10.8 Conclusion

There are many ways of sampling and many methods of calculating the value of a placer deposit. It is important to remember to use care in sampling and to select the method that best suits the type of occurrence that is being sampled, and it is also important to use the ore reserve calculation method that best applies to the configuration of the deposit and mode of deposition. There is nothing that replaces experience, whether a costly book or advanced software. A gold, diamond or tin placer has a personality of its own, but all placers in the same geological province area are similar. Many systems exist, but an off-the-shelf application will lead to a gross under- or over-estimation of the deposit. It is acceptable to be within 10% of underestimation, so optimism must be kept in check.

## 11.0 CHAPTER ELEVEN

### SUMMARY, DISCUSSION AND CONCLUSION

The Umkondo sediments were deposited into a foreland basin formed by the Frontier Series rocks located to the east of the present day Umkondo Basin. The Frontier Series were then pushed onto the Zimbabwe Craton to form the Umkondo Basin, in which the sediments were deposited.

The source of the Umkondo alluvial diamonds has remained elusive to many, and concerted efforts are therefore required to undertake an intensive scientific study of the Umkondo Basin. There is very little evidence to suggest that the diamond-hosting conglomerates and grits traverse the Umkondo Basin from the Save River in the west to the Chimanimani Mountains in the east on the border with Mozambique. The evidence of the existence of diamondiferous conglomerates and grits has been found on the eastern margin along the Haroni River and more prominently occurs along the north-western margin, in the Chiadzwa area. The marginal occurrence of diamonds is a normal mode with most placer deposits. The interior of the basin hosts very thick sediments, with the conglomerates expected to be sitting right at the base. However, in many places the base of the sedimentary pile has been exposed by erosion as a result of uplift, folding, and faulting, followed by deep dissections by rivers draining off the mountainous interior region of the Umkondo Basin. The exposures have, however, revealed very thin (up to 15 centimeters), discontinuous, and cherty conglomerate with sparsely-packed small sub-rounded pebbles and a very low grade diamond content of about 0.05 carats per hundred tons.

On the economic front, the conglomerates need to be explored in full to expose their full diamond potential. Petrographic and geochemical study of the conglomerates can shed more light as to the source of the constituent materials and the geological processes that they underwent through geological time, and hence as to the possible source of the diamonds. The mineability of the interior conglomerates remains doubtful due to their thinness, the huge sedimentary pile overlying them, the variable steep dips of the host tilted sedimentary block mountains, and faulting. Of economic importance, currently, is the 70 000-hactre western margin conglomerate and alluvial deposit which is currently being extensively exploited. The

deposit requires proper and systematic evaluation in order to expose its full economic potential.

The kimberlites discovered in the vicinity of the Umkondo Basin are barren, and younger than the diamond-hosting Umkondo conglomerates, which are estimated to be about 1.1Ga and thus are ruled out as the possible source of the Umkondo diamonds. The contributing kimberlites, or lamproites, or some form of unknown ultramafic host rocks for that matter, seem to have been located to the north to north-west of the present location of the Umkondo Basin. Whilst there is no known provenance of the Umkondo diamonds, the present inferences point to a continental source that may have since been eroded away, rather than to a local source. The actual ages of the conglomerates, the diamonds, and the kimberlites around the Umkondo Basin need to be determined in order to unravel the mystery surrounding the origin of the Umkondo Basin diamonds.

The Quaternary gravels of the Save Basin from its confluence with the Odzi River are very likely to be rich in gold, diamonds, and other heavy minerals. The Save Basin lies to the south of the Chiadzwa diamond fields and also lies south south-west of the Odzi and Mutare greenstone belts. Extensive networks of rivers drain the greenstone belts and the diamond fields into the Odzi and Save basins. Thus more exploratory work needs to be undertaken within this huge alluvial basin.

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