Characteristics, recovery and provenance of rutile from the Namakwa Sands heavy mineral deposit, South Africa

by A. Rozendaal*, C. Philander*, and C. Carelse*

Synopsis

The Namakwa Sands heavy mineral deposit is located along the West Coast of South Africa and the mine is a world class producer of high quality zircon, ilmenite and rutile concentrates from essentially unconsolidated marine and aeolian sands of Cainozoic age. The objective of this study was to characterize rutile with respect to distribution, grain size, textures, colour and mineral chemistry within the Namakwa Sands orebody with the aim to explain its overall poor recovery. A representative suite of heavy mineral concentrates from various sections of the orebody and stages in the recovery circuit has been investigated microscopically and by means of SEM-EDS and LA-ICP-MS. The rutile grain size distribution displays a wide range and is directly related to its variable chemistry and consequently density. In placer deposits such as Namakwa Sands, mineral sorting is a function of hydraulic equivalence, and high density grains are smaller than the lighter grains when deposited under similar conditions. Grain size is also a function of sediment maturity, and the highly mature red aeolian sand (RAS) component of the deposit has a coarser grain size than the less mature orange feldspathic marine sands (OFS). The above primary characteristics of rutile are responsible for the loss of the coarse-grained fraction during screening and, given the empirically determined relationship that increased substitution elements reduce conductivity, also during electrostatic separation. Provenance studies using geothermometry have shown that the heavy mineral suite has been sourced mainly by the proximal medium-to high-grade Namaqualand Metamorphic Complex. The positive relationship between substitution elements and temperature of formation explains their high concentration in rutile of this deposit. The heterogeneity of rutile, produced by the combination of a high temperature primary source and the typical marine-aeolian placer genesis is deposit specific and unfortunately not conducive to high recovery levels in the current Namakwa Sands beneficiation circuit.

Introduction

The Namakwa Sands world-class, heavy mineral placer deposit is located along the West Coast of South Africa and has declared mineral resources of more than 800 million tons at a grade of approximately 9% total heavy minerals (THM). The economic minerals constitute 0.8% zircon ($ZrSiO_4$), 0.2% rutile, 0.3% leucoxene (TiO_2) and 3.3% ilmenite ($FeTiO_3$) of the *in situ* ore. Namakwa Sands has an annual production capacity of 21 million tons run of mine, 350 kt ilmenite, 130 kt zircon and 25 kt rutile with a life of mine of more than 30 years.

Production comes from an open pit where dry mining is employed. The ore is transported by loaders and conveyors to a primary and secondary mineral separation plant where wet spirals (seawater) and magnetic and electrostatic separators are used to produce the marketable concentrates. Namakwa Sands exports two grades of zircon and rutile and the ilmenite production supplies their titanium smelter at Saldanha Bay. The smelter has annual production capacity of at least 160 kt of titanium slag and 100 kt of pig iron[1]. It is the second largest producer of heavy minerals in South Africa after Richards Bay Minerals and is an internationally leading supplier of titania slag, pig iron, premium ceramics grade zircon and rutile concentrate to several export markets.

Earlier in-house investigations have shown that the rutile population of the Namakwa Sands deposit is heterogeneous displaying a diversity of colours, chemistry and variable grain size and morphology. This diversity has a negative impact on the rutile recovery during conventional processes and should ideally be quantified. The present orientation study investigates the characteristics of rutile in the orebody and sections of the beneficiation process with the aim to contribute to the improvement of overall recovery of rutile. In addition, the mineral characteristics and chemistry will allow new insight into the provenance of rutile and the placer deposit as a whole.

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* *Department of Earth Sciences, University of Stellenbosch, Matieland, South Africa.*

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Methodology

An orientation set of 17 heavy mineral samples was collected and consisted of eight samples from various lithological units of the orebody and nine samples from the rutile section of the recovery circuit in the plant, ranging from the run of mine feed to the final product.

The samples were split by means of a micro riffler to ensure representivity and then mounted on a glass slide to produce a polished thin section. These mounts allowed the quantitative study of the heavy minerals by means of transmitted and reflected light microscopy, scanning electron microscopy and LA-ICP-MS. Operating conditions of the instrumentation used are presented in the Appendix.

Microscopic mineral identification and phase quantification were supported and confirmed by the SEM mapping. Although single grain mineral chemistry was done by EDX, high resolution results were obtained by LA-ICP-MS spot analysis for elements such as Sc, V, Cr, Fe, Nb, Sn, Zr, Y, Mo, Ba, Hf, Ta, W, U, Th, Pb, Mn and the complete suite of 14 rare earth elements. Between 30 and 50 single grains were analysed per sample and were considered representative for an orientation study of this nature.

Geological setting

Namakwa Sands deposit is hosted by a late Cainozoic sequence of unconsolidated near-shore marine and aeolian sands occurring along the West Coast of South Africa and Namibia[2–5]. The sediments have been deposited on a gently sloping arid coastal plain consisting of a basement of metamorphites of the Meso-Proterozoic Namaqualand Metamorphic Province and Neo-Proterozoic Gariep Supergroup and Paleozoic sediments during the mid Miocene (~17 Ma) to late Pleistocene (0.1 Ma)[6].

The area of heavy mineral enrichment has been divided into three deposits, Graauwduinen West (GD West), Graauwduinen East (GD East) and Graauwduinen Dunes (GD Dunes). The ore-bearing units are red, quartz-rich, and feldspathic aeolian sands (RAS and OFS) as well as high-grade (up to 40% THM) marine Strandlines located at 20 and 35 m.a.m.s.l. respectively. Their interrelationships, dimensions, and lithologies are demonstrated by a diagrammatic W-E cross-section orientated at right angles to the present coastline[2] (Figure 1).

Mineralogically the sands consist of well-rounded quartz grains and minor concentrations of potassium feldspar. The heavy mineral suite is dominated by non-economic garnet, pyroxene, magnetite, amphibole, tourmaline, sillimanite/kyanite, monazite, and a diversity of minor and accessory mineral phases. The economic minerals are ilmenite, leucoxene, zircon and rutile, representing approximately 51 per cent of the total heavy mineral population. The orebody displays the classical morphological and sedimentological characteristics of Tertiary heavy mineral deposits located at present-day coastal margins that have been formed by the interplay of marine and terrestrial processes active in a J-bay setting[7,8].

Superimposed on the coastal clastic Cainozoic ore-bearing sequence is a pseudo-stratigraphy of what is locally referred to as hardlayer, also known as hardpan or duricrust. The effect of this duricrust is that it cements or lithifies the mineralized sands to different degrees of hardness and renders them unsuitable for routine treatment by the presently established infrastructure. These lithified zones may be up to tens of metres thick and, as a result, a proportion of the present life-of-mine resources are effectively sterilized[9].

General characteristics of rutile

Rutile has a tetragonal crystal structure, one good direction of cleavage [110], hardness of 6.0 to 6.5 and simple chemical composition of TiO_2. It occurs as columnar, idiomorphic grains elongated along the crystallographic c-axis. The mineral is insoluble in acids. The density varies between 4.2 and 5.6 and is a function of substitution by high field strength elements in the rutile crystal lattice[10]. Colour varies from black to deep red and yellow, but is typically yellow to reddish-brown in thin section. Rutile is almost always typically twinned on [101] and [301] and mineral zoning is a common feature. It is also a mineral that naturally forms across a high P-T stability field. These are all characteristics that contribute towards the stability of rutile, resulting in its

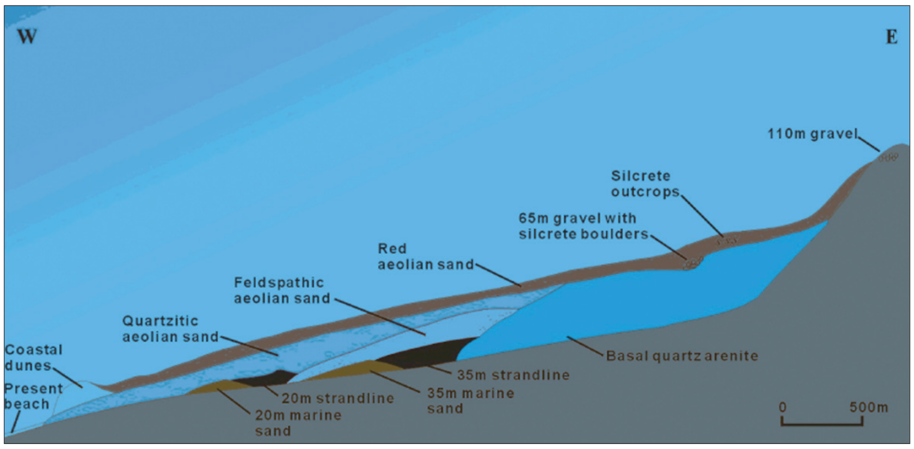

Figure 1—A cross-section of the Cainozoic Namakwa Sands heavy mineral placer deposit showing the various lithological units on a basement of Neo- and Meso-Proterozoic lithologies. Particular reference has been made to the strandlines (Strandlines), feldspathic aeolian sand (OFS) and red aeolian sand (RAS) in this study

survival during erosion, transport and finally deposition as a detrital heavy mineral component of placer deposits around the world.

Rutile differs from zircon and ilmenite, the other two economic mineral components of heavy mineral placer deposits, in that it has one strong cleavage direction and more variable chemistry, resulting in a wider density range. Thus rutile grains are in a sense more heterogeneous with respect to grain size, grain morphology and chemistry than zircon and ilmenite. Consequently this heterogeneity of rutile will negatively affect overall recovery from placer deposits and should be quantified. One of these features is rutile chemistry, which is a function of provenance and will differ between various placer deposits. The rutile chemistry should therefore be accurately determined as it characterizes individual deposits. In addition, variable chemistry will result in variable density and will affect the grain size distribution in placer deposits which have been concentrated under conditions of hydraulic equivalence[11]. The impact of the single strong cleavage direction implies the rutile component will decrease as the maturity of the placer deposit increases because of breakdown and reduction in grain size with resultant removal of the very fine fraction.

Rutile essentially consists of TiO_2; however, it may contain considerable amounts of both ferrous and ferric iron (nigrine) as well as niobium (ilmenorutile) and tantalum (tantalo-rutile; strüverite). High tantalum rutile may also be rich in tin whereas chromium, vanadium, zirconium and hafnium may also substitute titanium in the rutile lattice. The depth of colour of rutile from red to deep red is a function of the ferric iron, tantalum and niobium content[10]. A diversity of trace elements may, however, be present and include Si, Al, Ca Sc, Rb, Sr, Y, Zr, Mo, Sb, Cs, Ba, U, Th, Sb, Pb, W, Hf, Mn and REE[12,13]. When substitution element concentration exceeds the crystal lattice capacity, exsolution lamellae of, for example, haematite (Fe), ilmenite (Fe-Ti) and columbite (W) may occur.

Rutile in the Namakwa Sands deposit

Distribution

All the lithological units of the Namakwa Sands deposit, which include the red aeolian sand (RAS), orange feldspathic sands (OFS) and Strandlines contribute to the production of the final saleable rutile product. Rutile distribution follows a similar pattern as the other VHM (valuable heavy minerals defined as zircon+ilmenite+rutile+leucoxene) of the THM population and shows an increase in concentration from strandlines to OFS and RAS. This feature can be related to increased sediment maturity of the lithological units from original strandline to aeolian surface sands.

When the VHM-rutile ratio among the three ore types is compared, the most favourable ratio is hosted by the OFS and is paralleled by the distribution of leucoxene (Table I). This illustrates that the increase in sedimentary maturity from OFS to RAS, reduces the rutile component of the VHM population due to its relatively weaker resistance to transport by water and wind and results in mechanical breakdown. The same applies to leucoxene which dramatically decreases in the RAS. This would imply that the quality of rutile would be better in the RAS than in the OFS because of higher maturity. This could indicate a more favourable recovery during beneficiation.

Grain size, morphology, texture and colour

Philander and Rozendaal[14] reported that the grain size of the mineralized sands are classified as medium grained (250–500 micron) and show a clear upward fining relationship from the coarser grained strandlines to the finer grained RAS. The heavy mineral suite will obviously mimic this relationship although an order of magnitude finer because of the density contrast and principle of equilibrium operational in marine and aeolian depositional sedimentary environments.

The grain size distribution for rutile in the Strandlines, OFS and RAS of the Namakwa Sands deposit is shown in Figure 2. The broad and slightly flat shape of the histograms shows a wide range of grain sizes (d_{50}=104–118). This distribution is distinctly different from that of zircon and ilmenite which is generally finer grained and has a more narrow distribution (d_{50} of 104, and 111 respectively). Within the various parts of the orebody itself, the RAS has the more coarse grain size and is also supported by the size distribution of leucoxene and the light minerals (d<2.9) in

Table I

Ratios of rutile (Rut), leucoxene (Lcx) and ilmenite (Ilm) to total valuable heavy minerals (VHM) in the three main lithologies of the Namakwa Sands deposit

Unit	VHM	Rut	Lcx	Ilm
RAS	90.2	6.3	4.1	7.0
OFS	53.5	7.9	8.9	6.5
Strandlines	32.4	4.4	5.9	7.8

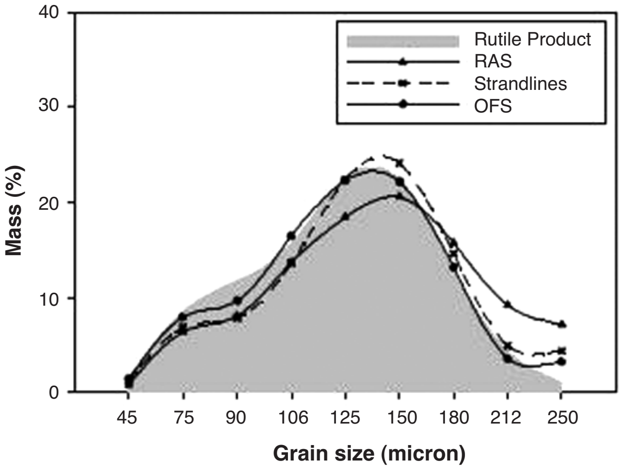

Figure 2—Grain size distribution of rutile in the three main units of the Namakwa Sands deposit and the final product. The red aeolian sand has a tail of coarse-grained rutile and is related to the high maturity of the sand. (RAS d_{50} = 118; OFSM d_{50} = 104; strandlines d_{50} = 114; final product d_{50} = 107)

the orebody. The wide grain size range for rutile is considered a function of its variable density, a feature to be discussed in the mineral chemistry section. It is interesting to note that the d_{50} value of 107 for the final product suggests that a very substantial contribution is made from the OFS. In addition, the coarse-grained rutile (>212 micron) is not recovered from the deposit and particularly affects the RAS and strandline contributions. At the same time it appears that the beneficiation process concentrates the <90 micron fraction.

The morphology of rutile is typical for detrital deposits and grains are subrounded to rounded and elongated with some pristine euhedral shapes. Several grains are parted along the main cleavage direction and have a stubby appearance. Pitted, corroded surfaces are common and the small holes are aligned parallel to the c-axis of the grain (Figure 3). RAS rutile is commonly coated by a patchy red veneer consisting of amorphous Si-Al-Fe-Ca. Rutile is clearly not homogenous and grains display twinning which produces a complex internal texture (Figure 3). Zoning is reasonably common and may be concentric or highly irregular, reflecting a complex crystallization history. Backscatter SEM images show that the zoning is produced by concentrations of heavy metals. Such grains are usually smaller than the rest because of the higher density. Exsolution features include orientated zircon, haematite and ilmenorutile laths or spots orientated parallel to the long axis of the grain or as blitz textures (Figure 3). Mineral inclusions and intergrowths are common and consist of ilmenite, zircon, quartz and leucoxene and in some instances present as complex aggregates.

The colour of rutile is variable and ranges from yellow to yellow red, deep red to almost black. This considerable colour variation is clearly a function of the concentration of elements substituting titanium in the rutile crystal lattice. The relationship between colour and chemistry is demonstrated in Figure 4 and will be discussed later in the text.

A quantitative estimation of the various colours has been made for the various parts of the orebody. For the sake of simplicity rutile has been classified into a red and yellow group and the ratios present are listed in Table II.

The Namakwa Sands rutiles are dominated by the red to deep red varieties which have a higher density because of more heavy metal substitution. It is interesting to note that the RAS unit contains the most red rutile and has the coarse grain size which supports its aeolian character. By contrast the OFS has a finer grain size and considerable more yellow rutile. It can be concluded that yellow rutile is finer grained because of less heavy metal substitution, and is probably removed in the aeolian upgrading process due to its lower density and mechanical breakdown of large, light grains.

Rutile chemistry

As indicated in the section on general characteristics of rutile, its mineral chemistry is extremely variable and this is also the case for the Namakwa Sands deposit. A diversity of elements has been analysed for by LA-ICP-MS; however, the most common elements present in significant concentrations include Nb, Zr, V, Fe and Cr (Table III). Minor concentrations of Sn, W, Ta and Hf are typical of the local rutiles. Total rare earth elements, uranium, thorium, yttrium, scandium, barium, manganese and lead are present in concentrations of

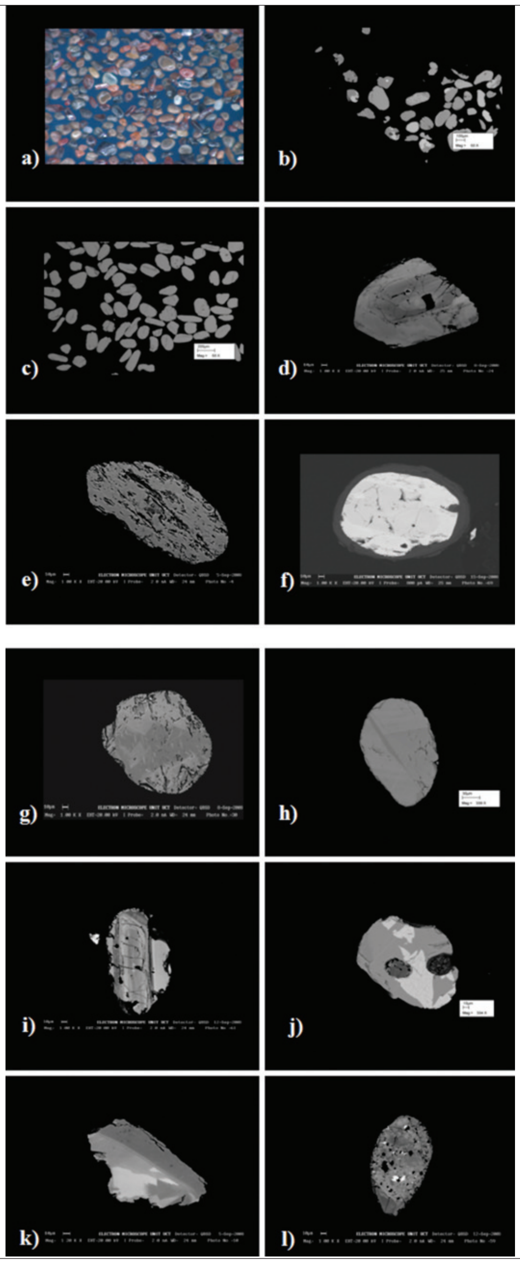

Figure 3—Textural features of rutile. (a) A typical distribution of rutile in the final product. Note the abundance of red to deep red and black grains. (b) SEM backscatter image showing ilmenite-rutile integrowths and heterogeneous grain size distribution in the OFS part of the orebody. (c) SEM backscatter image of the prime quality rutile product. The grain size is homogenous and gangue inclusions are minimal. (d) Prismatic and zoned stubby rutile grains with fracturing along the [110] cleavage plane. (e) Pitted and leached surface of detrital rutile. The pits are orientated parallel to the c-crystallographic direction. (f) Zoned rutile with a coating of Si-Al-Fe-Ca, a typical feature of the RAS section of orebody. (g) Complexly zoned rutile with small exsolved ilmenite lamellae forming a typical blitz texture. (h) Twinned rutile a typical feature of the orebody. (i) Two generations of rutile. A radially zoned grain is overgrown by a chemically homogenous later stage grain. These textures develop during crystallization in a terrane with several metamorphic events. (j) Complex grain with silicate inclusion and rutile-ilmenite intergrowth. Ilmenite shows a blitz texture of exsolved rutile lamellae. (k) Rutile with irregular zones of variable chemistry. The light grey zones are enriched in high field strength elements whereas the dark grey areas are almost pure TiO_2. (l) A complex rutile texture with abundant inclusions in particular the light grey zircon. Zonal features have effectively been destroyed. The texture is considered primary and is not fully understood

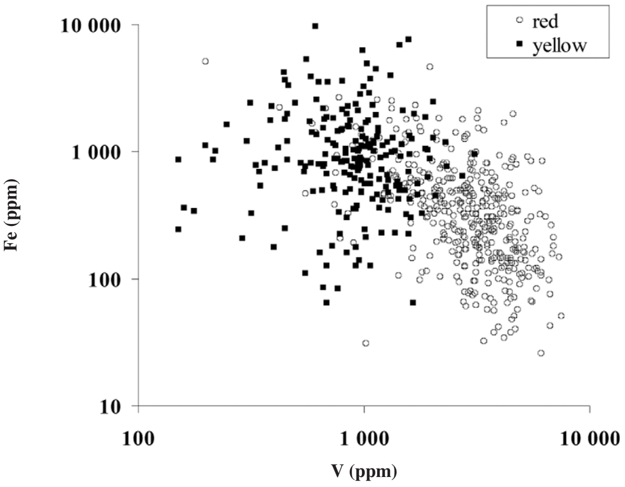

Figure 4—Chemical relationship between red and yellow rutile (from Philander and Rozendaal[14]). Red grains are enriched in vanadium as well as in zirconium and hafnium and depleted in iron (n= 600)

Table II

Simplified rutile colour relationships in the three ore classes, product and rejects

Unit	Red	Yellow
RAS	69.1	30.9
OFS	59.8	40.2
Strandlines	66.7	33.3
Rutile product	66.5	33.5
Quartz rejects	53.5	46.5
Rutile rejects	75.1	24.9

Table III

Mean and range of rutile composition determined by single grain LA-ICP-MS analyses (n=166)

Element	Mean	Range
V	2310	1–6809
Cr	699	1–4696
Fe	1087	1–16410
Zr	1165	1–5954
Nb	2010	1–17050
Sn	91	1–2727
Ta	132	1–1298
W	328	1–9130
TREE	20	5–40
U	27	1–430
Th	3	1–52
U+Th	30	2–431
Y	2	1–34
Mo	31	1–299
Ba	33	1–716
Hf	51	1–219
Pb	14	1–778
Mn	10	1–43
Sc	12	1–46

less than 30 ppm. The total concentration of substitution elements may be as high as 3% and indicated the presence of some ilmenorutile in the local population (Figure 6). Compared to other reported occurrences of rutile from low metamorphic sources[15] these values are particularly high.

A correlation coefficient matrix of the entire rutile population showed a strong (r=0.95) association of coupled substitution between Zr and Hf. This correlation also indicates that the analytical technique used is accurate and precise. Vanadium also shows a good correlation with Zr-Hf (r=0.65) a relationship that will be discussed in the following section. The good Nb-Ta correlation is typical for rutile and high concentrations are indicative of a felsic provenance[15,17]. The moderate correlation between Sn-Nb-W-Sc supports this association. Similarly, the moderate Cr-V correlation is indicative of a contribution from a mafic igneous source to the total rutile population[15,17]. The elemental associations of the rutile population are diverse, but systematic and can be used to identify particular populations for provenance or mineral beneficiation studies.

The relationship between rutile chemistry and grain colour is demonstrated in a binary diagram of iron against vanadium (Figure 4). Red to deep red rutiles are enriched in vanadium whereas the yellow-red rutiles contain less vanadium, but are enriched in iron. According to the above elemental association the red rutiles are also zirconium and hafnium enriched.

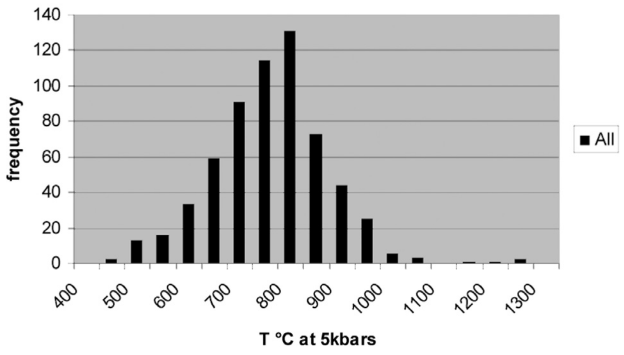

Figure 5—Single grain rutile temperature data generated by using the pressure adjusted zirconium geothermometer after Tomkins *et al.* (2007)[16]. The distribution indicates that rutile has a medium- to high-grade metamorphic provenance with most temperatures ranging between 700 and 850°C

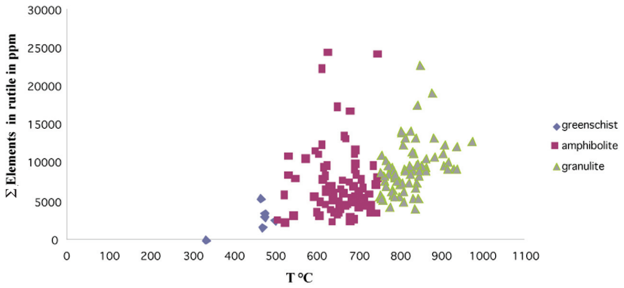

Figure 6—The temperature of formation and total substitution elements in rutile displays a positive linear relationship. The metamorphic grades have been colour coded and the population consists mainly of rutile from a medium- to high-grade metamorphic terrane (n= 166)

Geothermometry and provenance

Research by Zack *et al.*[12,13] has empirically demonstrated that the partitioning of zirconium into the crystal lattice of rutile in the presence of quartz and zircon, is a function of temperature[12,13]. High concentrations of zirconium in rutile indicate high temperature of formation. Watson *et al.*[18] confirmed this association experimentally and improved on the positive log-linear equation of Zack (op cit.). The effect of pressure on this relationship was investigated by Tomkins *et al.*[16] and necessitated further adjustment.

Mineral chemistry of rutile from this study allowed the application of the modified zirconium thermometer to the Namakwa Sands deposit. A histogram of the results shows that most of the rutiles were formed under temperature conditions equivalent to granulite and amphibolite facies of metamorphism whereas a small population reflects greenschist facies and igneous temperatures (Figure 6). This distribution equates with conditions similar to the formation of the high-to medium-grade metamorphosed and proximal Namaqualand Metamorphic Complex and the low-grade Gariep Group[19]. It can therefore be concluded that the most if not all of the rutile and the heavy mineral of the Namakwa Sands deposit were locally derived and probably within a radius of 30 km.

Suggestions by Ramdohr[20] that the substitution element content of rutile is a function of temperature are confirmed. A binary plot of total substitution element content versus temperature shows an increase with increased temperature of formation (Figure 6). The temperature relationship between yellow red and red to deep red rutiles shows that the red population was formed at higher temperatures (Figure 7). This also implies that the red grains host a higher concentration of substitution elements, as was demonstrated by the vanadium, hafnium and zirconium content, for example. From these relationships it can be concluded that a large section of the rutile population at the Namakwa Sands deposit is dominated by grains that formed at medium to high temperature, that are red to deep red and contain an abundance of substitution elements.

Geometallurgical implications

The Namakwa Sands orebody consists of three different ore types (strandline-type ore, OFS and RAS) that are blended in demand-specific proportions to feed a single processing plant. Rutile recovery is generally lower compared to that of ilmenite and zircon, and requires explanation.

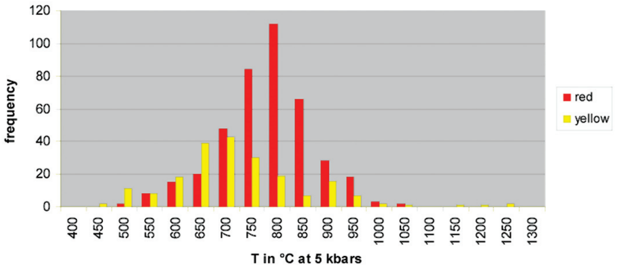

Figure 7—Temperature of formation and rutile colour relationship. Red rutiles have formed at higher temperatures and contain larger proportions of elements substituting titanium in the rutile lattice (n=166)

General rutile characteristics and from the three ore types in particular, have been discussed above. These results have demonstrated the heterogeneity of rutile, a feature controlled by primary factors genetically inherent to the deposit.

Although the entire deposit is classified as a typical Cainozoic marine placer, subunits have formed under different sedimentological conditions. For example, the strandline-type formed under typical high energy beach conditions over relative short periods producing a coarse-grained immature heavy mineral assemblage. By contrast, the OFS is overlying windblown sand with an upgraded heavy mineral content and increased maturity produced over a long period. The RAS is a surficial deposit that covers a large area and has been upgraded by wind action over an even longer period, a process still active today. As a result, characteristics such as grain size and concentration of rutile will differ among the three ore types. Consequently the rutile supplied for beneficiation will have a highly variable grain size and is not the ideal feed for a plant with fixed screen sizes and could result in reduced recovery. In addition, rutile from a high maturity source such as RAS is more coarse grained and of better quality and hosts fewer intergrowths of low density minerals. The same process also removes the less dense, yellow rutile.

Mineral chemistry of rutile has been demonstrated to be highly variable due to replacement of titanium by a diversity of high field strength elements. As a result the rutile density is also highly variable. During the process of placer formation clastic grains are sorted according to hydraulic equivalence, which is a function of grain density. This indicates that the larger the density variation the larger the grain size distribution, a feature typical of the Namakwa Sands deposit. As indicated above, this could be responsible for poor rutile recovery.

Rutile from the RAS part of the orebody is generally coated by a thin sheen consisting of amorphous Si-Al-Fe-Ca which adversely affects recovery by means of magnetic or electrostatic separation. This coating should ideally be removed. Similarly rutile from the OFS is affected by superimposed duricrust which causes a Ca-Mg-oxide-hydroxide coating.

Reconciliation between rutile characteristics of *in situ* ore and final product indicate that the:

- ➤ Bulk of the coatings has been successfully removed
- ➤ Product contains fewer grains with lockings of light silicates and oxides
- ➤ Product contains less intergrowths and exsolution features
- ➤ Mean grain size of the product is finer than that of the RAS
- ➤ Ratio of yellow to deep red rutile in the product is very similar to that of the RAS and Strandlines, but differs sharply from OFS which contains more yellow rutile.

From the above we can conclude that the grain size distribution of the rutile products shows that the coarse fraction is lost in the mineral separation process (d_{50} ~107; Figure 2) due to the 180 micron screens, and contributes to the low recovery. The relative gain in the <90 micron fraction in the final product indicates an above average recovery and is not fully understood. In addition, empirical results show that the conductivity of rutile decreases with an increase of the total substitution elements. This results in the loss of black to deep red rutile during electrostatic separation and is a further contributing factor to overall poor recovery.

Recommendations to increase rutile recovery are limited and revolve around grain size distribution and mineral chemistry. Blending of the three ore types to produce a homogenized and consistent size distribution is imperative to maintain optimum recovery. This optimum will not be comparable to that of ilmenite and zircon.

Conclusions

The present study of the rutile population from the Namakwa Sands deposit allowed their morphological, size, textural, mineral chemistry, colour and provenance characterization. From the results it is concluded that:

- Most of the rutile population was derived from the proximal medium-to high-grade Namaqualand Metamorphic Complex (NMC). As a result the population is dominated by red to deep red, medium to high temperature rutile substantially enriched in substitution elements
- Rutile chemistry demonstrated that most grains have a felsic provenance, but a mafic igneous input has also been identified. This would correlate well with the dominantly gneissic and granitic character of the NMC
- Variable rutile chemistry caused by substitution of titanium by high field strength elements produces variable density. During the formation of placer heavy mineral deposits, hydraulic equivalence is a function of density during mineral transport and is responsible for the grain size distribution. The variable density of rutile is consequently responsible for the broad grain size distribution
- Grain size distribution of rutile is not the same for the entire orebody. Rutile from the sedimentologically more reworked and mature RAS has a coarser grain size than the OFS and strandlines. From a mineral processing point of view, blending of these units will produce a wide range of rutile grain sizes, a feature that could adversely affect recovery
- Rutile is generally coarser grained per individual unit than ilmenite or zircon
- The sedimentological process of reworking has concentrated the higher density red rutile in the RAS unit with respect to the equal proportion yellow and red grains in the OFS. This could be explained by the fact that the yellow grains have a lower density and are preferentially removed during reworking and upgrading. This natural process will ultimately produce a better quality rutile
- Red to deep red rutile dominates the saleable products, but in general contains less iron than the red yellow types. This is a positive relationship from a marketing perspective
- Rutile composition and characteristics are not universal, but are deposit genesis and provenance specific. Consequently beneficiation processes and recovery will be deposit specific. Rutile derived from high temperature sources, like Namakwa Sands, may have a poor recovery
- During the recovery process wide grain size range is responsible for most of the losses. During the electrostatic separation stage rutile with high concentrations of substitution elements are lost due to decreased conductivity properties
- Blending of the three ore types to produce a homogenized and consistent size distribution is imperative to maintain optimum recovery.

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Appendix

The scanning electron microscope used in this study is an Oxford Instrument® 133 KeV detector and Oxford Inca Software at Stellenbosch University. Beam conditions were set at 20 kV and 1.5 nA. A working distance of 13 mm was used with a specimen beam current of -3.97 nA. Counting time was 50 s. For the standardization and verification of the results, internal Astimex Scientific Mineral Standards were used. To correct for detector drift, pure Co and Fe and Ti in ilmenite were used periodically.

Trace element analysis was also performed by LA-ICP-MS at Stellenbosch University. A New Wave 213 nm laser ablation system connected to an Agilent 7500ce ICP mass spectrometer was used. The instrument allowed detection limits of 0.1 ppm for the REE and 1 ppm for the other trace elements. About 30 to 44 spot analyses were done on each thin section using grains that were free of cracks or inclusions. Only one spot analysis per rutile was done. The pulse rate was set at 10 Hz with a spot size of 55 mm and 75 mm for bigger grains. The background counting time was 17 s with a data acquisition time of 40 seconds. A gas blank was measured for 60 s before each sequence of spot analysis. For quantification of trace elements in the rutile grains, the NIST 614 and 612 series of glass standards were used for calibration. Titanium, measured as 47Ti was used as an internal standard, using the average Ti concentration obtained from the 600 SEM analyses. This internal standard was used to correct for factors of machine drift and matrix affects. To establish the level of accuracy of the data-set, a standard reference material, namely BHVO-2G, was used. Data acquisition and processing were done using the software packages Agilent 7500 ICP-MS Chemstation and Fileview32. ◆