Recovery of duricrust sterilized heavy mineral resources at the Namakwa Sands Mine South Africa: a geometallurgical challenge

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Namakwa Sands, an Anglo Operations Limited subsidiary, is a world-class producer of heavy minerals. A layer of duricrust imposes a pseudo-stratigraphy to the primary deposit and has sterilized part of the generally unconsolidated ore in the open cast mine. The bulk of this ore cannot be treated by the present infrastructure, which employs conventional mineral separation technology. The mineralogy of the cementing agent consists of magnesium and calcium silicates and minor carbonates in addition to clay minerals such as sepiolite and those from the smectite group. Although the duricrust ore is friable and can be easily crushed, the significant clay-sized slime fraction produced, in particular the highly sorptive sepiolite, adversely affects mineral separation. The geometallurgical challenge is to cost-effectively remove the slimes from the ore before it is delivered to the concentrator.

Introduction

The Namakwa Sands heavy mineral deposit is located at Brand se Baai along the West Coast of South Africa and is a world-class producer of premium quality zircon (ZrSiO₄), ilmenite (FeTiO₃) and rutile (TiO₂) concentrates from essentially unconsolidated marine and aeolian sands of Cenozoic age (Figure 1). Resources are in excess of 800 million tons of ore at a grade of approximately 10 per cent total heavy minerals with a life-of-mine of 30 years. Approximately 17 million tons are mined per annum, which results in the production of 350 000 tons ilmenite, 120 000 tons zircon and 25 000 tons rutile. Production comes from an open pit where dry mining is employed. The ore is transported by loaders and conveyors to two primary concentrator plants (PCP) that utilize wet spirals to upgrade the heavy mineral concentration to around 90%. These concentrates are pumped to a secondary concentrator plant (SCP) where wet high-intensity magnetic separators (WHIMS) are used to produce a zircon-rich non-magnetic concentrate, and a magnetic concentrate comprising mainly ilmenite. SCP concentrates are separately trucked and treated at the mineral separation plant (MSP) near Koeckenaap, where a series of magnetic and high-tension separators are employed to produce the marketable products. Namakwa Sands exports two grades of zircon and rutile and the ilmenite production supplies their titanium smelter at Saldanha Bay. The smelter produces 180 000 tons of titanium slag and 120 000 tons of pig iron for the export market per annum.

Superimposed on the coastal clastic Cenozoic ore-bearing sequence is a pseudo-stratigraphy of what is locally referred to as hardlayer, also known as hardpan or duricrust. The duricrust effectively cements or lithifies the mineralized sands to different degrees of hardness and renders it unsuitable for routine treatment by the present infrastructure. These lithified zones may be up to 15 m thick and, as a result, a proportion of the present life-of-mine resources are effectively sterilized. The cementing agent occupies primary pore space and does not adversely affect average ore grades.

An expansion programme is presently in progress, which will allow the processing of the hard mineralized ore. The objectives of the present study are to establish the vertical
and lateral distribution of such layers in the mine area and to determine the mineralogy and geochemistry of the cementing agent. Based on the results, the impact of these conditions on cost-effective mineral separation from these lithified units will be discussed.

Methodology

The duricrust has been studied by measuring, photographing and sampling 13 vertical profiles in the mine area. These profiles are representative of the lithological variations observed and thirty samples have been selected for detailed mineralogical and geochemical studies. Binocular and polarizing microscopy provided limited assistance because of the very fine nature of the cement. Scanning electron microscope energy dispersive spectroscopy (SEM-EDS) supported by X-ray diffraction (XRD), proved to be the most effective tools for positive mineral identification. Elemental mapping by SEM-EDS was particularly successful to demonstrate the interrelationships of the various phases.

Crushing, milling, sedimentation and centrifugation were used to extract the clay fractions from the consolidated samples. XRD patterns of differently treated clay fractions were obtained using a Philips® PW 1130 diffractometer equipped with a Cu(Kα) radiation source and operated at 50 kV and 40 mA in the angular range 5° ≤ 2θ ≤ 70°. Major element chemistry was obtained with a Philips® 1404 XRF spectrometer fitted with an Rh(Kα) tube operating at 50 kV and 50 mA, using the standard lithium borate/tetraborate fusion preparation methodology. Polished bulk sample fragments were carbon coated and analysed in backscatter mode using SEM-EDS instrumentation comprising a Leo 1430VP and Link EDS system operated at 20 kV and 1.2 nA. Working distance was set at 13 mm and counting was performed for 50 s live-time. Anglo American Research Laboratories independently verified the analytical results.

Geological setting

The Namakwa Sands Deposit is hosted by a late Cenozoic sequence of unconsolidated near-shore marine and aeolian sands occurring along the West Coast of South Africa and Namibia. The sediments have been deposited on a gently sloping coastal plain consisting of a basement of metamorphites of the Meso-Proterozoic Namaqualand Metamorphic Complex, Neo-Proterozoic Gariep Group and Palaeozoic Table Mountain Group sediments during the mid Miocene (~17 Ma) to late Pleistocene 0.1 Ma. The ore-bearing units are red, quartz and feldspar rich aeolian sands as well as high grade (up to 40% total heavy minerals) marine strandlines located at 20 and 35 m.a.m.s.l. (Figure 2).

Mineralogically the sands consist of well-rounded quartz grains and minor concentrations of potassic feldspar. The economic minerals are ilmenite, leucoxene, zircon and rutile, which constitute approximately 60 per cent of the total heavy mineral population. Non-economic garnet, pyroxene, magnetite, amphibole, tourmaline, sillimanite/kyanite, monazite and a diversity of minor and accessory mineral phases represent the remainder of the heavy mineral suite. The total heavy mineral population predominantly reflects a medium to high grade metamorphic provenance that can be equated with the proximal Namaqualand Metamorphic Complex. Sensitive High Resolution Ion Microprobe (SHRIMP) dating of zircons confirms this assumption, but also suggests the contribution by populations from the early Proterozoic Vioolsdrift Suite, Gariep Group, Neoproterozoic/Paleozoic Cape Granite Suite and intrusive associated with the break-up of Gondwana during the early Cretaceous.

The orebody displays the classical morphological and sedimentological characteristics of Tertiary heavy mineral

![Figure 2. Schematic east-west geological cross section showing the distribution of the mineralized clastic units of the Namakwa Sands deposit](image-url)
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. This nomenclature refers to the shape of the bay that trapped the heavy minerals.

**Duricrust**

By broad definition, duricrust is a hard layer that forms by surface processes where unconsolidated clastic deposits of marine or terrestrial sedimentary origin are cemented by illuvial silica or other cements such as calcium and magnesium carbonates and silicates that are precipitated from percolating groundwater. The nomenclature used in the literature to describe these superimposed features is extremely variable and in many respects confusing, mainly because of its morphological and mineralogical complexity. For the sake of simplicity, the universal term duricrust will be used throughout the text.

Duricrust is well developed along the western and southern coastal margins of South Africa and has been described as silcrete, calcrete and dorbank, a local term. It selectively cements the Cenozoic coastal sediments into a positively weathering pseudo-stratigraphy, which may occur at several different elevations above sea level. This feature has been poorly studied from a correlation, mineralogical or geochemical perspective either in profile or laterally in the past. The age of this superimposed process is controversial and poorly constrained. Although a minimum age of Middle Miocene has been suggested for silcretes along the West Coast, the duricrust pseudo-stratigraphy is much younger and probably formed during the late Quaternary.

**Duricrust at Namakwa Sands**

Duricrust present at the Namakwa sands mine forms part of the regional coastal distribution and is prominently developed immediately below the surficial, well-mineralized red aeolian sand (Figure 2). Duricrust cements sands of the feldspar- and quartz-rich aeolian beds and can be cross-cutting with respect to the sedimentological bedding. The vertical thickness of the cemented unit is variable and has a range between 2 and 15 m; however, laterally it can be discontinuous. On mine scale it follows the contours of the dune topography and as a result the elevation of the unit varies from 120 m.a.m.s.l. in the east to 20 m.a.m.s.l. towards the coast. This is a clear indication of the perched palaeo-water table control on the development of the duricrust. A typical example of well-developed pseudo-stratigraphy is illustrated in Figure 3, showing the vertical colour variation as well as interbeds of unconsolidated sand.

The initial approach was to define a chemostratigraphy of the hitherto poorly studied duricrust, by means of whole rock chemistry. The most conspicuous and unexpected feature was the vertical partitioning of calcium and magnesium. The top of the pseudo-stratigraphy is magnesium-rich and gradually becomes calcium-magnesium-rich towards the base (Figure 3). This relationship was confirmed by the mineralogy, which demonstrated sepiolite \( \text{Mg}_8(\text{OH})_4\text{Si}_{12}\text{O}_{30}(\text{H}_2\text{O})_{12} \), an aluminum-free fibrous clay, to be the dominant cementing agent towards the top (Figure 4). Sepiolite occurs in association with minor opaline silica, palygorskite and clays of the smectite group such as nontronite, montmorillonite and saponite-stevensite (Figure 5).
The abundance of sepiolite has been previously reported in soils\(^1\), but not in profile and its presence has important implications for recovery of the heavy minerals. It has unique sorptive characteristics and can retain up to 200 per cent of its weight in water. Towards the base of the pseudo-stratigraphy, calcium and calcium-magnesium silicates, hydroxides and carbonates dominate. The above vertical associations occur throughout the mine area.

**Genesis**

Duricrust developed along the West Coast is generally thought to be the result of groundwater activity during periods of arid climatological conditions\(^1\). The elevation of this semi-continuous unit is morphologically controlled and cementing minerals are chemical precipitates from saturated solutions. The vertical partitioning of magnesium and calcium is a function of a fluctuating water table elevation due to evaporation and replenishment and the resulting changes in pH of the groundwater. Alkaline groundwater favours high solubility of Mg and Si and hence the precipitation of sepiolite\(^2\). Although the source of the anomalously high concentration of magnesium is difficult to explain\(^3\)-\(^5\), the influence of coastal marine aerosols as a contributor is one possibility.

**Geometallurgical implications**

The Namakwa Sands infrastructure is geared for the treatment of unconsolidated mineral sands. Consequently, the presence of duricrust in the open cast operation has a detrimental effect on the routine mining and beneficiation process. The results of the morphological, mineralogical and geochemical study showed that the duricrust cemented ore has a mappable distribution and distinct composition. The generally very low opaline silica content and dominance of clay minerals produces a friable ore with variable hardness that can be processed, but will require a crushing stage. As a result, significant capital expenditure has been allocated to process this ore and enhance production\(^6\). Natural slaking of the ore by exposing it to the arid surface conditions along the coast was tested, but proved unsuccessful due to the inert mineralogy (e.g. sepiolite) of the cement.

Most sections of the duricrust-imposed pseudo-stratigraphy have a cement matrix with the capacity to generate a significant volume of slimes, consisting mainly of clay sized (<2 μm) particles. Excessive slimes are expected not only to affect the mining stages but also various stages of the recovery process such as wet spiral separation efficiency, the treatment of process water, amount of water tied up in the process, the tailings disposal operation and even the final mineral product. In addition, the abundance of sepiolite with its highly sorptive properties can thicken fresh and salt water, entrapping liquid and increasing the viscosity even at very low concentrations and consequently impede efficient mineral separation in wet spiral and slurry systems. Ores with high slime content are also more difficult to pump than pure sand due to the higher viscosity of the slurry.

The challenges associated with resources of variable hardness and the removal of the high slimes content prior to its delivery to the concentrator will have to be successfully addressed to allow continuation of the low cost production of heavy minerals from the mine. Comprehensive metallurgical test work confirmed that autogenous milling is superior to other conventional comminution techniques, yielding mineral liberation rates better than the standard 90% target. Consequently, mineral recoveries associated with the successful beneficiation of the duricrust resource are projected to be significantly better than the existing norm. As anticipated, actual plant trails generated more post-milling slimes than usual, but the introduction of extra desliming cyclones, operated in a clustered fashion and a new high-rate thickener with a dedicated flocculant facility are envisaged to effectively deal with this problem.

**Conclusions**

The presence of laterally continuous duricrust in the mine area adversely affects the recovery of heavy minerals by...
conventional methods. A diverse clay mineral suite, dominated by sepiolite, is the main cementing agent and renders the resources conducive to comminution, which in the process will create significant volumes of clay-sized slimes. The presence of sepiolite with its highly sorptive properties is an added complication to the recovery of heavy minerals. The metallurgical challenge that faces the mine is the removal of slimes from the ore before delivery to the concentrator, and in the process remains a low cost producer.

References