Mineral Sands: An Overview of the Industry

Greg Jones

ABSTRACT

Mineral sands are different to most commodities, however they share similarities with other commodity types, such as the importance of quality constraints of iron ore and coal or the importance of physical properties of diamonds. The mineral sands industry consists of two principal product streams; titanium dioxide minerals – in the form of rutile, ilmenite and leucoxene; and zircon. The principal valuable heavy minerals (VHM) include ilmenite, leucoxene, rutile and zircon. Variations of other titanium minerals occur between the end members of ilmenite and rutile, including pseudo rutile and anatase.

Most mineral sands deposits are found in unconsolidated fossil shorelines several hundreds of metres to tens of kilometres and occasionally hundreds of kilometres inland from the present coastline. Mineral sands orebodies essentially fall into two categories based on the mode of deposition: alluvial or aeolian. Alluvial deposits are further split into marine beach placers (or strandlines) and lacustrine heavy mineral (HM) accumulations.

Exploration for mineral sands involves the positive identification of key criteria leading to the focus of exploratory surface sampling, augering and drilling. Assaying is primarily focused around determining the percentage of HM contained within a given sample. Other results of interest include clay fines, sand and oversize. Metallurgical/mineralogical assessment is often undertaken by via laboratory scale bench tests that replicate the wet concentration and dry mill processing routes.

The most critical component in resource assessment for mineral sands is about quantifying HM grade, then mineralogical assemblage and then quality of those mineral species. This will determine whether a mineral sand final product is marketable or not. Mining of mineral sands is conducted either wet or dry. Wet methods are generally preferred for large tonnage, unconsolidated and low clay orebodies. Where ground conditions are hard and orebodies are small, high grade and discontinuous, dry mining techniques are generally employed. Concentration of mineral sands from the primary ore is carried out in two sections; wet, utilising sizing and gravity differentiation between HM, VHM, clay and quartz, and dry, exploiting the magnetic, electrostatic and to a lesser extent SG properties of the minerals of interest.

Mineral sands exploration, mining and processing faces the same operating challenges as the rest of the resource sector. Added to this are the issues that are unique to mineral sands and to which the industry devotes considerable resources to developing solutions.

INTRODUCTION

Mineral sands are different to most commodities, however they share similarities with other commodity types, such as the importance of quality constraints of iron ore and coal or the importance of physical properties of say diamonds. The term "mineral sands" normally refers to concentrations of heavy minerals (HM) in an alluvial (old beach or river system) environment. Occasionally these deposits are referred to as "beach sands". However mineral sands are also found in large aeolian sand systems or “dunal sands”.

The exploration, development, mining and processing of mineral sands is atypical within the resource sector, because at virtually every stage it is possible to visually estimate the grade and composition of the HM and valuable heavy mineral (VHM).

Even the rehabilitation of mineral sands mining is unique in an industry where rehabilitation of pit voids and stockpiles is now accepted good practice. Part of the operating license for mineral sands mining is to complete the backfill and rehabilitation back to a pre-mining land usage, or an alternative usage provided for in landholder agreements.

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OVERVIEW: TITANIUM AND ZIRCON

Mineral sands represents less than one per cent of the value of the global resources sector. The mineral sands industry consists of two principal product streams:

⇒ Titanium dioxide minerals – in the form of rutile, ilmenite and leucoxene. Ilmenite is also used to manufacture titanium slag and synthetic rutile products; and
⇒ Zircon.

Titanium Dioxide

Titanium dioxide minerals are used mainly as feedstock for the world’s titanium dioxide (TiO₂) pigment industry. As a pure white, highly refractive and ultraviolet light absorbing product, titanium dioxide pigment is commonly used in architectural and automotive paints, plastics, paper, textiles and inks. Titanium dioxide feedstock is also used in the manufacture of welding electrodes. Titanium minerals are non-toxic, non-fibrogenic and biologically inert and they can be used safely in foodstuffs, pharmaceuticals and cosmetics (Iluka, 2008 and TZMI, 2008).

Titanium feedstocks supply different markets however world demand for ilmenite, leucoxene and rutile is determined by the demand for titanium oxide pigment. The pure white pigment is used as an opacifier in paints, plastics and paper, accounting for around 93 per cent of global titanium feedstock consumption (Figure 1) (TZMI, 2008; Iluka, 2008). Titanium dioxide pigment is produced by two alternative process routes: the chloride and sulphate processes.

Rutile, synthetic rutile and titanium slag can be used to produce titanium metal. Due to the combination of strength and lightness of titanium metal, it is used for advanced engineering applications, including architectural coatings, the aerospace and defence industries as well as a range of other applications, including sporting equipment and jewellery. Titanium metal is also used in desalination plants and corrosive chemical industries and its non-reactive properties make
titanium metal one of the few materials that can be used in the human body for hip replacements and heart pacemakers.

**Zircon**

Zircon is the other major product of the mineral sands industry and is a co-product of titanium mineral production. In most projects zircon is only a minor by-product and only rarely would zircon be considered the principal product (Iluka’s Jacinth-Ambrosia project), with titanium minerals as co-products. An increase in the importance of zircon has resulted from increased demand and the flow on increase in zircon prices in recent years. This is in addition to the discovery of higher grade zircon provinces (TZMI, 2008).

The most important application for zircon is in the ceramics industry in the production of opacifiers used in surface glazes and pigments. Prior to the 1980s refractory applications were the most common use of zircon, used to make refractory bricks and shapes for use in steel and glass industries. Limited supplies, and high prices of zircon during the late 1980s, forced steelmakers to switch to alternative refractory materials. The significant market share in this application has now been lost, as these alternatives are now preferred for technical reasons (TZMI, 2008).

Due to its high melting point (2200°C) zircon is used as a foundry sand in moulds, and as a milled "flour", particularly in higher temperature applications where maintaining the quality of the surface of the casting is important. The specialised area known as "investment casting" is a growing application for zircon in this industry (TZMI, 2008).

Zircon is also used for the production of zirconia, zirconium metal and zirconium chemicals. These are high value and growing applications for which total consumption of zircon is becoming significant.

**GEOLOGY**

Mineral sands is the term given to a group of minerals commonly found and mined together from water or wind concentrated deposits. The principal valuable minerals include ilmenite (Fe,TiO₃), leucoxene (FeTiO₃,TiO₂), rutile (TiO₂), zircon (ZrSiO₄) and monazite (Ce, La, Th, Nd, Y)PO₄. *(Table 1)*. In recent times, however, monazite has not been regularly sold as a product and stockpiling or returning to pit void, is common. Smaller volumes of garnet and staurolite are sold as niche products for specialised use. Variations of economically exploitable titanium minerals occur between the end members of ilmenite and rutile, including pseudo rutile and leucoxene, as well as the other polymorphs of TiO₂, anatase and (more rarely) brookite.
### Table 1: Common mineral sands, their physical properties and chemistry (source Iluka).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Valuable</th>
<th>Magnetic Susceptibility</th>
<th>Electrical Conductivity</th>
<th>SG</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ilmenite</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
<td>4.5 - 5.0</td>
<td>Fe.TiO₃</td>
</tr>
<tr>
<td>Rutile</td>
<td>Yes</td>
<td>Low</td>
<td>High</td>
<td>4.2 - 4.3</td>
<td>TiO₂</td>
</tr>
<tr>
<td>Zircon</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
<td>4.7</td>
<td>ZrSiO₄</td>
</tr>
<tr>
<td>Leucoxene</td>
<td>Yes</td>
<td>Semi</td>
<td>High</td>
<td>3.5 - 4.1</td>
<td>Fe.TiO₃,TiO₂</td>
</tr>
<tr>
<td>Monazite</td>
<td>No</td>
<td>Semi</td>
<td>Low</td>
<td>4.9 - 5.3</td>
<td>(Ce,La,Th,Nd,Y)PO₄</td>
</tr>
<tr>
<td>Staurolite</td>
<td>No</td>
<td>Semi</td>
<td>Low</td>
<td>3.6 - 3.8</td>
<td>Fe₂Al₉Si₄O₂₂.(OH)₂</td>
</tr>
<tr>
<td>Kyanite</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
<td>3.6 - 3.7</td>
<td>Al₂SiO₅</td>
</tr>
<tr>
<td>Garnet</td>
<td>No</td>
<td>Semi</td>
<td>Low</td>
<td>3.4 - 4.2</td>
<td>(Fe,Mn,Ca)₃.Al₂(SiO₄)₃</td>
</tr>
<tr>
<td>Quartz</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
<td>2.7</td>
<td>SiO₂</td>
</tr>
</tbody>
</table>

The components of mineral sands deposits all have high specific gravity (greater than 2.85 g cm⁻³) and tend to lag or concentrate during storms when lighter components, such as quartz, are carried offshore or along shore by strong littoral drift. HM accumulation occurs during periods of fair weather beach building and it is this HM that provides the basis for the thicker HM strandlines formed during major storm events.

Most mineral sands deposits are found in unconsolidated fossil shorelines several hundreds of metres to tens of kilometres and occasionally hundreds of kilometres inland from the present coastline.

Repeated storm erosion and reworking over centuries or millennia may progressively enrich a mineral sand deposit. This can be observed within individual deposits being mined today and can result in enrichment of HM and occasionally VHM (through winnowing out of lighter trashy or gangue HM) within a deposit.

Deposit preservation occurs over geologically longer periods through subsidence of coastal sediments, changing sea levels caused by ice ages or isostatic adjustment of continental margins. This may cause shorelines to migrate inland (marine transgression), potentially resulting in reworking older HM accumulations into larger deposits. Alternatively migration seaward (marine regression) can occur leaving reworked deposits preserved inland (Figure 2) (Boggs, 1987).
HM assemblage is predominantly reflective of the local or regional provenance although extreme variation can occur within deposits and individual strandlines. The chemical characteristics are also reflective of the provenance although post depositional influences such as weathering/induration can result in beneficial or deleterious changes to the chemistry of some minerals.

Most mineral sand deposits being mined today were formed during the Holocene and Pleistocene periods (that is over the past 1.8 million years) but some date back into the Eocene period (58 million years ago) (Baxter, 1977; Shepherd 1990; Wallis and Oakes, 1990; Hou and Warland, 2005). Over this period changes in the sea level of between minus 300 m and plus 350 m from current sea level, caused principally by ice ages, interglacials and associated eustatic adjustments, resulted in repeated reworking of sediments deposited by rivers in coastal shorelines and existing HM laden coastal sediments (Iluka, 2008).

**OREBODY TYPES**

Mineral sands orebodies essentially fall into two categories based on the mode of deposition: alluvial or aeolian. Alluvial deposits are further split into marine beach placers (or strandlines) and lacustrine HM accumulations. Aeolian deposits are generally closely associated with marine beach placers, having been formed by the erosion, transport and deposition of HM from adjacent marine beach placers by prevailing winds.

**Figure 2:** Schematic showing a model for phases of HM accumulation, concentration and preservation of marine beach placer (source Iluka).

The size and grade of mineral sand deposits vary considerably. Marine placers are typically 100 to 200 m wide, five to 15 m thick and two to 20 km long and HM grades can vary from several per
cent to 90 per cent. Some marine placers comprise strandlines that are deposited in close proximity to each other and as such can form accumulated deposits up to one kilometre across strike. Dunal deposits close to the shore tend to be larger, more irregular in dimension and lower grade (generally 0.5 per cent to 15 per cent HM).

The composition of mineral sand deposits reflects the type of rocks or provenance from which the sands containing the heavy minerals are derived. For example granitic and gneissic source rocks principally provide ilmenite and zircon and metamorphic rocks provide ilmenite and rutile.

During erosion cycles, river courses change providing different sediment loads and heavy mineral suites to the ocean. Repeated reworking of a particular deposit may also produce mineral zonation. Later weathering may enhance the value of a mineral sand deposit by leaching iron out of ilmenite. This may increase the TiO₂ content of ilmenite from 55 per cent to a maximum of about 90 per cent.

The zonation of HM within deposits and individual strandlines generally follows the following trend from oldest deposited to youngest:

- zircon, monazite ⇒ ilmenite, rutile ⇒ garnet, leucoxene ⇒ staurolite, kyanite ⇒ quartz

Leucoxene is commonly present as an alteration product after ilmenite and generally not within the original HM sediment feed.

**EXPLORATION**

Exploration for mineral sands involves the positive identification of key criteria to focus exploratory surface sampling, augering and drilling. Key criteria can be provenance studies identifying favourable mineral assemblage suites, geomorphological studies identifying key HM trap sites and identification of favourable sedimentary facies within marine sequences.

**Drilling**

When a favourable exploration region has been identified the main exploration method employed is drilling. Usually small, 4WD-mounted reverse circulation air-core (RAC) drilling rigs are used. In the past auger drilling was commonly used and more recently Sonic Drilling has become popular for advanced geotechnical investigations and resource definition drilling.

The RAC drilling method - where air or water is forced down an annular tube and cuttings are returned up the central tube, through a small cyclone - produces a clean uncontaminated sample at the surface (given ideal conditions). Drill rod sizes commonly range from AQ to NQ for RAC and from 10 to 15 cm for Sonic Drilling.
Drill grids are generally aligned in fence lines perpendicular to the strike of the orebody (spaced at 10 to 100 m) and spaced along strike at intervals from 50 to 400 m. This spacing will be dependent on the continuity and dimensions of the orebody morphology and homogeneity of HM and VHM grades.

If a potential orebody is identified, more drilling is carried out on closer spaced grids as required for resource and reserve estimation.

**Logging and Sampling**

Samples are bagged at regular intervals of generally between one and three metres and, if heavy mineral is present, sent to a laboratory for analysis.

A small sub sample is generally taken from the sample bag for washing and panning by a geologist or geotechnician on site. The washed sample is logged for estimates of the percentages of clay, rock and HM. During drilling, attention is paid to recording the presence of ground water and for the estimated hardness of each sampling interval as these are important factors that will influence the economics and eventual mining methodology.

Estimating the degree of induration in mineral sands deposits during logging is notoriously difficult. Observations are based on drilling pressures and penetration rates as well as chip/sand logging of sachets. Pulverisation by the drill bits and disaggregation during sample return can make indurated layers very difficult to identify.

Sampling can also be undertaken at this time for more advanced metallurgical assessment and environmental studies (investigation of potential acid forming soils and acid sulphate soils). After each hole is drilled, it is filled in or plugged using cuttings to prevent injury to livestock or native animals and to prevent erosion.

As a part of normal sampling procedures, duplicate sampling, submission of blind field standards and twin drilling are conducted as per other commodities to facilitate appropriate QA/QC.

**Assaying**

Throughout the mineral sands industry assaying is completed by a combination of internal company and external commercial laboratories. Assaying is primarily focused around determining the percentage of HM contained within a given sample. Other results of interest include clay fines (generally less than 53 to 75 µm), sand (generally 53 or 75 to 500 µm or 2.0 mm) and oversize (generally greater than 500 µm or 2.0 mm). Sizing criteria are not standardised across the industry.
and companies have often developed a range of different sizings as a direct result of the unique physical sizing characteristics of key deposits and as a response to process metallurgy requirements.

A range of drying, weighing, crushing, soaking and washing stages are followed to prepare a sand fraction containing principally quartz and HM which is then separated using a heavy liquid. The most commonly used liquids are tetra-bromo-ethane (TBE), Bromoform and lithium-sodium-tungstate (LST) which can be calibrated to a specific gravity (SG) of between 2.85 and 2.93 \( \text{g cm}^{-3} \).

A sub-sample of sand (approximately 50 to 100 grams) is mixed with the heavy liquid which results in the relatively low SG quartz floating and the HM sinking allowing recovery of the HM component. The HM is retrieved, dried and weighed and the weight per cent estimate is calculated for the original sample.

Exploration blind standards, laboratory standards and field and laboratory duplicate analyses are also conducted to facilitate appropriate QA/QC analysis.

Further metallurgical assessment is commonly conducted on the HM sink component using magnetic separation and/or electrostatic separation and SG heavy liquid Clerici Solutions (TMF or Thallium malonate/Thallium formate solution). The minimum mass required and the cost for this detailed mineralogical assessment will often necessitate compiling multiple samples into HM weighted composites for analysis.

Table 2 lists the typical heavy liquid SG fractions and the minerals that can be expected to report within each SG range. Each fraction is visually examined to determine the presence of contaminants and trash minerals.

<table>
<thead>
<tr>
<th>SG Range</th>
<th>Magnetic</th>
<th>Non-Magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mineral</td>
<td>SG</td>
</tr>
<tr>
<td>- 3.85</td>
<td>Trash</td>
<td>- 3.79</td>
</tr>
<tr>
<td>- 3.85 + 4.05</td>
<td>Magnetic Leucoxene</td>
<td>- 3.79 + 4.05</td>
</tr>
<tr>
<td>- 4.05 + 4.38</td>
<td>Altered Ilmenite</td>
<td>- 4.05 + 4.38</td>
</tr>
<tr>
<td>- 4.38 + 4.9</td>
<td>Primary Ilmenite</td>
<td>- 4.38 + 4.9</td>
</tr>
<tr>
<td>+ 4.9</td>
<td>Monazite</td>
<td>+ 4.9</td>
</tr>
</tbody>
</table>

Other forms of metallurgical/mineralogical assessment are often undertaken using laboratory-scale bench tests that replicate the wet concentration and dry mill processing routes. This information provides recovery indicators in addition to the mineralogical and quality (analyte) information used
for resource and reserve development. X-ray diffraction (XRD), QEMSEM (quantitative evaluation of minerals by scanning electron microscopy) and grain counting of polished thin sections and microscope slides are also undertaken for mineralogical assessment. These methods do not provide recovery information and are used to quantify the relative proportions of mineral species. Mineral analytes (chemistry) are determined by x-ray fluorescence (XRF) and electron microprobe analysis.

RESOURCE TO RESERVE DEVELOPMENT

Resource development in mineral sands is similar to elsewhere in the resources sector. It involves the collation of data from drilling, assaying, mineral testing, geological interpretations and the preparation of some form of two or three dimensional seam or block model. Geostatistical evaluation is generally more simplified than for other commodities and commonly polygonal, nearest neighbour or inverse distance weighting (IDW) methods are employed for grade interpolations. Occasionally kriging is used however variography is more commonly used to test the confidence of drill spacing in order to assist in the determination of suitable Mineral Resource and Ore Reserve categories.

Geological Interpretation

As with any commodity understanding the geology in mineral sands is vital for resource estimation. The morphology of mineral sands orebodies is generally regular and constrained by trap sites. There is typically a sharp mineralisation cut-off on the landward side and more of a gradual tapering of grade off shore and vertically.

The definition of mineralised boundaries is a hybrid of grade cut-off and geological boundaries. Detailed examination and logging of HM sink fractions can aid in determining boundaries by recognising gross changes in mineralogy and induration and mineral coatings by lateritisation. The identification of these domains becomes the basis for further metallurgical testwork and the geological and resource model.

Mineral Characterisation

Following the geological interpretation (and often iteration between stages) is the development of metallurgical bulk samples to provide information on the identified domains. As discussed earlier there can be considerable mineralogical and quality variability within strandlines and deposits, so it is important to get the best compromise for sample delimitation versus cost while at the same time targeting different domains.
The results of mineral characterisation are generally applied to resource estimates on an averaged domain or strandline basis, or with nearest neighbour or polygonal assignment. It is important to understand that mineral sands modelling is about quantifying HM grade, then mineralogical assemblage and then quality of those mineral species. This will determine whether a mineral sand final product is marketable or not.

**Geostatistical Evaluation and Resource Estimation**

Geostatistics are not commonly used in mineral sands and their effective use is restricted by sampling support of domain mineralogy that will be used for grade estimations. It is possible to derive meaningful semi-variograms from the primary assays such as HM, clay and oversize, however the sample support for mineral bulk samples (and the smaller number of samples) is not regular and variography is therefore of limited or no practical use. The morphology of some mineral sands orebodies and the resultant high anisotropy makes the orientation of variograms quite sensitive to small changes in direction.

The primary assay variography, particularly for HM, is used to prepare appropriate search volumes for computational grade interpolations. Mineral sands orebodies typically display low nugget effect, and while the purist resource estimator may eschew the use of IDW methods of estimation, they certainly work effectively as attributed by HM grade reconciliations at current mine sites (Iluka 2008).

Volume to tonnage conversion factors are facilitated by dry bulk density (BD) algorithms. These are generally based on single variable (HM) straight line and multi-variable (HM and clay) curve algorithms (Baxter, 1977; Iluka 2008). Often for low grade HM dunal deposits, a simple BD of quartz sand (1.60 g/cm$^3$) is used for volume to tonnage conversion. The use of an appropriate BD algorithm is important when estimating resources and reserves.

**Reserve Development and Mine Design**

Reserve development takes into consideration the Modifying Factors as outlined in the JORC Code 2004. Mining software is used to apply the necessary mining and mineral recoveries, costs and revenues to the geological model. From the geological model an optimised and potentially economic block model is prepared using an optimisation package such as Whittle.

A mining pit is then designed taking into account overburden, clay and rock content, mineral assemblage and quality, land use restrictions and end land use and rehabilitation requirements.
Scheduling (tails management, waste rehandle, HMC scheduling)

Scheduling for a mineral sands operation involves the coordination of the mining, overburden rehandle and backfill, sand and clay tails management and heavy mineral concentrate (HMC) grade and quality production requirements.

There is a fine balance in the scheduling of mineral sands to optimise mineral recoveries and meet the feed rates, mineral grade and quality requirements for the dry plant and final product. There is a requirement to ensure that there is enough topsoil and overburden pre-stripped to allow mining to feed a wet concentrator or ROM stockpile and to ensure that there is a working void large enough to enable direct back haul and replacement of overburden and sand tails.

Factors that will impact on the scheduling process includes wet weather slowing the overburden stripping, hard material in the ore impacting on mining rates and the availability of water affecting the HMC production and tailings management.

MINING

Mining of mineral sands is conducted either wet or dry. Wet methods are generally preferred for large tonnage, low clay orebodies. Dredging with a bucket wheel and suction is one of the lowest cost options for this method. Dry methods employing earth moving equipment (self-elevating scrapers, bulldozer traps, truck and excavator and front end loader) are used to excavate and transport the sand to a feed preparation section. Variations to these methods involve different means of transporting the dry-mined sand: either by pumping or the use of conveyors. Hydraulic mining with high pressure water is also employed as a variation on both themes, being used in dredging (to encourage face rilling) and in dry mining to slurry sand, clay and HM.

Figure 3: Dredging operations at CRL North Stradbroke Island showing working pond, suction cutter dredge and floating concentrator for the Enterprise operation (left) and with a floating thickener at the Yarraman operation (right). Both concentrators are rated at between 3000 and 4000 tph of sand feed (source Iluka).
Dredging is highly dependent on ground conditions and availability of water. In a wet mining operation, a floating dredge cuts the ore under the surface of a pond and pumps the ore slurry to a wet concentrator floating in the pond behind the dredge (Figure 3).

Rock and high clay are not conducive to effective dredging, as are small, discontinuous, high grade and irregular orebodies. Where ground conditions are hard and orebodies are small, high grade and discontinuous, dry mining techniques are generally employed.

If scrapers are used, the ore is mined from the top of the face to the toe of the face and across the face to ensure a feed blend to the concentrator that is consistent in HM grade and sand and clay composition (Figure 4). A consistent sand/clay mix will ensure that processing through the primary screening circuits is maximised. If a deposit is too high in clay the scrubbing circuit will bog down and become inefficient, and if too low the increased friction results in problematic pumping of feed through the circuit. Other forms of dry mining sometimes use stockpiles to achieve a constant blend.

Figure 4: Ore mining with elevating scrapers (left) and overburden removal by excavator and truck (right) at the Iluka Douglas operation in Victoria (source Iluka).

Feed hoppers and associated plant are towed forward as the mine face advances. Extra conveyors or pipes are added to ensure the loading units maintain an optimum haul cycle.

At the first stage, any material in the ore that is approximately 150 mm or greater is screened through a hopper or a primary scalping screen and returned to the mining pit. The remaining ore is then transported by conveyor or in a slurry form through pipes to a larger screening circuit away from the mining pit. After the initial screening at 150 mm in the mine, further screening is carried out at the concentrators to remove remaining oversize material.
PROCESSING

Concentration of mineral sands from the primary ore is carried out in two sections; wet, utilising sizing and gravity differentiation between HM, VHM, clay and quartz (Figure 5), and dry, exploiting the magnetic, electrostatic and to a lesser extent SG properties of the minerals of interest (Figure 7).

Concentrators vary widely in form, equipment, design and capacity. Wet concentrators, also known as wet concentration plants (WCP) vary in capacity from 50 tph units servicing dry mining operations to large 4000 tph units for dredging operations (Figure 3). Dry separation plants, generally known as dry mills or mineral separation plants (MSP) are larger due to the range of equipment required to separate and refine to a final product, and will range in capacity from 10 tph through to 200 tph. The tonnage per hour capacity is rated by dry sand tonnes.

**Wet Concentration**

The objective of wet concentration is to produce a high-grade (between 85 and 98 per cent) HMC, retaining valuable minerals and minimising gangue within the concentrate.

Ore that passes through the primary scrubbing and screening plant is slurried and then pumped to a hopper at the WCP. This is then pumped to a bank of hydro cyclones that remove very fine particles (generally less than 63 µm and comprised predominantly of clay).

Fine material now separated from the HM and quartz sand is mixed with flocculent to induce settling and is thickened, remixed with the quartz sand tails and pumped to the mining void. Alternatively, the thickener underflow is pumped to solar evaporation ponds where it is dried. The dried clay is then returned to the mining pit or mixed with topsoil material to enhance the rehabilitation process.

The hydro cyclone underflow (or coarser material) is fed to a constant density (CD) tank. This is then pumped, at a constant density, feed rate and HM grade (to optimise mineral concentration and recovery) to primary spirals in the WCP.

Spiral separation of HM from the quartz sand on the spirals occurs through gravity separation. The spirals’ troughs are raked at an angle and the heavy mineral moves to the inside of the trough as the slurry travels down the spiral. WCP spiral circuits generally consist of four to six different stages:

- Primary or rougher spiral stage;
- Middlings spiral stage;
Figure 5: Typical WCP process flow sheet (source Iluka).
⇒ Cleaner spiral stage;
⇒ Re-cleaner and/or upgrade spiral stage; and
⇒ Scavenger spiral stage.

Intermediate HMC from each spiral stage passes to the next stage to be further concentrated, spiral middlings are usually recirculated, and tails scavenged to collect un-recovered HM.

WHIMS (wet high intensity magnets) can be used at the end of the wet concentration stage to separate magnetic ilmenite from other VHM. Final HMC is stockpiled on site using dewatering cones or cyclone stackers (Figure 6) and allowed to drain to minimise moisture content before transportation to the secondary concentration plant or MSP.

WCP sand tailings are pumped to the mining pit where it is discharged via a monitor or cyclone stackers. The sand is re-contoured before overburden, clay and topsoil replacement, ready for rehabilitation.

The water used in the WCP is recycled into a clean water dam from which the process water is drawn. Surplus water is discharged back into the water system (subject to environmental monitoring) while extra water is pumped from pit dewatering or sourced from groundwater.

Figure 6: HMC wet stacking following a WHIMS separation to produce a predominantly non-magnetic HMC (as evidenced by the lighter coloured HM sand - wet stack in the foreground, dry stack in the centre of photo), Iluka Douglas operations, Victoria (source Iluka).

Attritioning and Secondary Concentration

Attritioning is carried out on HMC to clean the mineral surface thereby increasing MSP electrostatic separation efficiency and assisting with minimising MSP dust levels. Attritioning and secondary concentration may be undertaken in the same plant. The advantage of this is that the fine particles removed from the mineral surfaces during attritioning are removed in the subsequent up-current classifier stage and disposed with the fine clay and sand tailings. The up-current classifier
also removes fine quartz and other fine non-valuable minerals upgrading HM content in the final HMC to about 98 per cent.

Figure 7: Typical MSP process flow sheet (source Iluka).
Dry Mill Processing

Dry mill processing uses screening, magnetic, electrostatic and gravity separation circuits to separate valuable minerals from non-valuable minerals, and also to make different ilmenite, rutile, leucoxene and zircon product grades for specific customer requirements.

Rare earth drum magnets are used to remove ilmenite from HMC feed. Ilmenite is the most magnetic of the minerals in the MSP feed (occasionally magnetite is present, however generally not in economic quantities). This allows most of the ilmenite to be recovered as final product with no further processing.

Not all of the ilmenite can be separated from the non-valuable semi-magnetic minerals at this stage. Ilmenite that is weathered and altered loses Fe and becomes less magnetic. A small proportion of the ilmenite must go through electrostatic separation to remove non-conductor mineral contaminants such as monazite, garnet and staurolite from the conductive ilmenite.

Non-magnetic minerals go on to a primary electrostatic separation circuit. Several stages of high tension roll separators and electrostatic plate separators are used to separate non-conductors (consisting of zircon, kyanite, quartz, monazite and staurolite) from conductor minerals (rutile and leucoxene). The non-conductors pass to a gravity separation circuit to remove the lower SG material (quartz, kyanite, garnet, and staurolite) from the higher SG zircon (Iluka, 2008).

Electrostatic separation after gravity separation removes residual conductors from the zircon. Traces of monazite and staurolite are removed with induced roll magnets. A final pass across an air table removes fine quartz and residual kyanite that has not been rejected by the gravity separation circuit.

Zircon can be stained by iron oxide coatings and sulphuric acid leaching is used to strip these coatings from the zircon particle surfaces to make it more acceptable for use in ceramic glazes.

The non-conductor minerals in the primary electrostatic separation circuit rutile-rich conductor stream are removed using additional electrostatic separation stages. Induced roll magnets are used at the final stage to produce separate leucoxene, which is semi-magnetic, and rutile products.

REHABILITATION

The rehabilitation of areas disturbed by mining commences with field research and the development of rehabilitation objectives, well before mining commences. A rehabilitation plan forms part of the application for mining and operations to the relevant State and Territory regulators.
Initial field surveys can involve studies on current and proposed land use and flora and fauna populations with an emphasis on rare and endangered species, restricted vegetation units and dieback status. Other features such as soil structure, texture and hydraulic conductivity along with soil fertility, pasture composition and productivity are also taken into account.

Detailed topographic surveys are undertaken to ensure re-contouring to original land surfaces is possible. Local weather conditions are monitored prior to and during mining operations using remote automatic weather stations. Groundwater conditions and surface water flows are measured and monitored using a network of piezometer bores and through installation of gauging stations and weirs.

Before mining commences and topsoil stripping takes place all vegetation and infrastructure is removed from the area to be mined. In bushland there is an intensive seed collection effort before any clearing takes place. Topsoil in bushland is stripped in two cuts - a first cut to concentrate seed and propagules from the top 100 mm and where possible to spread directly onto prepared rehabilitation sites, and a second cut making up the remainder of the topsoil layer. In agricultural areas a single topsoil layer is taken and stockpiled.

Subsoil or overburden layers are stripped and stockpiled separately in deeper deposits so they can be used to reconstruct the original soil profile. As the active mine area moves forward the mining void is backfilled with overburden, processing oversize and with sand and clay extracted during the wet concentration process. This backfill is then covered with the stockpiled subsoils or selected overburden to recreate the design landform.

In some operations the sand and clay from the wet concentration process is mixed and disposed hydraulically into the mine void. In other operations the clay is first dried in solar evaporation drying dams and used as dry fill in the backfill process. In dunal deposits that lack stockpiled subsoil, the dried clay is often spread onto a finished sand landform and mixed using earthmoving and agricultural equipment to form a sandy loam.

Once the design landform is complete the area is ripped to loosen the soil and then graded smooth. Stockpiled or freshly stripped topsoil is spread in late summer or autumn, just before the seasonal onset of winter rains. Monitoring of rehabilitation areas generally continues for up to ten years post mining.
MARKETS AND MARKETING

The sale of mineral sands products relies on a marketing team contacting customers and selling agents to facilitate the sale of titanium and zircon products. There is no open market trading of mineral sands products or exchange of pricing and marketing information. The process is similar to coal and iron ore where a contract is entered into with a customer to supply a tonnage at a certain grade and quality.

The majority of titanium dioxide feedstocks are sold worldwide by Rio Tinto and Iluka with Iluka the leading zircon producer followed by Exxaro (Figure 8).

![Titanium dioxide feedstock and Zircon](image)

Source: Iluka and TZMI estimates

Notes:
1. The titanium slag products of Rio Tinto and BHP Billiton are currently marketed by Rio Tinto.
2. Includes 100% of CRL output, which Iluka markets on CRL’s behalf.
3. Exxaro has a 50% interest in the Tiwest JV.

Figure 8: Major titanium dioxide feedstock and zircon producers, 2007 estimates (source TZMI and Iluka).

ISSUES: THE CHALLENGES

Mineral sands exploration, mining and processing faces the same operating challenges as the rest of the resources sector. Added to this are the issues that are unique to mineral sands and to which the industry devotes considerable resources to developing solutions.

Drilling

Issues that can affect drilling in mineral sands are centred around ground conditions that are generally unfavourable for RAC, such as:

⇒ Indurated or lateritised sediments (impeding the blade and penetration);
⇒ Alternating wet and dry ground conditions (creating sample hang up in drilling and sampling equipment);
High water inflow combined with free-flowing sand (creating excess sample and causing rod jamming); and

High grade plastic clays (blocking inner tubes and impeding the blade).

Deeply buried targets can also be a challenge for RAC drilling due to the small air capacity carried by most RAC drill rigs, the larger number of rods required to reach target depth (generally three metre rods are used) and the length of time required to drill deeper holes cutting into productivity.

A hammer can be fitted to RAC drill rigs to penetrate hard material, however this tends to skew the hardness logging that is conducted by the geologist or geotechnician. Unconsolidated sediments associated with mineral sands do not represent ideal drilling conditions for hammers and bogging frequent results in the loss of drill tools.

To overcome the issues associated with wet and dry drilling in RAC, minimal water injection is used where possible during the drilling process to prevent sample hang up (and potential sample contamination).

Exploration targets are invariably located in coastal or near coastal regions sub-parallel to current shorelines. These areas are invariably heavily populated (east coast of Australia, south-east coast of USA, east coast of India) and have extensive National Parks, Reserves and other restricted access due to environmental sensitivity. Access to explore by drilling is difficult in these areas.

**Sampling**

Issues that can affect sampling in mineral sands are centred around ground conditions and material types, such as:

- Poor sample splitting (cored material and oversize do not get split representatively);
- Sample contamination (lag in the drill string or sample sticking in the drill string, cyclone and associated sample collection and splitting equipment);
- Flushing sample retention in the drill string (resulting in sample contamination);
- Wet and dry drilling conditions that can also result in sample hang up in drill rods, hoses, cyclones and splitters;
- Hard drilling that results in the washing down of material outside the drill string and contaminating the sample, particularly when below the water table;
- Extremely high HM grades (resulting in down hole contamination); and
⇒ Sample delimitation and grade dilution (sample intervals transgress domains of HM and non-HM mineralisation).

Mineral sands exploration sampling is also vulnerable to conventional sampling errors such as mislabelled bags, out of sequence numbers, lost samples and the like.

**Resource Assessment**

Resource assessment for mineral sands can be expensive compared with other commodities. The cost of RAC drilling is quite cheap, the required spacing for drilling is not as tight as other commodities and there is no requirement for grade control drilling. However the primary assaying will cost in the order of $20 to $70 per sample and more detailed mineralogical assessment can cost $150 to $2000 per sample.

Sample assaying is a multi-staged process which is unique to mineral sands. First there is the determination of the primary constituents of a given sample (HM, clay, sand and oversize), then there is the determination of the mineralogy of the HM and finally the analysis of mineral chemical quality. The turn around time for standard assays is commensurate with other commodities, as the procedure is essentially a washing, screening and gravity separation process (typically one week). The timing of further mineralogical assessment will depend on the methodology and requirements for further work. It takes approximately one week for detailed mineralogical analysis to be returned and often another week for detailed chemistry of mineral species.

Detailed primary assays are prepared for each sample interval, however the cost of detailed mineralogical assays prohibits this being conducted for each sample. Therefore samples from similar geological or (logged) mineralogical domains are composited together and assayed as a ‘mini-bulk’ sample. This creates smoothing of mineralogical information when preparing resource estimates as the samples are no longer the size of the minimum sample width.

Another issue is getting an accurate determination of mineral quality, either due to unrepresentative samples or difficulty in obtaining an accurate analysis (eg XRF) especially when the analyte levels are low and often close to specification limits.

**Mining**

Rock and induration creates a number of issues for mining in mineral sands including increased costs associated with additional ripping of hard material, displacement and poor recovery of mineral sands and extra wear and handling on the feed preparation circuit that is not always designed to
handle heavy duty and high energy workloads (this has been a focus for companies in recent years to ‘bullet-proof’ their plant and equipment and has resulted in capital increases).

The lack of grade control drilling or a closer spaced drilling pattern prior to mining can have a negative impact on the final pit and geological contact delineation. This is offset by the excellent visual acuity that mineral sands affords mining staff, however it does not assist with ore that might disappear into a pit wall because the pit was not drilled out to the extents of the mineralisation.

Mining heavy clays can be an issue for conventional equipment such as scrapers as it often requires additional pushing and pulling by teams of scrapers.

**Processing**

Mineral processing relies on the physical characteristics and properties of different mineral species to facilitate separation. Minerals that have similar specific gravity, magnetic and electrostatic properties will be preferentially recovered to similar sections of a wet concentrator and dry mill.

For example:

- Garnet and monazite are high SG trash minerals and follow similar routes as ilmenite, rutile and zircon in a wet concentrator;
- Kyanite has very similar electrostatic and magnetic properties as zircon although is lighter and preferentially rejected in a WCP. However if the ratio of zircon to kyanite is low, additional zircon losses may be incurred in the MSP through requisite additional gravity separation;
- Minerals that have a bimodal grain size can recover poorly in a dry plant circuit due to the effect of grain size on electrostatic separation;
- Mineral that is coated with iron oxide and clay cement will be affected in both wet and dry separation; and
- Minerals that are light but valuable such as leucoxene are not well recovered by a wet concentrator and then in a dry mill can have variable electrostatic and magnetic behaviour depending on the degree of alteration.

High clay in a dredging operation will cause the pond water suspended solids and viscosity to increase, which can affect spiral HM recovery. Clay in a dry mining scenario will be rejected during the scrubbing and screening process at the head of the WCP, however hydrophobic clays will tend to ball and collect mineral in the scrubbing circuit, thus prematurely removing HM from the circuit when rejected as oversize.
Titanium and Zircon Products

Sizing and quality constraints for final titanium and zircon products are often key drivers of the economics of mineral sand deposits due to the requirements of customers. Customer queries often revolve around:

⇒ The problems that out of specification titanium and zircon products will produce for their plant and equipment;
⇒ The by-products that are produced from down stream processing that require disposal; and
⇒ The requirements of end users in relation to waste by-products.

CONCLUSION

Mineral sands mining and processing is a specialist and niche segment of the global resources sector. It supplies raw products input to the commercial manufacture of a wide range of end product applications, as diverse as pigments, paints and coatings, metal and specialist alloys, ceramics and a range of chemical and specialty applications, which have both industrial and end consumer applications.

Almost every technical aspect of mineral sands from sampling and assaying to mineralogical evaluation, mining and processing is unique and at times challenging. Mineral sands requires careful technical consideration of different grade, assemblage and quality characteristics in order to produce marketable and saleable final products.

The mineral sands industry is one of few in the resource sector that has the ability, by nature of the extractive process, to be involved in the complete rehabilitation of areas disturbed to a final agreed landform and land use.

ACKNOWLEDGEMENTS

The author wishes to thank Iluka and TZMI for allowing the publication of information and figures that appear in this paper. Thanks also go to those who reviewed this paper and provided valuable suggestions, feedback and direction, including Brett Gibson, Vic Bruinsma, Peter Benjamin, Vincent O’Brien, David Whitworth, Robert Porter and Tim Johnston.

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