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Coastal evolution and associated titanium sand mineralisation of Jangamo district, Inhambane Province, Mozambique

J. Dumouchel, F. Hees and M. P. Alvin*

Extensive grassroots exploration along the southern coast of Mozambique has resulted in the discovery of significant titanium heavy mineral (HM) sand mineralisation and subsequent definition of the large Mutamba deposit, within the Jangamo and Inharrime districts of Inhambane Province. As part of the economic assessment a geological model of the deposit was developed and this has contributed to a better understanding of Quaternary coastal evolution within the area of the Inhambane Peninsula. The correlation of geomorphological and geological characteristics of the deposit area, which included analysis and interpretation of satellite and air photo imagery, field observations, drill sample observations (reverse-circulation, hand-auger, sonic and vibracore) of sand texture and laboratory analyses for total HM and slime content, has resulted in identification of a stratigraphic sequence of mixed marine–continental origin deposited in a marginal-marine environment. Understanding the stratigraphy and geographic distribution of sediments that host the Mutamba deposit has been a critical element for the economic assessment of the deposit and will be fundamental for any future mineral sand exploration in the region.

Keywords: Ilmenite, Rutile, Zircon, Heavy mineral sand, Coastal evolution, Mutamba, Jangamo, Mozambique

Introduction

The coincidence of high-grade metamorphic basement terranes inland of the coastal plain (e.g. Pinna 1995; Boyd *et al.* 2010; Macey *et al.* 2013), numerous large perennial rivers that flow into the Indian Ocean (e.g. Ncomati, Limpopo, Save, Zambezi, Lurio, Lugenda and Rovuma rivers), strong longshore ocean currents and common cyclonic storm events (e.g. Aramuge Rocha and Silva 2014; Siteo *et al.* 2015) create ideal conditions along the Mozambican coastline for development of various styles of placer heavy mineral (HM) sand deposits. The first systematic evaluation of the HM sands potential of Mozambique was undertaken by Cilek (1985) who described extensive beach sand and dune deposits extending 80-km inland, which present significant potential for HM sand deposit development. In Cilek's (1989) detailed work on the industrial mineral endowment of Mozambique, it is estimated the country may host up to 120 Mt of contained HM within beach and dune sand deposits along the coastal zone. Based on the significant scale of the HM sand deposits in Mozambique Lehto and Gonçalves (2008) suggest that the country has the potential to become the world's largest titanium and zircon sand producer. A conservative estimate of US\$30 billion

is provided by Wright (1998) for the *in situ* value of HM deposits in Mozambique. The relatively short distance to Asian markets combined with large deposits amenable to low-cost mining methods provide the Indian Ocean region of southeast Africa with a significant competitive advantage in the global titanium sand industry (Taylor and Moore 1997). In the decade after the end of Mozambique's civil war in 1992, there were very few HM sand exploration licences granted in the country; however, this has now progressed to a landscape with hundreds of exploration permits and tens of mining concessions granted in the years since 2002. Development of the Moma mine operation in central Mozambique, and the discovery and evaluation of the Chibuto and Moebase deposits, have highlighted Mozambique's global importance with respect to HM endowment (Table 1).

As part of a global exploration initiative, Rio Tinto Iron and Titanium, Inc. (Rio Tinto) identified Mozambique as a country to explore and conducted limited surface sampling at selected sites, specifically to understand mineral assemblage and ilmenite chemistry. Based on encouraging HM data and general potential for discovery of deposits with large tonnage and low production cost, exploration tenure was secured in Gaza and Inhambane Provinces of southern Mozambique (Fig. 1).

An extensive exploration programme was undertaken between 2000 and 2006 within the coastal areas of Inhambane Province. The provincial capital of Inhambane

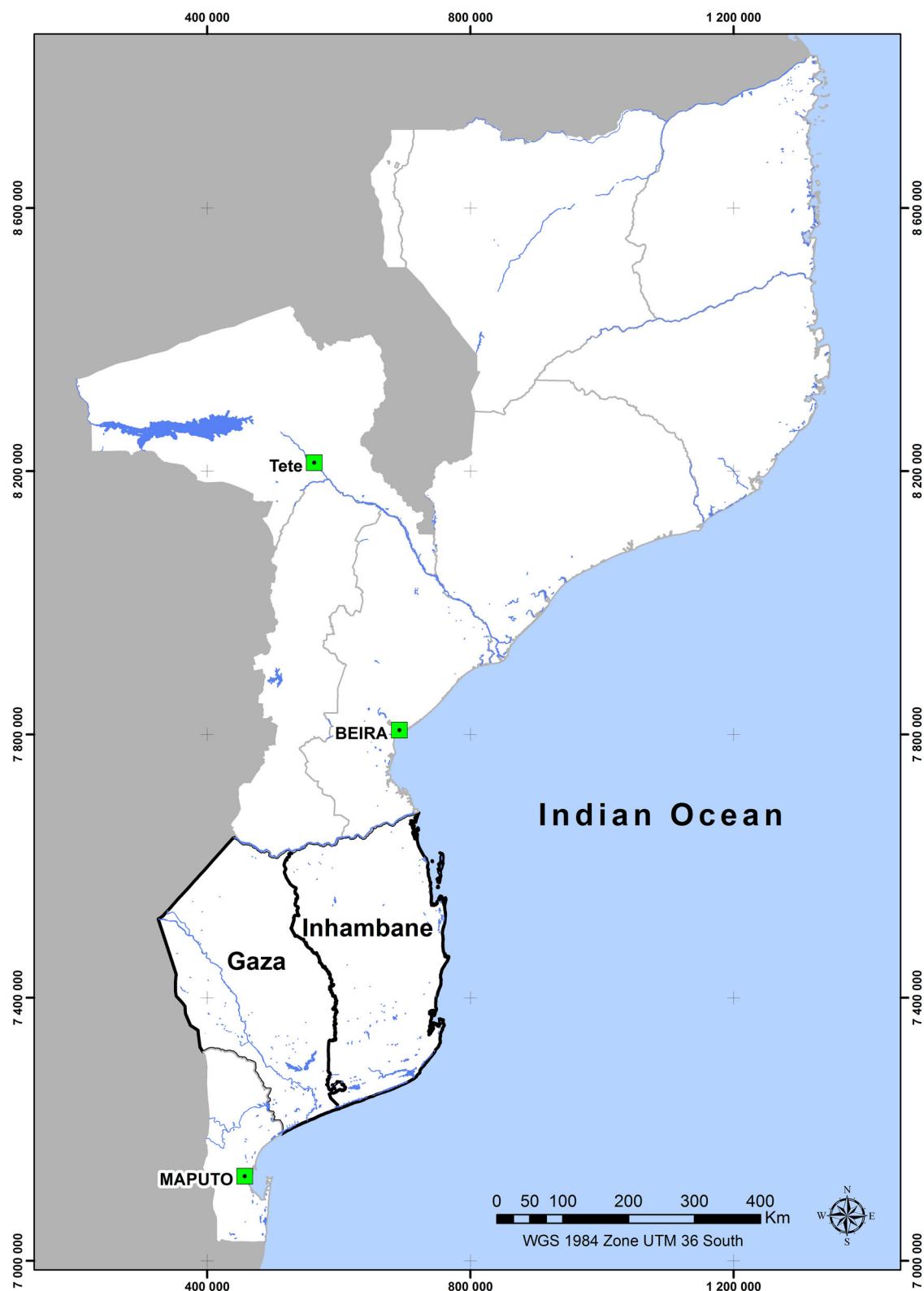
Rio Tinto Iron and Titanium, Inc., Canada

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Table 1 Summary of mineral resource data for Mozambican HM sand projects in operation or under evaluation

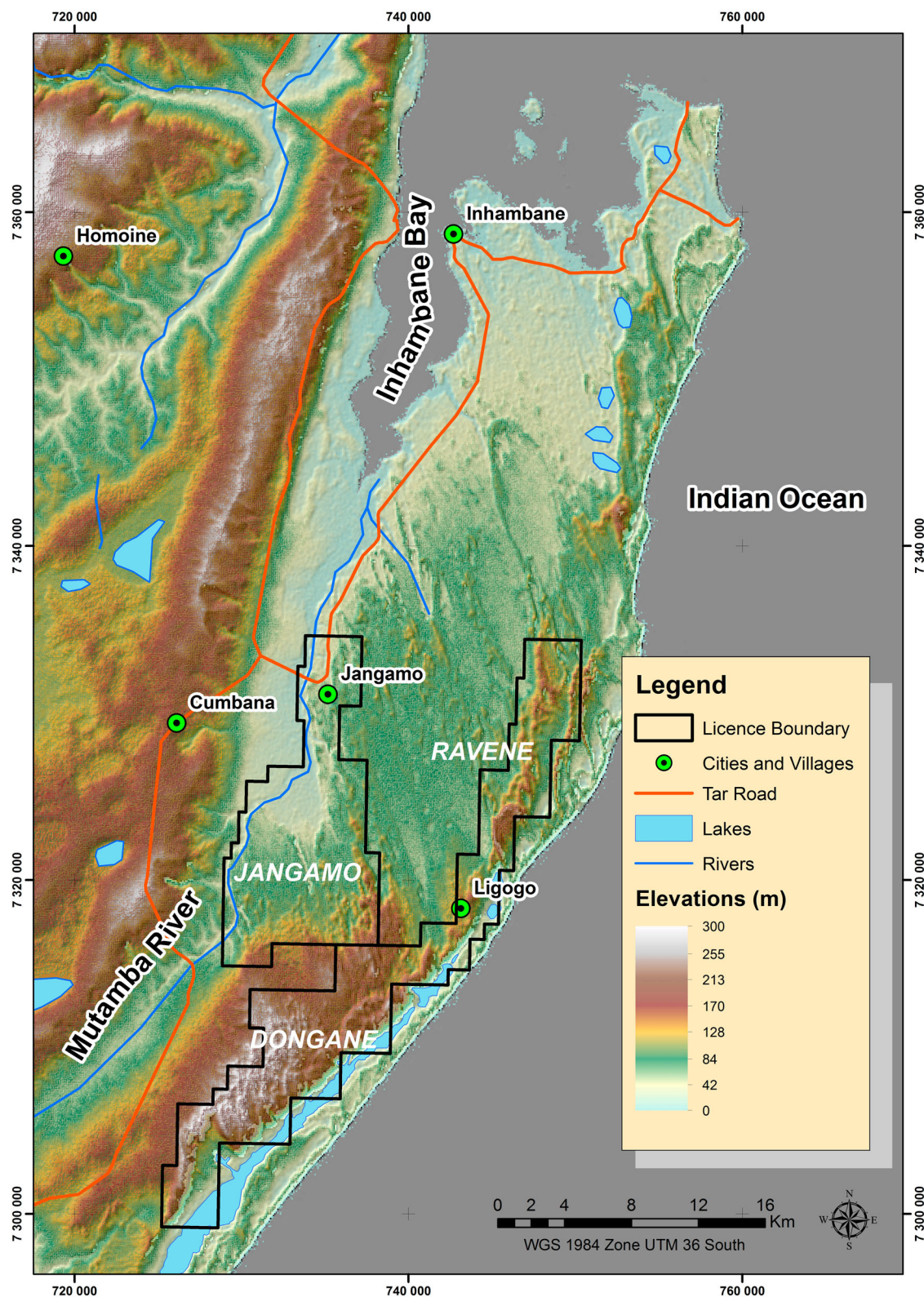
Project name	Project location	Project owner (2016)	Mineral resources (Mt)	Total heavy mineral (%)
Moma ^a	Nampula Province	Kenmare Resources	7200	3.0
Chibuto ^b	Gaza Province	Anhui Construction	16 600	5.3
Moebase ^c	Zambezia Province	Pathfinder Minerals	2021	3.6

Sources: ^aKenmare Resources (2016), ^bWestern Mining Corporation (2003, written communication), ^cPathfinder Minerals (2011).

**1 Map of Mozambique showing Gaza and Inhambane Provinces**

Province is the bayside town of Inhambane, about 470 km by road north of Maputo. The HM exploration ultimately identified three significant mineralised zones – namely, Jangamo, Dongane and Ravene – collectively defined as the Mutamba deposit (Fig. 2). The three mineralised zones are located in Jangamo district 40 km south of Inhambane town, and occupy a stretch

of Indian Ocean coastline approximately 45-km long and 10-km wide, which forms the southern end of the Inhambane Peninsula. The results presented here provide the first integrated geological model for the Mutamba deposit and in doing so provide significant insight to the coastal evolution in the Jangamo area of Inhambane Province.



2 Hillshade digital elevation map of the Mutamba deposit area, showing the location of Jangamo, Dongane and Ravene zones

Regional geological setting

The coastal region of southern Mozambique forms part of the Mozambique basin, which has an onshore area of about 270 000 km² and long axis of about 1200 km (Förster 1975; Matthews *et al.* 2001). The basin is up to 400-km wide (Förster 1975) and is broadly defined by the present day Limpopo River. The basin is characterised by a complex succession of Cretaceous to Quaternary age sedimentary rocks (Fig. 3; Table 2) and unconsolidated sand deposits which rest unconformably on Karoo Supergroup sedimentary and volcanic rocks (Salman and Abdula 1995; Schlüter 2008; Emmel *et al.* 2011). At the base of the post-Karoo sedimentary sequence is a very thick continental sediment known as the Red Beds Formation (Cilek 1989; Mashaba and Altermann 2015). Overlying the Red Beds are glauconitic sandstones and arenaceous limestones of the Maputo Formation which defines a transition to marine conditions during the Neocomian (Salman and Abdula 1995). Through the remainder of the Cretaceous a variety of rock types occur which represent marine, continental and transitional environments, suggesting tectonic activity caused differential uplift (Förster 1975; Salazar *et al.* 2013).

The onset of the Cenozoic in the Mozambique basin seems to vary regionally, as different authors ascribe some well-defined formations to the Cretaceous and other authors ascribe them to the Cenozoic (cf. Pinna *et al.* 1987; Botha and de Wit 1996; Rutten *et al.* 2008). The bulk of the Cenozoic succession is characterised by shallow-marine facies typical of a passive continental margin (Salman and Abdula 1995; Rutten *et al.* 2008) with two sedimentary cycles noted, a Palaeocene–Eocene cycle and Oligocene–Neogene cycle, separated by an unconformity. Sediments of the Palaeocene–Eocene cycle comprise glauconitic sand, clays and marls, whereas sediments of the Oligocene–Neogene cycle comprise terrigenous deposits of the Limpopo River and Zambezi River deltas. The intervening zone between the Limpopo and Zambezi Rivers during the Neogene remained a shallow-water environment and comprises the Inharrime, Temane and Jofane Formations (Salman and Abdula 1995). Widespread regression at the end of the Neogene (Pliocene) to early Pleistocene resulted in extensive coast-parallel dunes, alluvial river terraces and lacustrine deposits, gradually building the coastal plain seaward (Förster 1975; Wright 1998).

The present coastal plain of the Mozambique basin is an extensive zone of low-lying, unconsolidated Quaternary to Recent sediments (Palalane *et al.* 2015), separated from the Indian Ocean by older stable palaeodunes and presently active dunes. The active dune cordon can be up to 2 km in width and over 100 m above sea level (ASL) in many places (Momade and Achimo 2004).

Modern beach rock occurs intermittently along the exposed coastal shoreline, which is characterised as a high-energy wind and wave-dominated shore (Armitage *et al.* 2006; Peché 2012). Cilek (1985) describes the modern beach rock within the Inhambane area as cemented calcareous sandstone.

Wright (1998) notes that coastal erosion processes in concert with rapid Quaternary sea level change in Mozambique have caused the unconsolidated coastal sediments to be subjected to numerous cycles of erosion,

transport and deposition. These cycles have allowed winnowing of enriched secondary sources of more resistant minerals, including rutile, ilmenite and zircon, into localised HM placer deposits.

Background and exploration history

During the years 2000–2002 regional reconnaissance hand-auger drilling was undertaken over a broad area within a number of districts, including Homoine, Inharrime, Jangamo, Mandlakaze, Panda, Xai-Xai and Zavala (Fig. 4). Drill traverses were typically spaced at about 2-km intervals orthogonal to the coastline or interpreted palaeocoastline, and drill holes stationed at 1-km intervals along the traverses. Owing to the large number of samples required to be processed, a heavy liquid separation laboratory was established in the town of Inhambane, where all drill samples were processed.

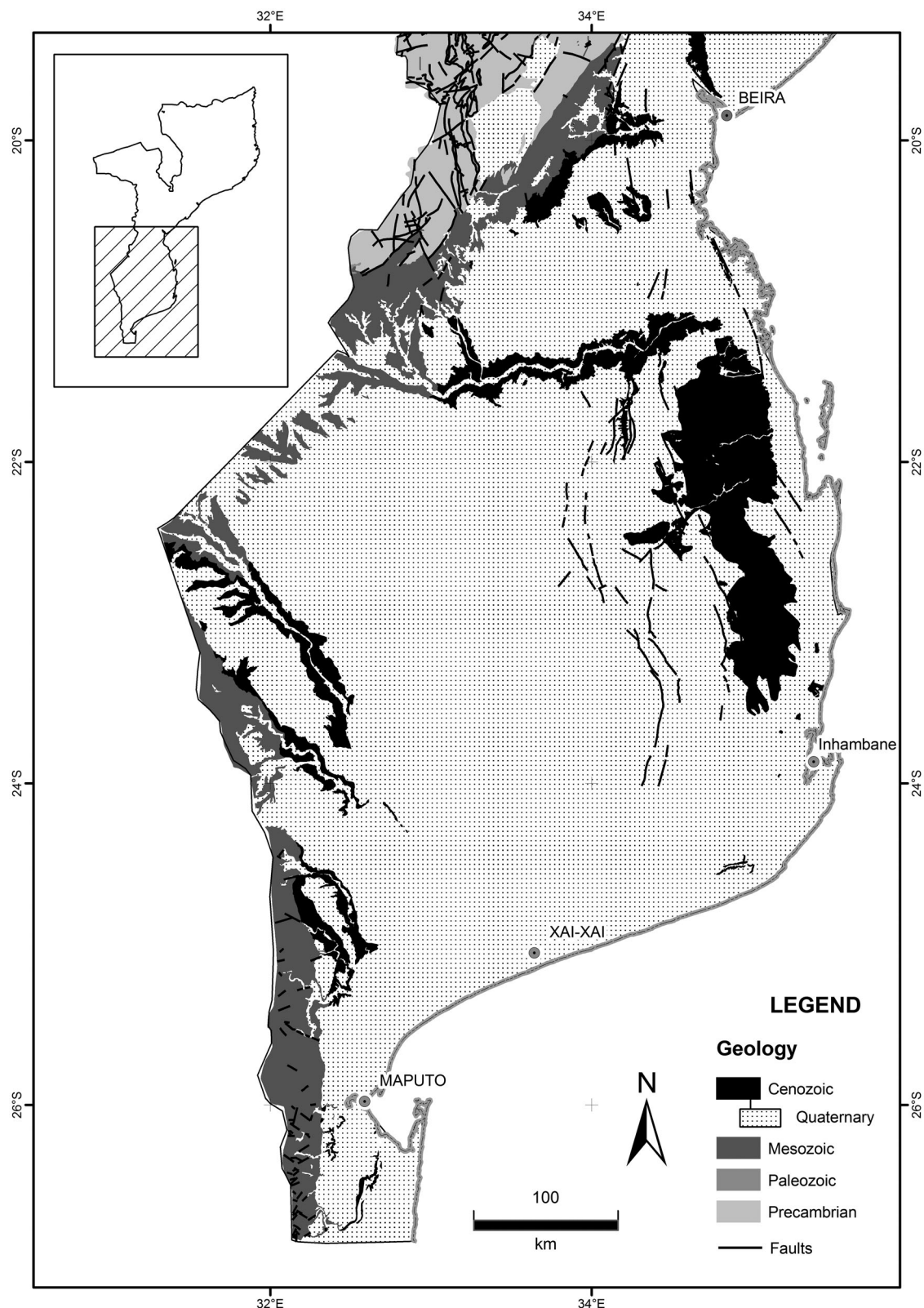
The results of the regional auger drilling suggested that the most prospective areas for discovery of large tonnages of high-grade total heavy mineral (THM) within a host of free-flowing, low-slime sand amenable to dredge mining, was in Jangamo district, extending south from Jangamo village for about 20 km. From 2002 to 2007, the Jangamo and Inharrime districts became a focus of HM sands exploration which comprised relatively shallow (<15 m) manual hand-auger and vibracore drilling methods, as well as deep (>50 m) mechanised reverse-circulation (RC) drilling on a 500 m × 500 m grid. From 2007 until present, additional RC drilling and sonic drilling have been undertaken as part of order of magnitude and pre-feasibility phase evaluation studies on the areas defined as Jangamo, Dongane and Ravene zones (Fig. 2).

A combined exploration target of 7–12 billion tonnes (Bt) of mineralised sand with a grade range of 3–4.5% THM has been defined for mineral resources in the Jangamo and Xai-Xai districts, the bulk of which is hosted within the Mutamba deposit. In total, the Mutamba deposit area contains approximately 2300 drill holes undertaken with RC, hand-auger, vibracore and sonic techniques, which have produced over 20 000 drill samples (Fig. 5; Table 3).

Coastal evolution in the Jangamo area

Essential to the economic evaluation of a mineral deposit is a sound geological model that defines controls on mineralisation and characterises the material that hosts the mineralisation. In order to develop the Mutamba geological model, it was necessary to look at the broader Jangamo area and understand the variety of active and palaeodepositional environments that occur there and determine what relationship they have with the mineralisation. This was achieved by combining qualitative data from drill logs with quantitative laboratory data and is outlined here in terms of the overall stratigraphy of the area.

This first integrated geological model for the Mutamba deposit provides insight into the coastal evolution in the Jangamo area of Inhambane Province. Details of seven informal lithological units are presented, with an outline of the main parameters used to characterise the sediments



3 Simplified geological map of southern Mozambique (adapted from data in Hartzer et al. 2008)

and most importantly the identification of units that are the more highly mineralised.

Method

Analysis of satellite imagery and high-resolution air photography combined with surface mapping is widely used

in correlation of Quaternary geomorphology and geology (e.g. Carter and Woodroffe 1997; Trenhaile 1997; Bird 2008). Erosional features and the relative age of geological units are fundamental elements used in the correlation of landscape forms and environment of deposition. In this study, contacts between different geomorphological domains were used as the main indicator of possible

Table 2 Summary of the stratigraphy of the Mozambique basin (adapted from Sasol Petroleum Temane Limitada 2003)

Era	Period	Epoch	Formation name or lithological unit
Caenozoic	Quaternary	Holocene	Recent dunes
		Pleistocene	Older dunes
	Neogene	Pliocene	Alluvium
		Miocene	Jofane Formation
		Eocene	Inharrime Formation
	Palaeogene	Eocene	Cheringoma Formation
		Palaeocene	Formation
Mesozoic	Cretaceous	Upper	Grudja Formation
		Lower	Maputo and Domo Formations
	Jurassic		Karoo Supergroup
		Triassic	sediments and volcanics

contacts between sedimentary units. These contacts were later revised using an analysis of lithological descriptions of drill samples with respect to parameters such as colour, grain-size, roundness, sorting, slime and THM content.

All hand-auger drill samples were collected as 1.5 m composite intervals, whereas all RC samples were collected as 3 m composite intervals. The samples were analysed for THM content by heavy liquid separation using lithium-heteropolytungstate with a specific gravity of 2.85. Complementary slime (<45 µm) and oversize (+1 mm) fraction data for each sample were also collected. The bulk of the THM, slime and oversize analyses was undertaken at a laboratory in Inhambane. Selected samples for detailed

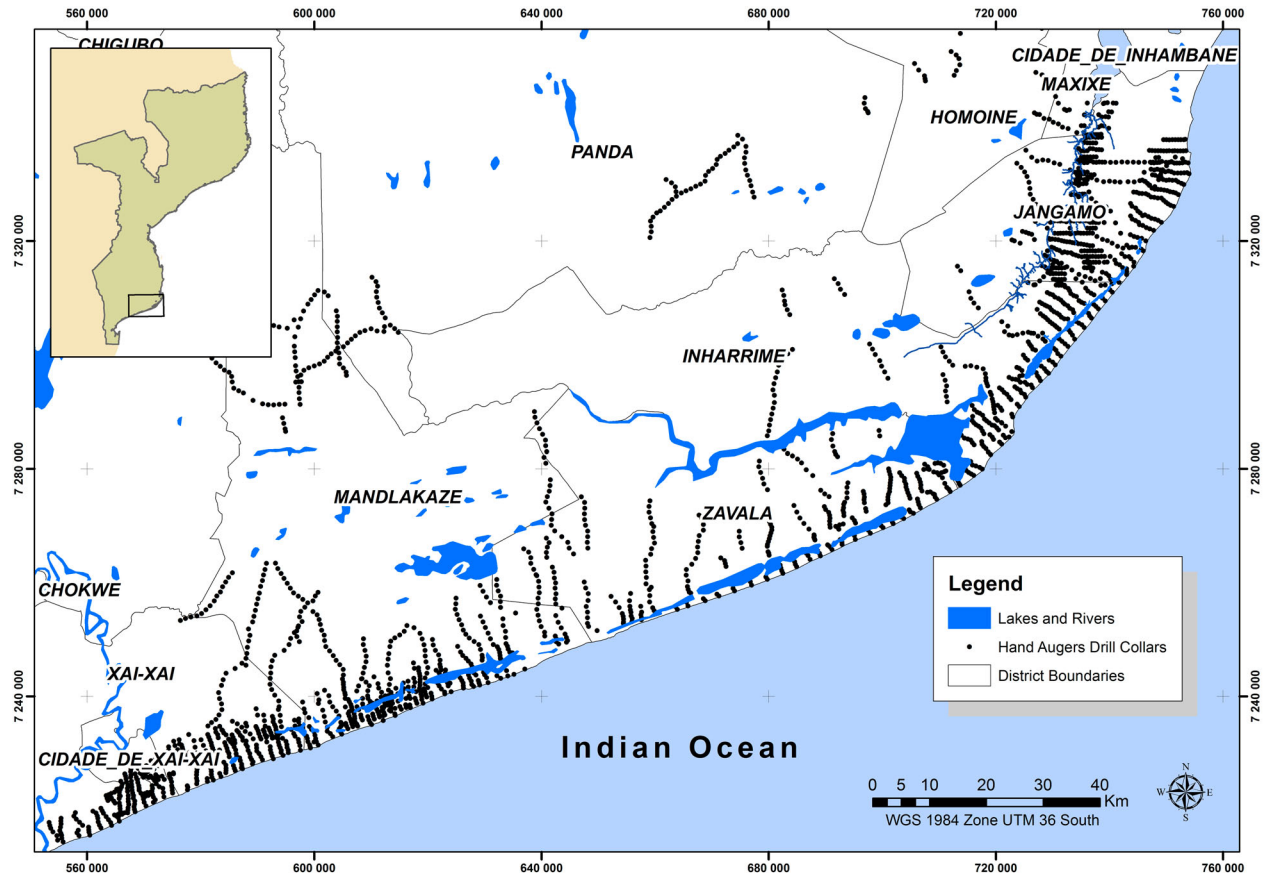
mineral assemblage and chemical analysis were sent to a laboratory in Sorel, Canada.

A total of 20 801 drill sample intervals for the Mutamba deposit (Table 3) were logged and revised using attributes from a geodatabase; including laboratory results for THM content and slimes content, and field descriptions comprising colour, grain-size, sorting, roundness and location information. Elevation data were acquired from a high-resolution LiDAR scan survey undertaken in 2007 and were used to update the collar elevation of the drill holes as well as the 'from-to' elevation of each drill sample interval. The new drill hole collar elevations extracted from the LiDAR data allowed construction of detailed cross-sections. Cross-sections were prepared using software with direct links to the geodatabase.

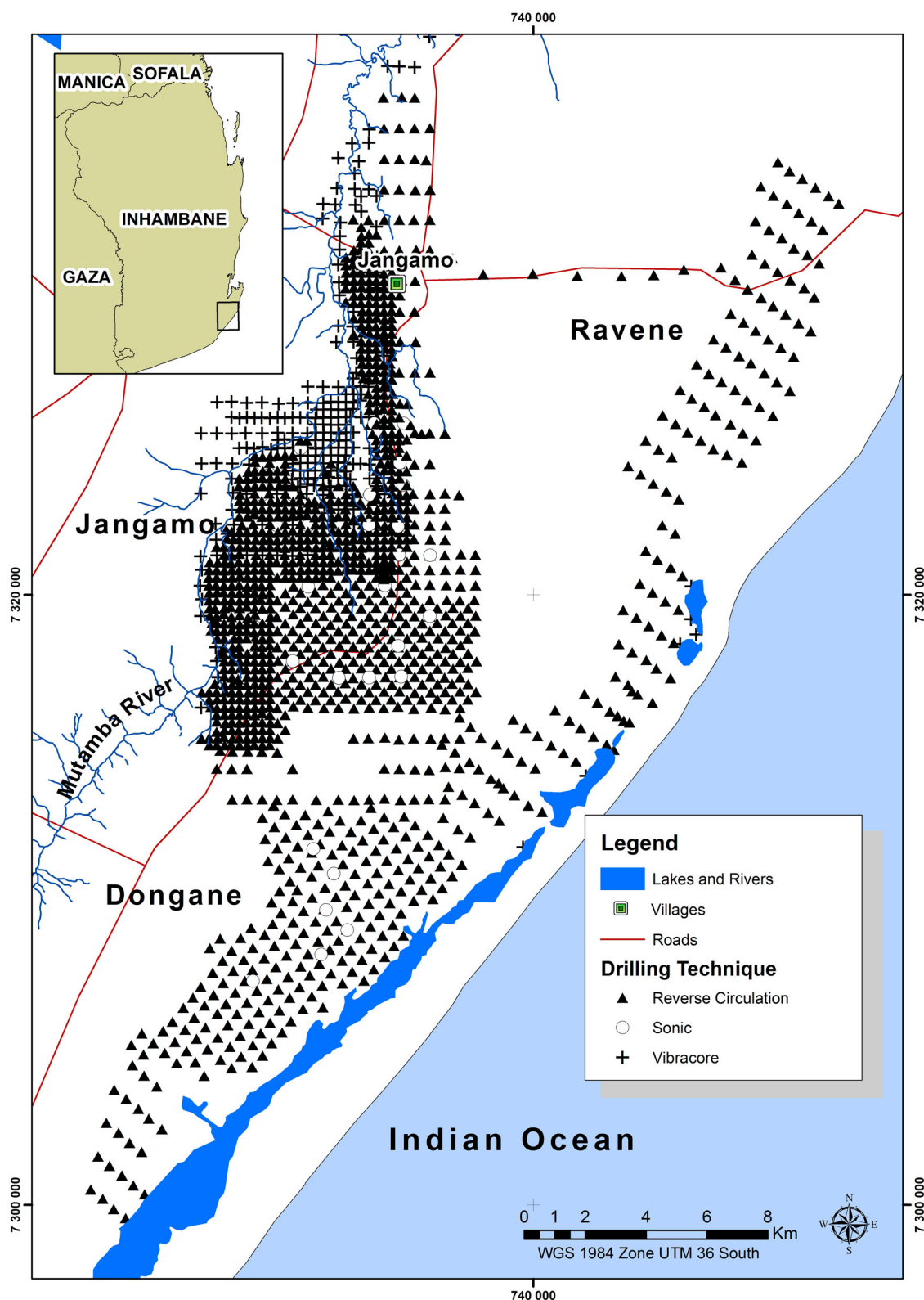
Samples from each individual drill hole were reviewed, followed by correlation with samples from the nearest neighbouring drill holes. This re-interpretation of geological data was then populated to a new geodatabase used to construct a final geological model for the Mutamba deposit.

Physiography and geomorphology

Interpretation of the various physiographic and geomorphologic features in the Jangamo area was an important part of the early exploration and subsequent development of the geological model. Distinct dune structures were able to be identified and targeted for drilling and several geomorphic domains were defined which aided stratigraphic correlation and understanding contact



4 Map showing location of regional reconnaissance hand-auger drilling in southern Mozambique



5 Map of the Mutamba deposit area showing the extent of application of various drilling techniques relative to the Jangamo, Dongane and Ravene mineralised zones

relationships between lithological units. The main surface features found in the Jangamo area are described here to demonstrate the variability between the different mineralised zones.

The Jangamo area is located at the southern end of the Inhambane Peninsula, which is flanked to the east and north by the Indian Ocean and Inhambane Bay to the

west (Fig. 2). Inhambane Bay extends southwards and passes into a swampy wetland where the Mutamba River flows into the bay.

Parabolic dune blowouts with long axes northwest–southeast are common in the area and indicate a southeast prevailing wind. Similar parabolic dunes are described by Botha and Porat (2000) on the Maputaland

Table 3 Summary of drilling data for each mineralised zone used as the basis of the geological modelling for the Mutamba deposit

Mineralised zone	Drilling method	Hole diameter	Number of drill holes	Grid spacing (m)	Number of samples
Jangamo	HA	50 mm	165	2000 × 500	1239
	VC	BQ	201	250 × 250	1303
	RC	NQ	987	250 × 250	11 991
	Sonic	PQ	34	1000 × 1000	628
	Total		1387	250 × 250	15 161
Dongane	HA	50 mm	77	2000 × 500	569
	VC	BQ	1	Random	12
	RC	AQ	105	1000 × 500	1436
	RC	NQ	156	1000 × 500	2110
	Sonic	PQ	7	Random	155
Ravene	Total		346	500 × 500	4282
	HA	50 mm	71	1500 × 500	512
	RC	NQ	101	1000 × 500	1407
	VC	BQ	4	Random	52
	Total		176	1000 × 500	1971

Note: HA, hand-auger; VC, vibracore; RC, reverse-circulation.

coastal plain in northeastern South Africa, which were formed by southeast winds and prograded over several older dune systems. The highest elevations of 180–192 m ASL are located in the Ravene and Dongane zones, in contrast with the Jangamo zone where the highest elevation is 117 m ASL (Fig. 2). The centre of the Jangamo zone is typically a relatively flat landscape where the Mutamba River and its tributaries drain northwards to Inhambane Bay. The elevation of this flat area is approximately 10–12 m ASL, with the lowest elevation being the bench level of the Mutamba River of 4 m ASL, near the village of Jangamo.

Dune crests are elongated and undulate gently in the Jangamo zone, whereas in the Dongane and Ravene zones the crests of the dunes are shorter with steep slopes. In the Dongane and Ravene zones, inland lakes are levelled at approximately 7 m ASL (Fig. 2), with the bottom of the deepest lake at 12.5 m below sea level.

Jangamo area stratigraphy

The sedimentary sequence of the Jangamo area was formed in a marginal-marine setting, where three main depositional environments have influenced coastal evolution and had a bearing on stratigraphic relationships and the textural characteristics of the host sand. These include marine, fluvial and aeolian depositional environments.

The sedimentary sequence is as summarised in Figs. 6–8. The sequence starts at the base with a very well-sorted, fine-grained quartz sand with equally fine shell fragments, which suggests this unit was deposited in a low-energy marine environment (Marine unit). The presence of foraminifera and gastropod fossils supports a marine origin for this unit (Saunders 2009). The gradational colour of the Marine unit from dark at the base to lighter grey higher up, the coarsening-upward sequence and the presence of poorly sorted sand indicate a possible shallowing of the marine depositional environment. Thin horizons of coarse shell fragments suggest that there was a gradual transition to an intertidal depositional environment (Intertidal unit). The upper contact of the Intertidal unit is defined by the first occurrence of horizons comprising the coarse shell fragments.

Interbedded clay (plus silt) and clean coarse quartz sand horizons suggest an environment where occasional

low-energy, shallow-marine inundation introduced alternating clay layers to a mainly sandy unit. Periodic reworking of the sediments and occasional storm activity could account for the alternating lithologies with significant textural variation.

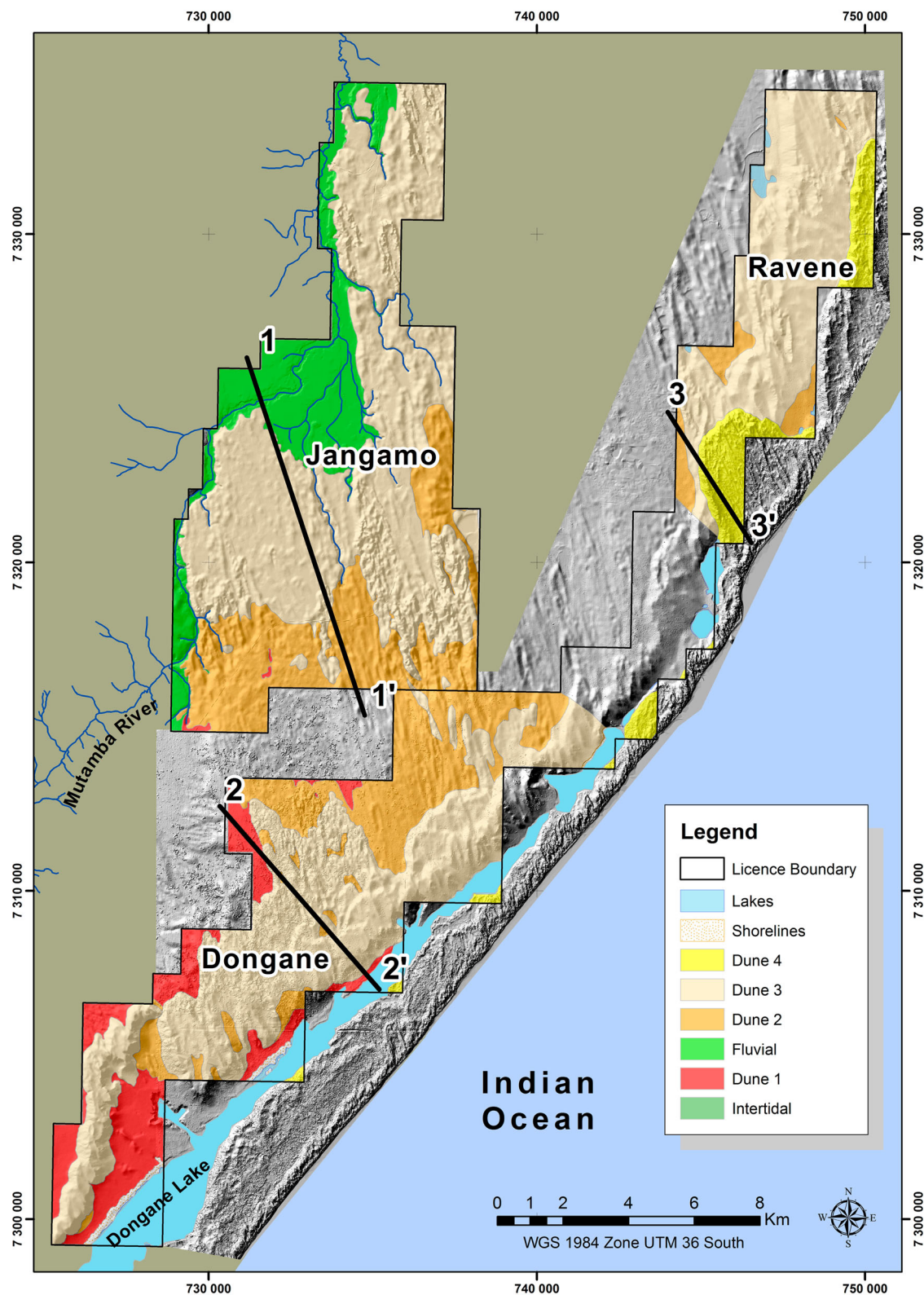
The average THM content of the Intertidal unit is 0.9% (Table 4), which is below the 1% cut-off for the mineralised envelope, and therefore is not considered part of the mineralised package. The Intertidal unit is exposed only rarely, so is mostly known from samples at depth in drill holes.

A distinct bimodal grain-size distribution of medium–fine sand distinguishes the Intertidal sediments from all of the other Jangamo area sediments. This bimodal distribution suggests a complex depositional environment or reworking by storm waves (Saunders 2009). Within the Mutamba River valley, the Intertidal unit is overlain by silty sand interpreted as the Fluvial unit. To the east, in the Dongane and Ravene zones, it is overlain by coarse to medium silt-rich sands with obvious palaeodunal surface morphology.

Sediment within the Fluvial unit has variable colour, from light to dark grey and yellow to light brown, but has consistent textural characteristics. The slime and THM characteristics for the Fluvial unit are as presented in Table 4, which shows an average THM grade of 3.5% and highlights the economic importance of the unit. Quartz grains in the Fluvial unit are easily distinguished from those of the aeolian units by their lack of a ferric oxide staining leaving the grains translucent to transparent.

The Fluvial unit is generally restricted to the Mutamba River valley and associated flood plain where fairly extensive alluvial sediments occur at surface. The Fluvial unit is still accumulating sediment, with active deposition associated with the contemporary Mutamba River system.

The oldest aeolian deposit that overlies the Intertidal unit is a dark red to red-brown silt-rich (>20%) palaeodunal quartz sand, known as D1 (Figs. 7 and 8). The average THM grade of D1 samples is 1.3% but is not considered part of the mineralised envelope based on the very high average slime content (Table 4). In the Jangamo zone, the D1 unit forms a core onto which subsequent aeolian sands were deposited and is associated with some of the highest elevation in the area (Fig. 7). The distinctive



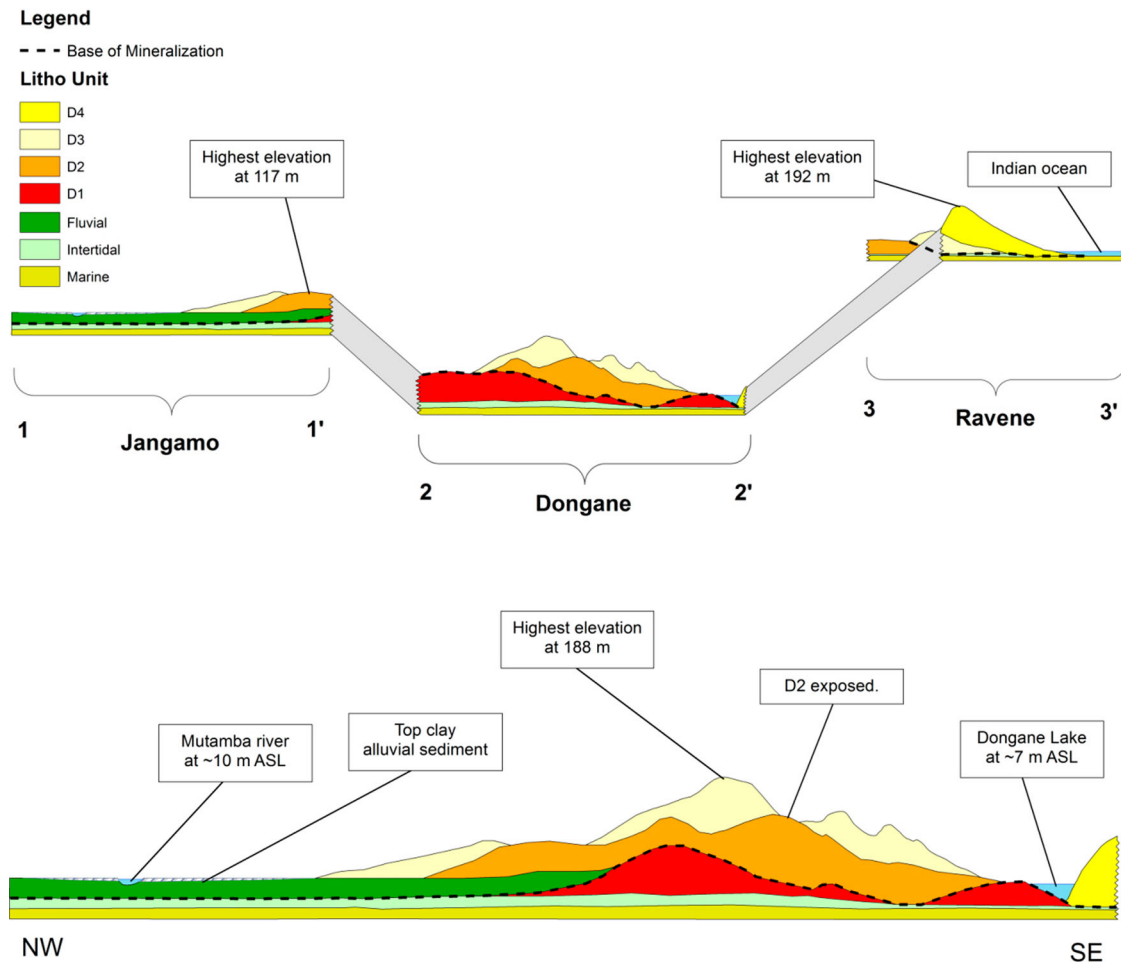
6 Geological map of the Mutamba deposit area showing the distribution of the various lithological units. The locations of cross-sections for Fig. 7 are annotated here

dark red colour and high slimes nature of this D1 unit are thought to be a result of degradation of ferric minerals.

X-ray diffraction (XRD) analysis indicates that the clay fraction of unit D1 comprises ~96% kaolinite and ~4% illite (Saunders 2009; Table 5), which is very similar to that of the clay mineral composition of the Fluvial unit. This similarity suggests a link between D1 and the Fluvial

unit, with the erosion and reworking of sediments from D1 possibly contributing a significant amount of finer-grained sediment to the Fluvial unit.

Most of unit D1 is completely overlain by younger sediments obscuring D1 dune crest and relief patterns. The contact between Intertidal and D1 units is not often noted in drill holes due to the high elevations where D1



7 Composite cross-section of the geological model for the Mutamba deposit area showing the relative age relationships and associations between the various lithological units

occurs but, where observed, it is a hard and distinct surface. The D1 unit shares its upper contact with at least two younger sand units (Fig. 7), both with surface morphology characteristic of palaeodunes and thus interpreted as aeolian in origin.

The most common unit that overlies D1 is light to dark orange-brown quartz sand with average slime content of 8%, known as unit D2 (Figs. 7 and 8). The contact between D1 and D2 is defined mostly by a distinct change in the slime content of about 18–20% (D1) versus 8% (D2). Sediment interpreted as D2 palaeodune has an average of 2.8% THM and is economically an important unit (Table 4).

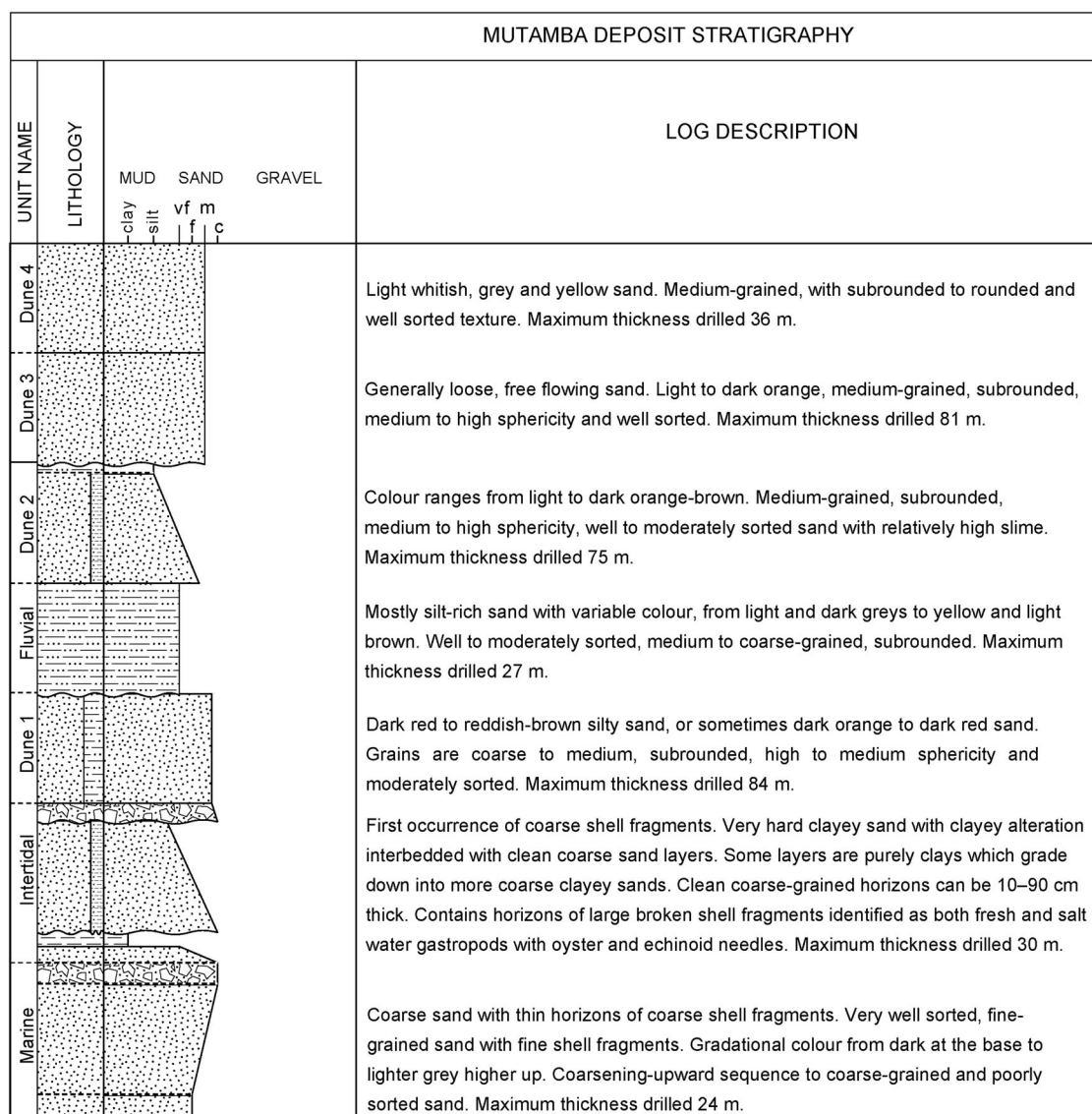
Overlying the D2 unit is a quartz sand sequence that is generally looser and more free-flowing. Organised into long, low parabolic landforms with northwest–southeast axes, it is interpreted as aeolian sediment and known as palaeodunal unit D3 (Fig. 7). The D2–D3 contact is best defined by the slime characteristics, which average about 6.3% in D3 compared to 8% in D2 (Table 4). Analyses of the clay fraction by Saunders (2009) indicate a higher illite content in D3 than in D2 (9.6% versus 5.8%; Table 5), which suggests a higher extent of paedogenesis in D3. At the transition from D2 to D3, it is common for the slime content to spike up to >20%, interpreted to represent a palaeosol horizon.

A total of 9841 drill samples are logged as unit D3 and have an average THM content of 3.3% and associated

average slime content of 6.3% (Table 4). This makes the D3 lithological unit the most economically important palaeodune system within the Mutamba deposit area.

Yellow-white and grey free-flowing quartz sand overlies D3, and represents the modern frontal dune system adjacent to the contemporary coastline (Fig. 7). These modern frontal dunes are defined as unit D4 and are still mobile with vast areas of exposed, unvegetated sand. The average THM grade for D4 is 2.7%, however, owing to the relatively fragile nature of these active dunes they were the target of limited drilling with a total of only 110 samples defined as D4 (Table 4).

In summary, the stratigraphic sequence in the Jangamo area represents accumulation of at least 160 m of older marine–intertidal–aeolian (D1–D3) sediments overlain by contemporary aeolian (D4) and alluvial material (Figs. 7 and 8). The development of such large volumes of mainly sand indicate a coastline supplied with significant sediment loads (from the Limpopo and Inharrime rivers to the south) and dominated by wind and wave action. In terms of economic geology, although the Fluvial unit hosts the highest average THM grade within the sediment package, the bulk of the mineralisation is hosted within the aeolian sediments D2–D3. There is a trend of increasing THM grade from the older unit D1 (1.3%) to the younger unit D3 (3.3%) suggesting reworking and gradual enrichment of HMs over time. The aeolian sediments form an overlapping complex of



8 Summary stratigraphic column for the Mutamba deposit area

palaeodunal landforms that control the distribution of mineralisation.

Mineralisation

In order to assess the overall prospectivity and rank the HM sand targets defined from the regional auger drilling, a THM value of 2% was initially established as a threshold for an anomaly over the greater exploration

area of Gaza and Inhambane Provinces. Based on the 2% THM threshold value, the Mutamba and Chilubane projects emerged as the two most important areas to focus exploration efforts (Fig. 9).

As exploration progressed over both Chilubane and Mutamba, with consistently higher *in situ* THM grades as well as higher economic HM content within the THM, the Mutamba project became a priority. With increasing drill hole density the three mineralised zones

Table 4 Summary of THM and slime data for the various units defined at the Mutamba deposit

Unit	Avg. of THM%	Min. of THM%	Max. of THM%	Avg. of slime%	Min. of slime%	Max. of slime%	Number of intervals with THM/slime	Number of intervals with description
D4	2.7	0.6	6.8	1.4	0.4	11.3	110	110
D3	3.3	0.1	30.2	6.3	0	90.7	9841	9867
D2	2.7	0.1	25.2	8.7	0.3	41.5	4966	4972
Fluvial/alluvial	3.5	0.2	22.6	7.6	0	87.7	1834	1838
D1	1.3	0.1	9.8	21.5	1.6	45.6	2248	2272
Intertidal	0.9	0.1	11.4	19.8	0	84.3	1606	1611
Marine	1.5	0.3	14.7	19.5	2.4	53.8	33	33

Table 5 Summary of clay mineralogy from XRD analyses of samples from Jangamo zone

Unit	Kaolinite (%)	Illite (%)	Smectite (%)	Chlorite (%)
D3	90.4	9.6	0.0	0.0
D2	94.2	5.8	0.0	0.0
Fluvial	96.1	3.9	0.0	0.0
D1	96.2	3.8	0.0	0.0
Intertidal	38.3	3.5	58.2	0.0
Marine	4.0	19.7	71.6	4.8

Source: Saunders (2009).

of Jangamo, Dongane and Ravene were defined, in which mineralisation characteristics are relatively similar. Figure 9 represents the surface expression of the minimum area of mineral resources at average THM grade intervals of 2–5%.

The ilmenite, rutile and zircon economic HM content within THM ranges from 60 to 80% with the bulk of the mineralisation hosted by the D2, D3 and Fluvial units. The THM grain-size distribution for Mutamba has a range 90–210 μm , with 50% of HM grains >142 μm . The overall slime content for Mutamba is 7.1% and typically comprises kaolinite and illite, with lesser amounts of smectite, chlorite and mica.

In 2009, an exploration target of 7–12 Bt was announced of mineralised sand with a grade range of 3–4.5% THM for the Chilubane and Mutamba projects combined. Drilling, sampling and metallurgical test work suggest that the two projects together have the potential to host 140–170 million tonnes (Mt) contained ilmenite in addition to 10–15 Mt contained zircon plus rutile (Table 6).

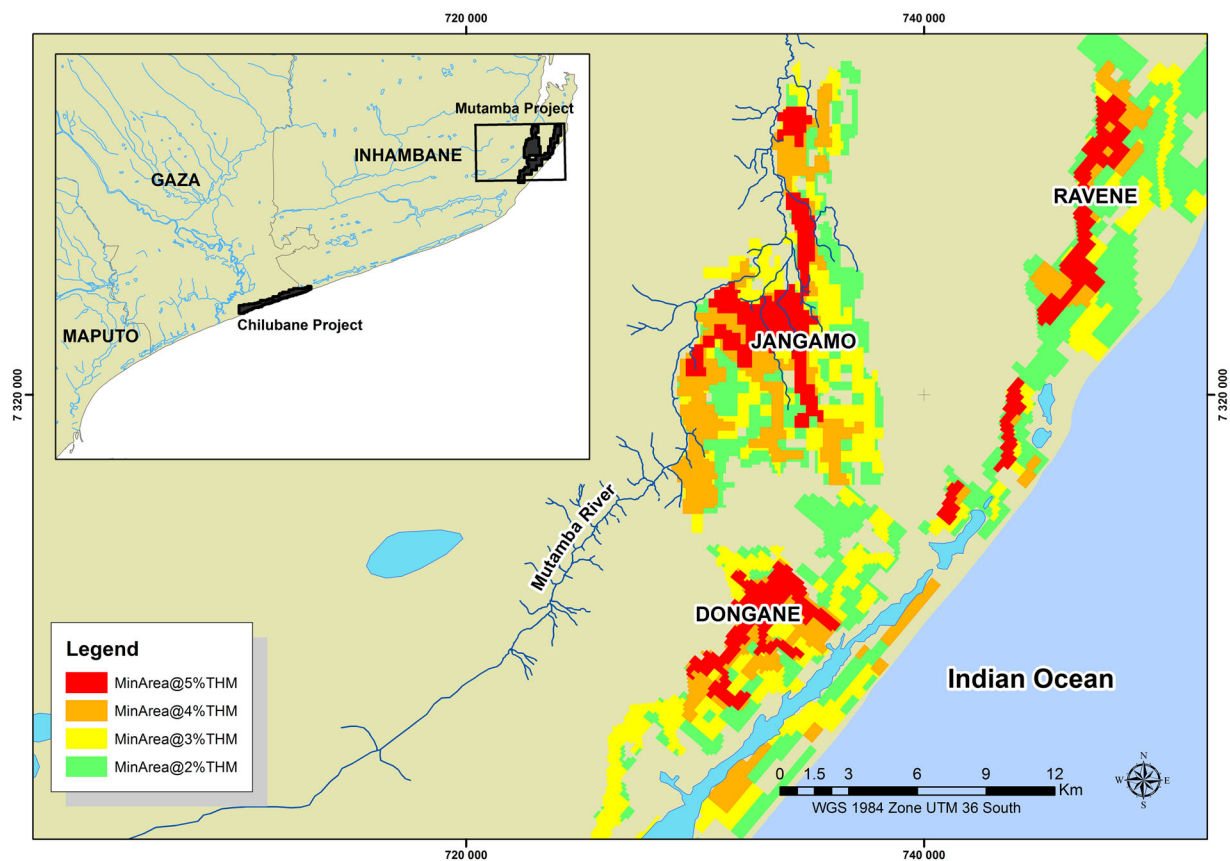
Summary and conclusion

The coastal evolution of the Mutamba deposit area is defined by the accumulation of a significant thickness (>100 m) of aeolian sediment defining a multi-generational palaeodune field deposited on what was likely a nucleus of alluvial marine sands exposed as a result of Pleistocene marine regression. The oldest unit interpreted in the area is a package of marine–intertidal sediments, which are likely analogous to the modern sediments being deposited in contemporary Inhambane Bay, the estuarine area of the bay and the Mutamba River valley. This interpretation is in accord with the study by Armittage *et al.* (2006) concerning the formation and evolution of barrier islands at Inhaca and Bazaruto, which concluded the islands formed as spits protruding north from coastal promontories on the seaward side of river estuaries at a period of higher sea level, with significant aeolian accretion.

Three generations of stable older palaeodunes (D1, D2 and D3) occur inland of the coastline, and host the bulk of associated titanium and zircon sand mineralisation. Unit D3 is the most important in terms of economic geology, with an average of 3.3% THM and low slime content, making it potentially amenable to low-cost dredge mining methods.

The better heavy sand mineralisation at Mutamba has been defined within three main zones, known as Jangamo, Dongane and Ravene, all of which have relatively similar mineralisation characteristics. The combined ilmenite, rutile and zircon economic HM content in THM is 60–80%.

With a globally significant Exploration Target of 7–12 Bt of mineralised sand at 3–4.5% THM, comprising >140



9 Map showing the distribution of mineral resources, based on various average THM grades from 2 to 5%

Table 6 Summary of exploration target for the Mutamba and Chilubane deposits combined

Exploration target – Mutamba and Chilubane deposits combined			
Tonnes (Mt)	Grade range (THM%)	Tonnes ilmenite (Mt)	Tonnes zircon + rutile (Mt)
7000–12 000	3–4.5	140–170	10–15

Note: Mt, million tonnes.

Mt of contained ilmenite, Mutamba and Chilubane deposits have the potential to support long-life mining operations comparable to that operated by Richards Bay Minerals in South Africa.

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