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MINERAL PROCESSING OF HEAVY MINERAL SANDS FROM MALAWI AND MALAYSIA

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Mineral processing of heavy mineral sands from Malawi and Malaysia

Clive J Mitchell

1. INTRODUCTION

Processing of heavy mineral sands involves many techniques including gravity, magnetic and electrostatic separation. As part of a laboratory programme to develop effective mineral processing techniques, two mineral sands from Malawi and Malaysia were processed using the standard techniques, with emphasis placed on the Carpco electrostatic separator. These sands were initially characterised mineralogically by scanning electron microscopy (SEM), electron microprobe analysis (EPMA) and X-ray diffraction (XRD). The same techniques were also used at a later stage to characterize the mineral concentrates. Mineral processing involved screening (to size the sands), gravity separation (to remove the less dense, or 'light', minerals), and magnetic and electrostatic separation (to produce concentrates of ilmenite, zircon, rutile and monazite).

Some of this work was carried out by Mohammed Anuar, Geological Survey of Malaysia, as part of his M.Sc. in Industrial Mineralogy (Leicester University). The bulk of the work, however forms part of the technique development component of the ODA/BGS project "Minerals for Development".

2. METHODOLOGY

A Hitachi S-520 scanning electron microscope (based at Leicester University), with an attached Link energy dispersive system (EDS), was used to determine the mineralogy of the sands and their processing products. The sands were mounted onto an aluminium stub and coated with carbon to facilitate mineralogical identification with the EDS. Approximately 500 grains of each processing product were identified, apart from the coarser fractions where there were fewer grains present. This large number of grain identifications was necessary in order to reduce the influence of single grains on the overall mineral contents and to reliably quantify subtle differences between processing products.

A Phillips PW 1700 X-ray diffractometer was used to identify selected mineral grains. Single grains were analysed by crushing them to a powder and dispersing them with acetone onto a silicon substrate. The traces were interpreted with reference to the JCPDS database (Anuar, 1992). The chemical composition of selected minerals (ilmenite, zircon, rutile and monazite) was determined by a Jeol JXA-860 Superprobe electron microprobe (based at Leicester University). Detailed results of the analyses are given in Anuar (1992). The analysis was facilitated by mounting the sands in polished resin blocks which were carbon-coated prior to analysis. A Cambridge Instruments Microscan V electron microprobe, with a Links EDS, was used for determining the chemical composition of the minerals in each electrostatic separation product and for image analysis of selected monazite grains.

Gravity separation, using a Mozley laboratory mineral separator Mk II (a form of shaking table) was carried out to remove the 'light' minerals, mainly quartz and feldspar, and produce heavy mineral concentrates. During separation the minerals present are segregated, with the heavy minerals sinking to the deck surface where, influenced by the 'end knock', they migrate upslope. The light minerals remain on the surface and are washed downslope. The point at which the 'heavy' and 'light' minerals separate into two distinct products is a gradual transition and there is a small amount of cross contamination. The instrumental running conditions were: side shake of 7.6 cm amplitude, setting of 70 rpm on the drive shaft pulley, 3° deck slope, water wash of 500 cm^3 per minute. The sand was separated in batches of 200g and each batch took approximately 15 minutes to complete.

Magnetic separation, using a Carpco high intensity induced roll magnetic separator (Model MIH (13) 111-5) was carried out to separate magnetically susceptible minerals from non-magnetic minerals, for example ilmenite from zircon. This separator has a laminated drum which in close proximity to a magnetizing block is used to produce a high magnetic field gradient that increases toward the drum surface. Sand is fed onto the rotating drum, which attracts any passing magnetic minerals, and non-magnetic minerals are thrown from the drum due to its momentum. The instrumental running conditions were: drum rotational speed of 100 rpm, feed hopper vibration of 50% (of maximum vibration) and, in most cases, a gap between the drum and magnetizing block of 4 mm. The separation was carried out using an increasing coil current series, starting with 0.3 A (approximately 2500 Gauss) to remove highly magnetic minerals such as magnetite, then repassing the 'thrown' (non-magnetic) product at a higher current and so on up to the maximum of 3.45 A (approx. 13,500 Gauss). The final 'thrown' sand was the non-magnetic product. The products were examined visually and combined to produce either two (magnetic and non-magnetic) or three (magnetic, middling and non-magnetic) products. The relationship between electromagnetic coil current and magnetic field intensity is given in Appendix D.

Electrostatic separation, using a Carpco electrostatic separator (Model HT (15, 25, 36) 111-15) was carried out to separate conductive from non-conductive minerals (Figure 1). This separator has a similar configuration to that of the Carpco magnetic separator, with a vibrating hopper that feeds sand onto a rotating drum. Two DC electrodes are arranged close to the drum surface, a dynamic (or beam) electrode at 60° from the horizontal and a static electrode at 35°. The dynamic electrode consists of a wire that produces a 'point' charge and this charges the mineral grains that pass under it. Conductive minerals allow this charge to dissipate quickly and are 'thrown'. Non-conductive minerals retain their charge and are attracted to the drum surface. The static electrode is a lozenge-shaped block that produces a diffuse charge. The conductive minerals are charged, and are then attracted to the static electrode which lifts them away from the drum surface. These two electrodes act in a complementary manner with the conducting minerals thrown from the drum and the non-conducting minerals 'pinned' to it. The non-conductive minerals are removed from the drum with an AC wiper electrode and a wire brush. The instrumental running conditions were a drum rotational speed of 80 rpm, feed hopper vibration 50% and a voltage of 25 kV DC and 5kV AC. Elevated temperature improves the conductivity of some minerals, for example rutile, and thus all sand was preheated to 110°C prior to separation and the drum was heated with an infrared lamp. After separation the sand temperature usually dropped to approximately 30-40°C. The feed rate was approximately 25-30 kg per hour. The conducting product was repassed, after reheating, to improve the concentrate grade.

3. GEOLOGY

3.1. Malawi beach sands

The beach sand from Malawi was collected from Nkudzi Bay on the SE side of the Cape Maclear peninsula, Lake Malawi, by AJ Bloodworth of BGS. The sands occur as dark layers on the beach formed by an active placer deposit, which has segregated black layers of ilmenite and red layers of garnet. The sands are likely to have been derived from the surrounding Precambrian basement, composed mainly of high-grade paragneisses and charnockitic granulites. These are intruded by Lower Palaeozoic micrograntic and microsyenitic dykes and granite ring complexes. Lacustrine sands and clays cover a large part of the peninsula (Dawson and Kirkpatrick, 1968). The mineralogical compositions of the rocks of the Cape Maclear peninsula are detailed in Appendix A and it can be seen that a full suite of heavy minerals are present as accessories.

3.2. Malaysian 'Amang' sand

'Amang' sand is a by-product from the mining of alluvial cassiterite and the sample studied was collected from Ipoh by Mr DE Highley of BGS. The alluvial tin is normally extracted by either dredging or hydraulic mining and the heavy minerals concentrated by jigs or 'palongs' (a simple form of sluice). Many heavy minerals occur with the tin, including ilmenite, zircon, rutile and rare-earth minerals (monazite and xenotime). The tin is extracted from these heavy minerals by magnetic and electrostatic separation. The by-product (Amang) is sold on to amang treatment plants which process the sand to extract any remaining tin and valuable heavy minerals. The alluvial placer deposits are derived from the Late Jurassic or Late Cretaceous granite intrusives that form the Main range to the East and the Kledang range to the West of Ipoh. The alluvium accumulated in the Kinta valley on top of a karstic Devonian-Permian limestone.

4. MINERAL PROCESSING

4.1. Sample preparation

The Malawi beach sand and Malaysian 'amang' sand were both dry screened from 2 mm down to 63 μm to produce closely sized material, more appropriate for mineral processing. The size fractions selected for processing were those between 1 mm and 125 μm for the Malawi beach sand and those between 500 μm and 125 μm for the Malaysian 'amang' sand. Selection of these fractions was based on their weight and only those in excess of 200g were processed further. The mineral processing route is shown diagrammatically in Figure 2.

4.2. Mineral processing

Gravity separation of the Malawi beach sand was carried out on the sand fractions between 1 mm and 250 μm. The -250 +125 μm size fraction and the Malaysian 'amang' sand were already concentrated in heavy minerals and did not require further gravity concentration. The 'light' mineral products were not subjected to any further processing.

Magnetic separations were carried out on three products of the Malawi beach sand: the -1mm +500 μm size fraction (recombined as no obvious mineral separation occurred), -500 +250 μm 'heavy' product and the -250 +125 μm size fraction. The second two were divided into three products: magnetic, middling and non-magnetic. Magnetic separations were also carried out on two products of the Malaysian 'amang' sand; the -500+250 μm and the -250+125 μm size fractions. These were divided into two products: magnetic and non-magnetic. The instrumental running conditions required to separate these products are detailed in appendix E.

Electrostatic separation was carried out on four Malawi beach sand products; the -1 mm +500 μm size fraction, the -500 +250 μm magnetic product and the -250 +125 μm magnetic and non-magnetic products. Electrostatic separation was carried out on three of the Malaysian 'amang' sand products; the -500 +250 μm magnetic and non-magnetic products and the -250+125 μm magnetic product.

4.3. Analysis

The untreated sands, their size fractions and separation products were examined by SEM (using EDS) to identify and determine the percentages of minerals present (Tables 1 and 2; Appendices B & C). The derived mineral percentages were converted to weight percentages by ratioing them to their specific gravity and, from these figures, mineral recoveries could be calculated. Selected minerals (ilmenite, zircon, rutile and monazite) were analysed by EPMA to determine their chemistry and to detect variations in mineral chemistry between separation products. Monazite grains were also 'element mapped' (i.e., the relative concentration of certain elements within a grain were determined by EPMA and plotted as a colour map) in order to detect zoning or other intragrain element variation.

5. RESULTS

5.1. Malawi beach sand

The Malawi beach sand was found to consist mainly of ilmenite (35%), quartz (25.4%), garnet (19.1%), magnetite, feldspar, zircon and sphene with a small amount of monazite, rutile, spinel, 'andalusite', olivine, staurolite, 'pyroxene', epidote, corundum, cassiterite, apatite, perovskite, wollastonite and columbite (Table 1). Screening resulted in concentration of heavy minerals from 68% in the head material to 99% in the <250 μm sand (Table 2). This is due to the natural sorting of minerals on a beach which causes small, dense minerals to behave in a similar fashion to large, 'light' minerals and hence they concentrate together.

Gravity separation removed most of the 'light' minerals, mainly quartz and feldspar, with the -1mm +500 μm size range upgraded to 94% heavy minerals and the -500 +250 μm size range to 98% heavy minerals (Appendix B). The former consisted mainly of garnet (51%), ilmenite and magnetite and the later mainly of ilmenite (48%) and garnet. A small proportion of 'light' minerals, such as quartz and feldspar, were concentrated together with the heavy minerals. These could not be totally avoided without drastically reducing the heavy mineral recovery from gravity separation. The small percentage of heavy minerals (<10%) present in the 'light' products indicates that gravity separation was reasonably efficient.

Magnetic separation of the sand successfully produced ilmenite and zircon concentrates (Appendix B). The -500 +250 μm magnetic product mainly contains ilmenite (84%), the middling product mainly garnet (61%) and ilmenite and the non-magnetic product contains a mixture of garnet (37%), quartz, feldspar and zircon. The -250 +125 μm magnetic product mainly contains ilmenite (50%) and garnet, the middling product mainly ilmenite (51%), garnet and zircon and the non-magnetic product mainly zircon (72%) and monazite. The magnetic separation has been efficient, with a small percentage (<5%) of non-magnetic minerals reporting to magnetic products and vice versa.

Electrostatic separation of the concentrates produced by magnetic separation upgraded the ilmenite and zircon contents of the sand (Appendix B). The -1mm +500 μm conductive product contained mainly ilmenite (95%) and the non-conductive product contained mainly garnet (81%). The -500 +250 μm conductive product contained mainly ilmenite (91%) and the non-conductive product contained mainly ilmenite (66%) and garnet. The -250 +125 μm magnetic product was split into a conductive product containing mainly ilmenite (70%) and magnetite and a non-conductive product containing mainly ilmenite (46%) and garnet. The -250 +125 μm non-magnetic product was split into a conductive product containing mainly rutile (40%), ilmenite and zircon and a non-conductive product containing mainly zircon (73%) and monazite. Electrostatic separation has separated conductive from non-conductive minerals with reasonable efficiency, but to improve mineral recovery several passes through the separator are required. This is standard industrial practice. Attempts to 'clean up' ilmenite and zircon concentrates from magnetic separation more often than not produced a small upgrade with a poor recovery as the mineral was split between the conductive and non-conductive products. For example with electrostatic separation of the -500 +250 μm magnetic product, the conductive product contained 91% ilmenite and the non-conductive product contained 66% ilmenite.

A summary of EPMA data for minerals from the Malawi beach sand is given in Table 3 (full data are given in Appendix F). The monazite present has an average composition of 27.5-28.9% P_2O_5, 28.7-29.5% CeO_2, 14.1-14.8% La_2O_3 and 10.2-11.1% Nd_2O_3. Zircon has an average composition of 59.3-66.6% ZrO_2 and 31.1-31.8% SiO_2. Rutile has an average composition of 90.4-91.3% TiO_2. Ilmenite has an average composition of 46.4-54.4% TiO_2 and 34.5-48.2% Fe_2O_3. The rare earth element data for the monazite from the Malawi beach sand were chondrite-normalised and are plotted in Figure 3. Chondrite normalization is standard practice for the presentation of REE data and gives useful information about the petrogenesis of the sample. Chondrites are undifferentiated meteorites which are representative of primitive solar system material. The REE analysis of an average chondrite is given in Appendix G and, to normalize, the sample value is divided by the chondrite value. Monazite from various sources (granitic pegmatite; granitic rocks; alkalic rocks and carbonatites) and commercial monazite (E & W Australia; Florida, USA; China) were also plotted to provide comparisons (Figures 4-6).

Monazite grains from the sand (-250 +125 μm) were also element mapped and Figures 7-15 show some of the typical monazite grains present. The colours of the image are based on an arbitrary scale increasing in element concentration in the order: purple, dark blue, blue, green, yellow and red. Figures 7-9 show a hexagonally shaped monazite grain from the non-magnetic, non-conductive fraction. A central zoning is evident with higher values of Nd, La and Ce. Figures 10-12 show a kidney-shaped grain from the non-magnetic conductive product. A central zone is highlighted by higher La values and the right-hand side is also higher in Ce and Nd. Figures 13-15 show an elongate grain from the magnetic non-conductive product. A concentric zone around the centre is partially picked out by higher Ce, La and Th values.

The shape of the monazite grains, as analysed by electron microprobe, were generally rounded wedge or lozenge shaped with heavy 'pitting' and irregular cracks. Euhedral (prismatic and hexagonal), kidney shaped and irregular grains of monazite were also observed.

5.2. Malaysian 'amang' sand

The Malaysian 'amang' sand was found to contain mainly ilmenite (91%) with small amounts of sphene, quartz, rutile, cassiterite, magnetite, monazite, zircon, feldspar, garnet, apatite, xenotime, olivine and columbite (Table 1). The screening of the 'amang' sand did not result in a significant preconcentration of heavy minerals; however the +500 µm size fractions contain higher proportions of quartz (approximately 20%).

Magnetic separation of the 'amang' sand was only partly successful in upgrading the ilmenite content as a large percentage of ilmenite remained in the non-magnetic products (Appendix C). The -500 +250 µm magnetic product contained mainly ilmenite (97%) and the non-magnetic product contained a mixture of ilmenite (43%), quartz and sphene. The -250 +125 µm magnetic product contained mainly ilmenite (86%) and the non-magnetic product contained mainly ilmenite (53%), quartz and cassiterite.

Electrostatic separation successfully increased the ilmenite contents of the concentrates produced by magnetic separation (Appendix C). The -500 +250 µm magnetic product was split into conductive and non-conductive products containing mainly ilmenite (98% and 90% respectively). The -500 +250 µm non-magnetic product was split into a conductive product containing mainly ilmenite (76%) and cassiterite and a non-conductive product containing mainly quartz (59%), sphene, ilmenite and zircon.

5.3 Discussion of results

The processing of both the Malawi beach sand and the Malaysian 'amang' sand has successfully produced relatively pure mineral concentrates with high mineral recoveries. Table 4 gives a summary of the grade, yield and recovery of concentrates produced from processing of the Malawi beach sand and Malaysian 'amang' sand.

Combination of the magnetic conductive products from the **Malawi beach sand** results in a concentrate that contains 90% ilmenite with a recovery of 72%. This concentrate also represents a third of the head material and half of the heavy minerals present in it. A second concentrate can be produced by combination of all the non-magnetic products and the magnetic middling of the -250 +125 μm sand. This contains 29% zircon (recovery of 60%), 6% monazite (80% recovery) and 4% rutile (recovery of 64%), and represents only 9% of the head material.

Combination of the magnetic conductive products of the **Malaysian 'amang' sand** results in a concentrate that contains 97% ilmenite with a recovery of 78%, and represents 73% of the head material.

The underlying principle for the separation of heavy minerals relies on differences in their physical properties, for example ilmenite has a high magnetic susceptibility and electrical conductivity whereas zircon is non-magnetic and non-conductive. These physical properties are a direct consequence of the chemical composition of the minerals and as mineral chemistry varies so will physical properties for individual mineral species. For example, ilmenite was found in most of the -250 +125 μm electrostatic separation products in varying amounts, and as can be seen from Table 5 the chemistry of the ilmenite is slightly different in each product. Thus any deviation from the behaviour expected during processing should be reflected in the chemistry of the individual minerals concerned, although other factors do have an influence on processing behaviour, such as particle size and shape.

In addition to ilmenite, zircon, rutile and monazite from the -250+125 μm electrostatic separation products of the Malawi beach sand were examined by EPMA in order to identify any variation in chemical composition and attempt to relate this to the electrostatic processing. There are few marked differences in mineral chemistry between separation products. **Ilmenite** is paramagnetic (i.e. attracted by magnetic intensities over 2000 Gauss) and conductive and concentrates in the expected product. Ilmenite shows significantly higher Fe_2O_3 and lower TiO_2 in the magnetic products relative to the non-magnetic product. There is a direct relation between Fe_2O_3 content of ilmenite and magnetic susceptibility. Fe_2O_3 content is inversely mirrored by TiO_2 content. Ilmenite, strongly magnetic, contains from 45-65% TiO_2, leucoxene, weakly magnetic, contains from 68-90% TiO_2 and rutile, non-magnetic, contains 90%+ TiO_2. The differences in iron content are sufficient to explain the presence of ilmenite in non-magnetic and non-conductive products, when it is expected to report to the magnetic and conductive fractions only.

Zircon is non-magnetic and non-conductive and concentrates in the expected product. Zircon shows higher ZrO_2 in the non-magnetic product relative to the magnetic product. The latter has higher Fe_2O_3 which indicates the presence of magnetic inclusions within the zircon grains and this is possibly sufficient to divert zircon into a magnetic product.

Monazite is paramagnetic and non-conductive, but it concentrates in the non-magnetic products. Monazite shows lower P_2O_5 and Nd_2O_5, with higher ThO_2, SiO_2, CeO_2 and La_2O_3, in the non-magnetic products relative to the magnetic product. There is little to chemically differentiate the non-magnetic products. Thorium is known to substitute for REE and the charge imbalance caused by this is countered by Si replacing P. Monazite is isostructural with huttonite ($ThSiO_4$) and a continuous solid solution series exists between these two end-members. This substitution could possibly explain the presence of most of the monazite in the non-magnetic products.

Rutile is non-magnetic and conductive (the latter at elevated temperatures, 200°C or higher) and it reports to the expected products. Rutile shows higher TiO_2 in the non-conductive product relative to the conductive product, and this is possibly sufficient to explain its deviation from expected behaviour during mineral processing.

The chondrite-normalised rare earth element data plotted for monazites from the Malawi beach sand are similar to those for monazite from a granitic source rock. This is supported by the presence of granites, granulites and gneisses within the probable source region for the beach sands (Appendix A). The Malawian monazite REE plots are similar to those for monazite available commercially from Australia and China. Appendix H compares the REE composition (in atomic percent) for average monazites from various sources (Fleischer *et al.*, 1991) with those for the Malawi beach sand, which bears most resemblance to monazite from a granitic source rock.

The Malawi beach sand (-250 +125 μm) monazite grains examined by element mapping do not display any systematic variations which might explain the observed deviations from expected processing behaviour. However only a small number of monazite grains were analysed by 'element mapping' and a larger number of grains would need to be examined before any trends would emerge. The monazite grains had a similar shape in all the electrostatic separation products and are probably not a cause of deviation from expected behaviour. It is likely that the separating conditions were not sufficient to concentrate the monazite

6. CONCLUSIONS

1. The sample of Malawi beach sand contains 68% heavy minerals, mainly ilmenite, garnet, magnetite, zircon and sphene and small amounts of monazite, rutile, spinel, andalusite, olivine, staurolite, pyroxene, epidote, corundum, cassiterite, apatite, perovskite, wollastonite and columbite.

2. The sample of Malaysian 'amang' sand contains 98% heavy minerals, mainly ilmenite, with small amounts of sphene, rutile, cassiterite, magnetite, monazite, zircon, garnet, apatite, xenotime, olivine and columbite.

3. Processing of the Malawi beach sand by gravity, magnetic and electrostatic separation was successful in producing heavy mineral concentrates. The largest concentrate contained 90% ilmenite with a recovery of 72% and the second concentrate contained 29% zircon (60% recovery), 6% monazite (80% recovery) and 4% rutile (64% recovery).

4. Processing of the Malaysian 'amang' sand by magnetic and electrostatic separation was successful in producing a heavy mineral concentrate and this contained 97% ilmenite with a recovery of 78%.

5. EPMA has indicated differences between individual minerals (ilmenite, zircon, rutile and monazite) in the electrostatic separation products of the -250 +125 μm fraction of the Malawi beach sand. The ubiquitous presence of ilmenite was due to variation in Fe_2O_3 content, with consequent variation in magnetic susceptibility and conductivity. Magnetic inclusions (indicated by higher Fe_2O_3 values) present in some zircon grains account for their presence in magnetic products. The substitution of Th for REE in monazite may account for its concentration in the non-magnetic rather than the magnetic products. The slight variation in TiO_2 content in rutile grain chemistries is possibly sufficient to explain its deviation from expected processing behaviour. Element mapping of monazite grains and examination of their shape did not indicate any systematic variations that could help explain the observed processing deviations.

6. The results suggest that the heavy mineral sand at Nkudzi bay, Lake Malawi is a potential source of industrial grade ilmenite with by-product zircon, rutile and monazite also available. More comprehensive sampling and laboratory studies are required to prove the resource. The Malaysian 'amang' sand is already processed to produce industrial grade ilmenite and other heavy mineral concentrates. Processing of these sands has demonstrated the effectiveness of the electrostatic separator (in conjunction with gravity and magnetic separation) for producing high-grade mineral concentrates as part of the evaluation of industrial minerals. It is

recommended that further laboratory processing studies should investigate the electrostatic separation of a wider range of industrial minerals, for example: the purification of graphite and garnet and the removal of iron oxides and other impurities from silica sand and feldspar.

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Table 1 Mineralogy of Malawi beach sand and Malaysian 'Amang' sand.

Mineral	Malawi beach sand (Weight %)	Malaysian 'amang' sand (Weight %)
Ilmenite	35.0	90.5
Quartz	25.4	1.9
Garnet	19.1	0.1
Iron oxide (Magnetite/Hematite)	7.8	0.9
Feldspar	4.9	0.1
Zircon	4.1	0.5
Sphene	1.5	2.6
Monazite	0.6	0.7
Rutile	0.5	1.4
Spinel	0.3	nd
Andalusite	0.2	0.1
Olivine	0.2	<0.1
Staurolite	0.1	nd
Pyroxene/amphibole	0.1	nd
Epidote	<0.1	nd
Corundum	<0.1	nd
Cassiterite	<0.1	1.2
Apatite	<0.1	<0.1
Perovskite	<0.1	nd
Wollastonite	<0.1	nd
Columbite	<0.1	nd
Xenotime	nd	<0.1
Total	100.01	100.0

N.B. Mineral contents determined using SEM (EDS) and converted to weight percentages by ratioing to mineral densities. nd = not detected.

Table 2 Particle-size distribution and mineralogy of size fractions

	Size fraction (Weight %)	Mineralogy
Malawi beach sand		
+2 mm	0.1	Mineralogy similar to -1mm +500 µm size fraction
-2+1 mm	4.7	
-1 mm +500 µm	24.8	Quartz (51%), garnet (31%), ilmenite (5%), feldspar (4%), iron oxide (4%), monazite (1%)
-500 +250 µm	38	Garnet (28%), quartz (21%), feldspar (15%), ilmenite (15%), sphene (11%), iron oxide (4%), zircon (1%)
-250 +125 µm	32	Ilmenite (76%), zircon (6%), sphene (6%), garnet (4%), iron oxide (4%), monazite (1%)
-125 +63 µm	0.4	Mineralogy similar to -250 +125 µm size fraction
-63 µm	0.1	
Malaysian 'amang' sand		
+2 mm	0.05	Mineralogy similar to -1mm +500 µm size fraction
-2 +1 mm	0.05	
-1 mm +500 µm	1.4	Ilmenite (42%), sphene (27%), quartz (21%), iron oxide (7%), andalusite (3%)
-500 +250 µm	44.6	Ilmenite (86%), sphene (11%), quartz (3%)
-250 +125 µm	50.5	Ilmenite (86%), sphene (7%), cassiterite (2%), quartz (2%), iron oxide (1%)
-125 +63 µm	3.3	Mineralogy similar to -250 +125 µm size fraction
-63 µm	0.1	

N.B. Full details of mineralogy are given in Appendices B and C.

Table 3 Summary of EPMA data for Malawi beach sand (-250 +125 μm products)

Monazite	CaO	P2O5	La2O3	CeO2	Pr6O11	Nd2O3	Sm2O3	Eu2O3	Gd2O3	Dy2O3	Ho2O3	Er2O3	Y2O3	SiO2	Al2O3	ThO2	UO2	Total
Non-mag / non-cond (52)	0.95	27.94	14.76	29.45	2.79	10.35	1.51	0.06	0.30	0.00	0.03	0.02	0.13	1.15	0.19	8.58	0.02	98.24
Non-mag / conductive (39)	0.79	27.46	14.65	29.31	3.01	10.18	1.33	0.07	0.40	0.04	0.00	0.03	0.12	1.18	0.00	8.15	0.00	96.72
Magnetic / non-cond (3)	0.98	28.87	14.07	28.74	3.14	11.08	1.78	0.00	0.96	0.00	0.00	0.00	0.21	0.50	0.00	6.52	0.00	96.86

Zircon	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Nb2O5	SnO2	Ta2O5	Total
Non-mag / non-cond (10)	31.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	66.61	na	na	na	98.03
Non-mag / conductive (10)	31.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.47	na	na	na	97.78
Magnetic / non-cond (11)	31.79	0.03	0.00	0.03	0.12	0.00	0.03	0.00	0.05	0.00	0.00	59.25	2.37	0.00	0.57	94.23

Rutile	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Nb2O5	SnO2	Ta2O5	Total
Non-mag / non-cond (16)	0.35	91.32	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	1.20	0.18	na	na	na	93.13
Non-mag / conductive (12)	0.25	90.43	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	1.03	0.09	na	na	na	91.87

Ilmenite	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Nb2O5	SnO2	Ta2O5	Total
Non-mag / conductive (5)	0.34	54.36	0.19	0.00	34.48	0.73	0.70	0.03	0.00	0.00	0.50	0.00	na	na	na	91.33
Magnetic / non-cond (20)	0.25	46.44	0.10	0.01	45.44	1.95	0.33	0.11	0.11	0.01	0.19	0.00	0.01	0.00	0.00	94.98
Magnetic / conductive (22)	0.21	46.43	0.02	0.00	48.23	1.78	0.33	0.00	0.12	0.00	0.40	0.00	0.00	0.00	0.00	97.53

N.B. All data expressed as weight percentages. These data are averages and the number of analyses per product is given in the brackets.
The monazite analyses used were those with totals greater than 95%.

Table 4 Summary of grade, yield and recovery

Product	Grade (Wt %)	Yield (Wt %)	Recovery (Wt %)
Malawi beach sand			
Ilmenite concentrate	89.7	34.2	71.8
Zircon concentrate	-	8.7	-
- zircon	29.1	-	59.5
- monazite	5.8	-	79.6
- rutile	3.9	-	63.9
Malaysian 'amang' sand			
Ilmenite concentrate	97.2	72.6	64.1

N.B. The Malawi beach sand ilmenite concentrate is formed of the -1mm +500μm heavy conductive, -500+250 μm heavy magnetic conductive and the -250 +125 μm magnetic conductive products. The zircon concentrate is formed of the -500 +250 μm non-magnetic, -250+125 μm magnetic middling and non-magnetic products. The Malaysian ilmenite concentrate is formed of the -500+250 μm and -250+125 μm magnetic conductive products. Grade is the mineral content of the concentrate. Yield is the proportion of the total weight of the starting material contained in the concentrate. Recovery is the proportion of total mineral present in the head (or unprocessed material) which reports to the concentrate.

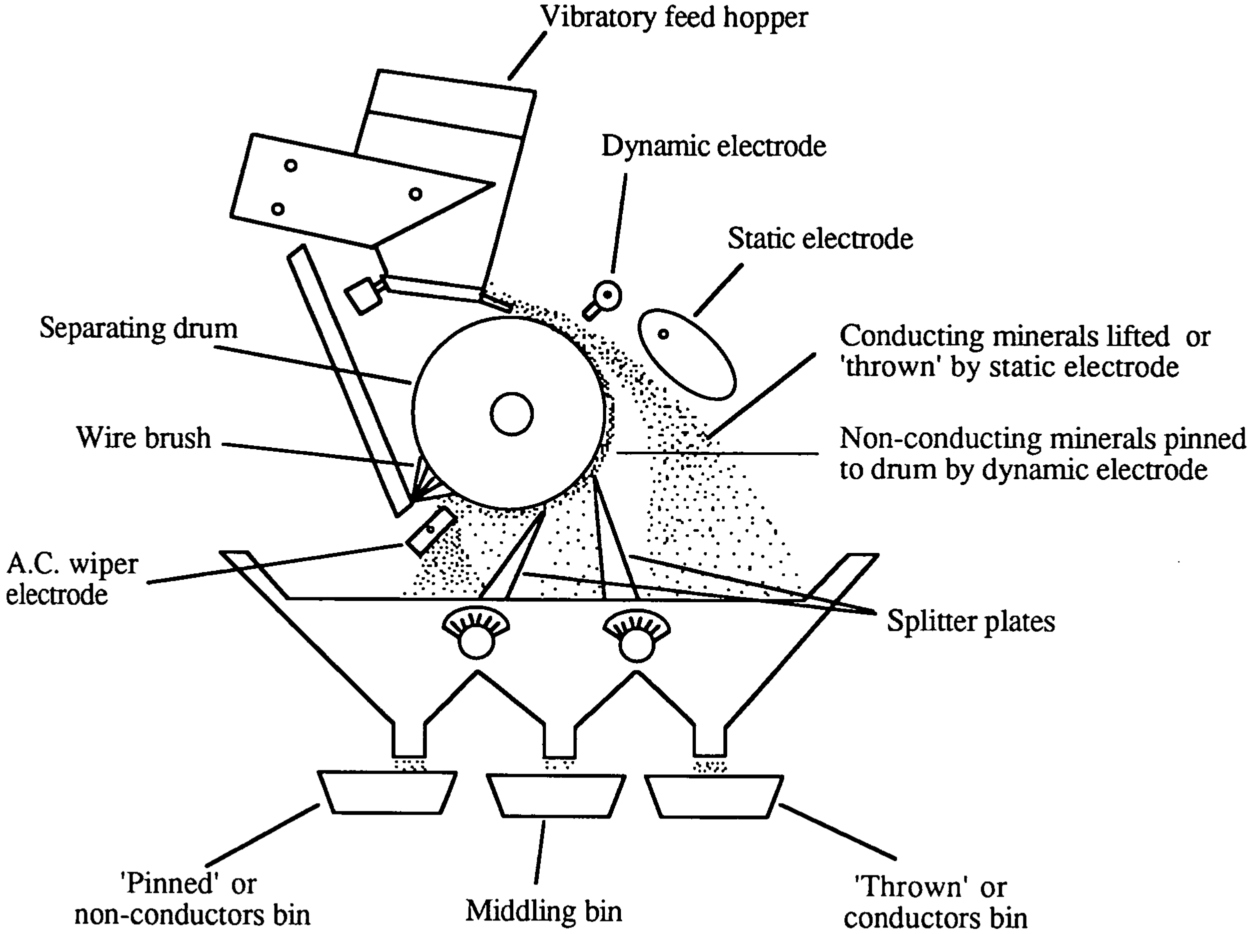

Figure 1. Electrostatic separator

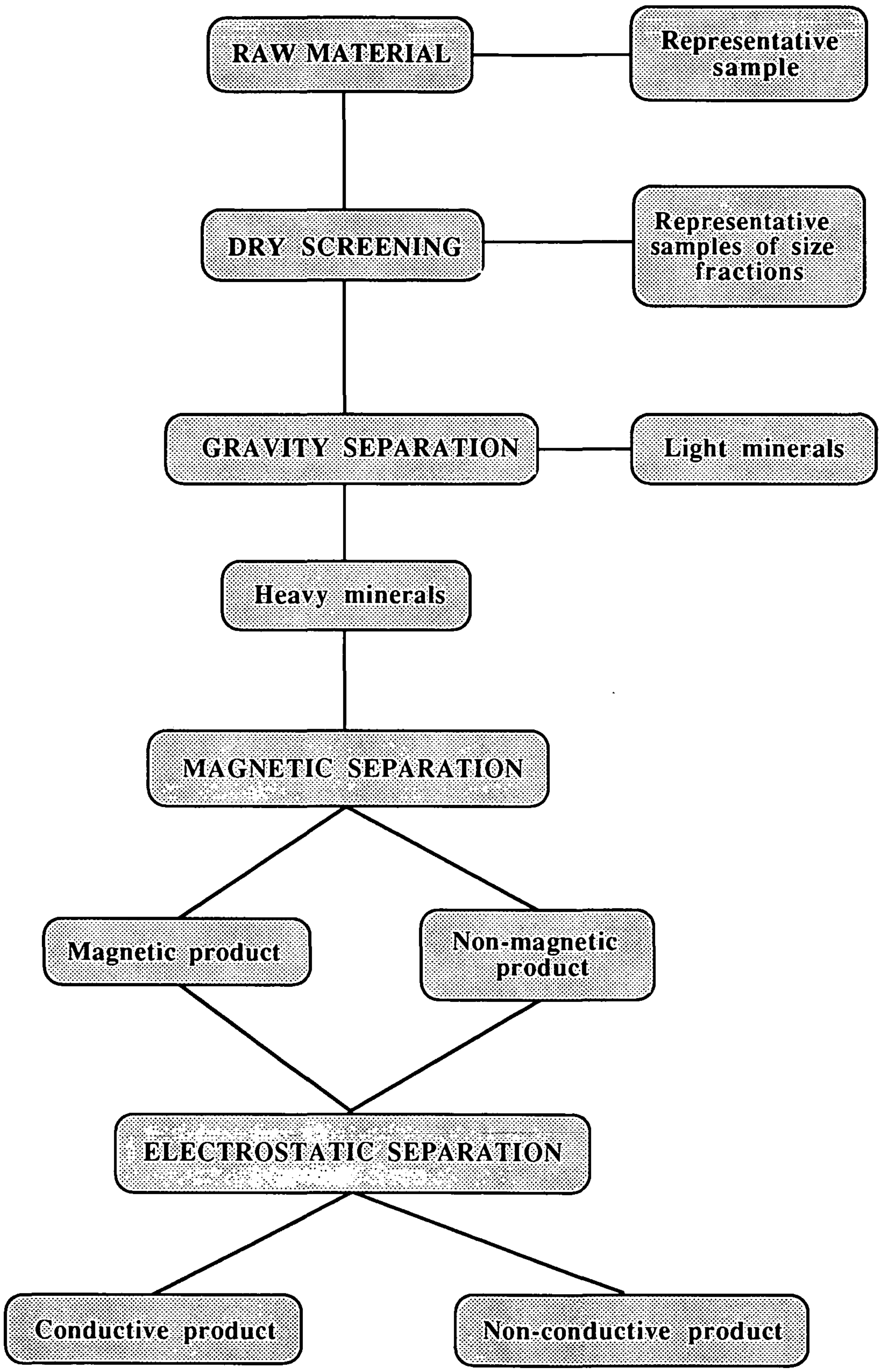

Figure 2. Mineral processing flowchart for the heavy mineral sands from Malawi and Malaysia

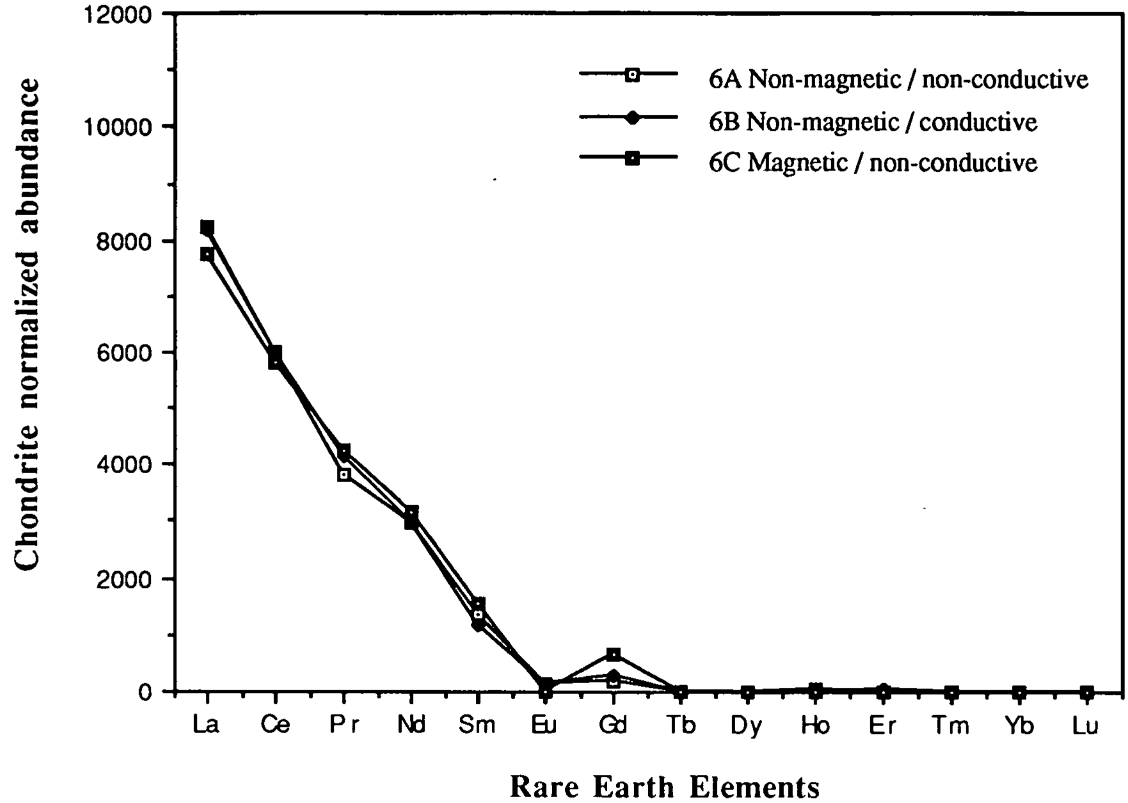

Figure 3. Chondrite-normalized REE data for monazite, beach sand, Malawi

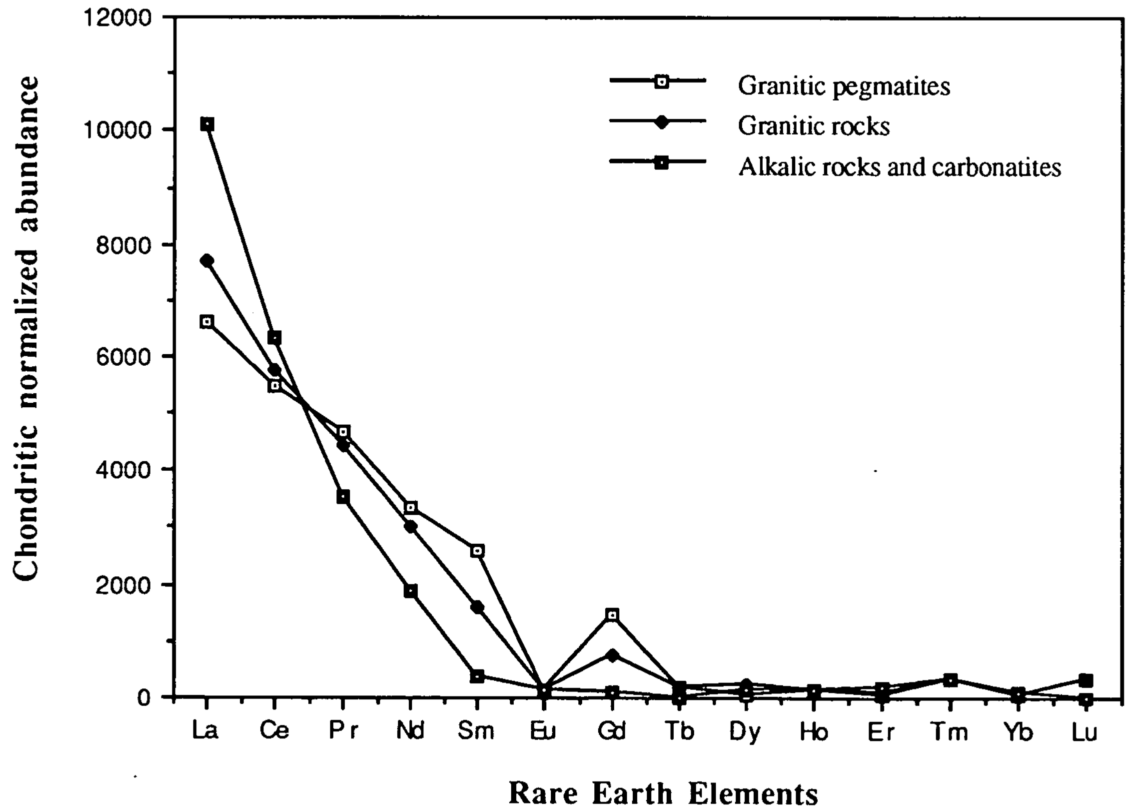

Figure 4. Chondrite-normalized REE data for monazite from typical source rocks (Fleischer and Altschuler, 1969)

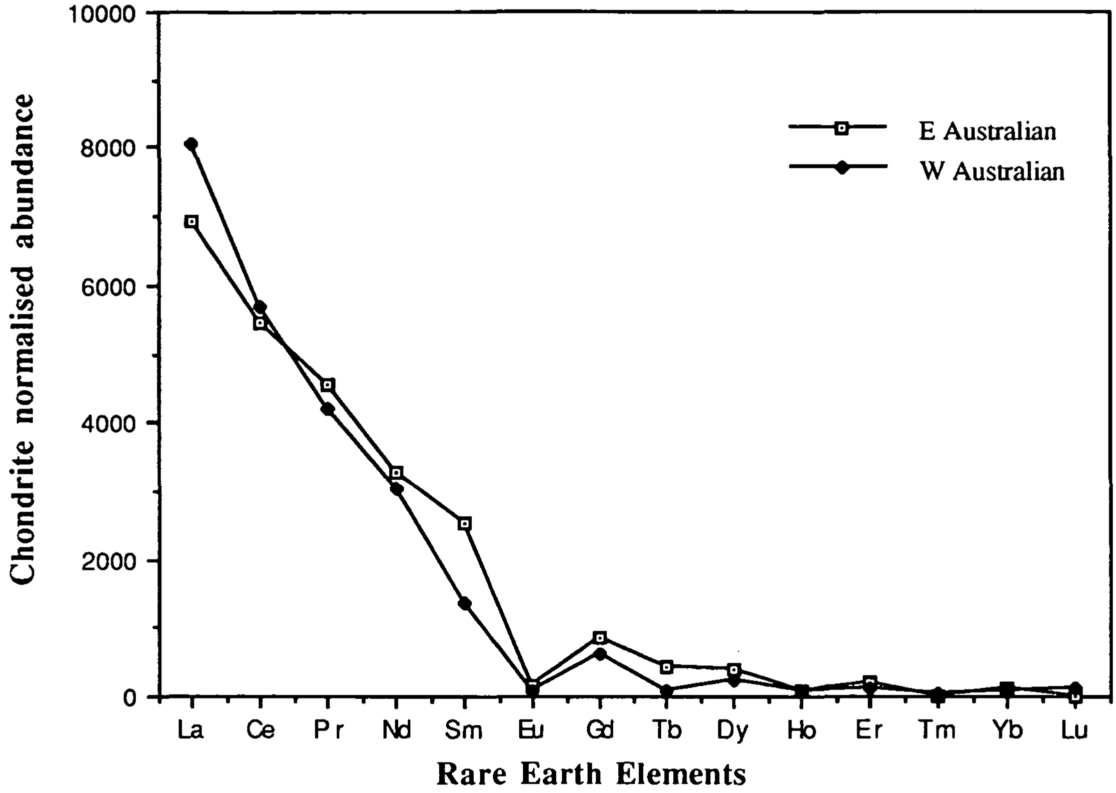

Figure 5. Chondrite-normalized REE data for commercial monazite, Australia (O'Driscoll, 1988).

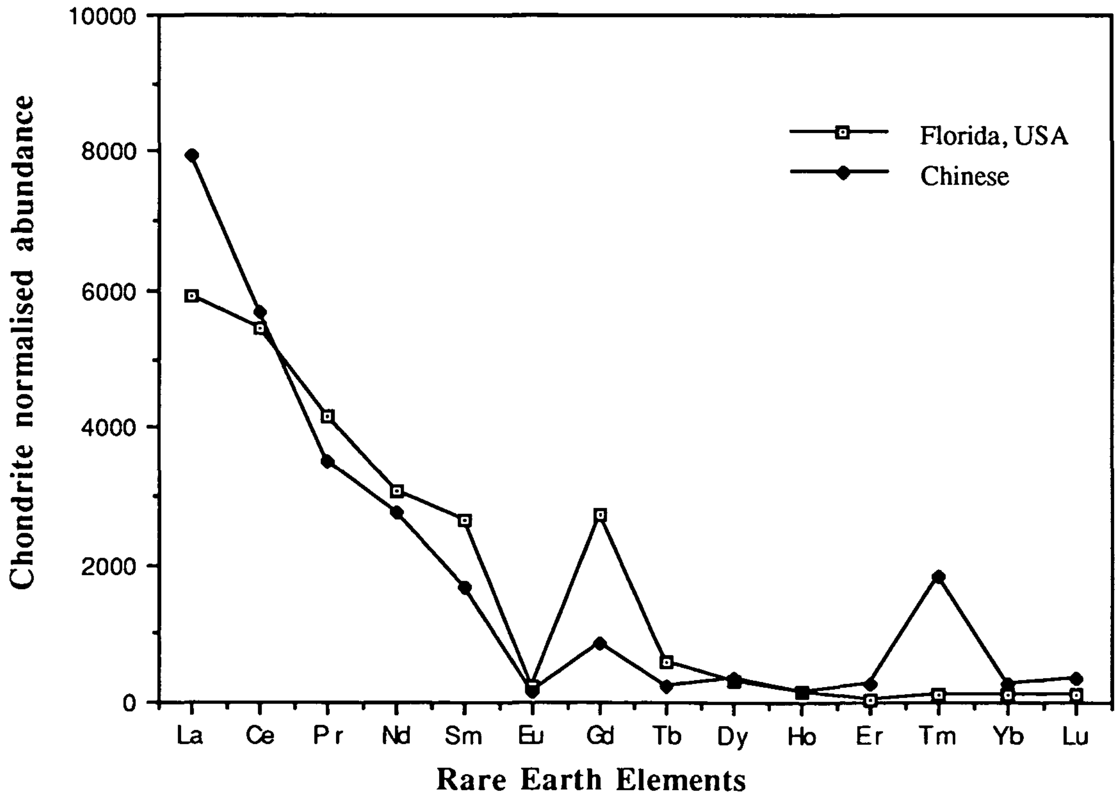

Figure 6. Chondrite-normalized REE data for commercial monazite, Florida, USA and China (O'Driscoll, 1988)

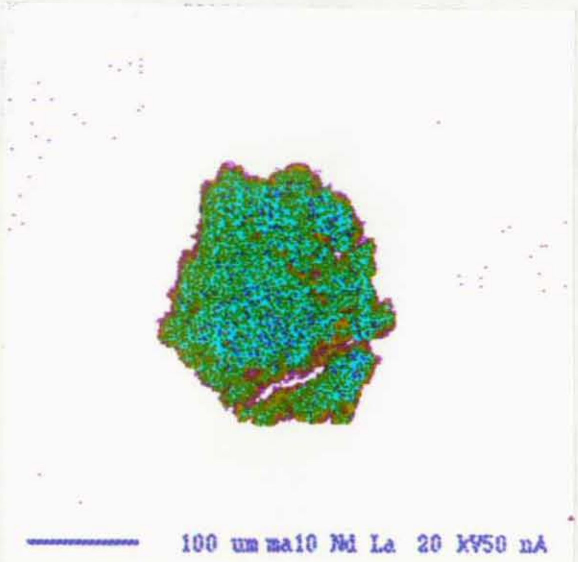

Figure 7. Element map (Neodymium) of monazite grain from non-magnetic, non-conductive product of -250+125μm fraction of beach sand, Malawi.

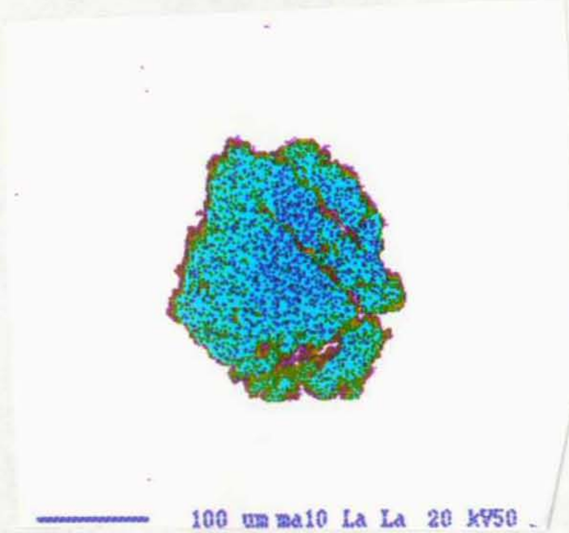

Figure 8. Element map (Lanthanum) of monazite grain from non-magnetic, non-conductive product of -250+125μm fraction of beach sand, Malawi.

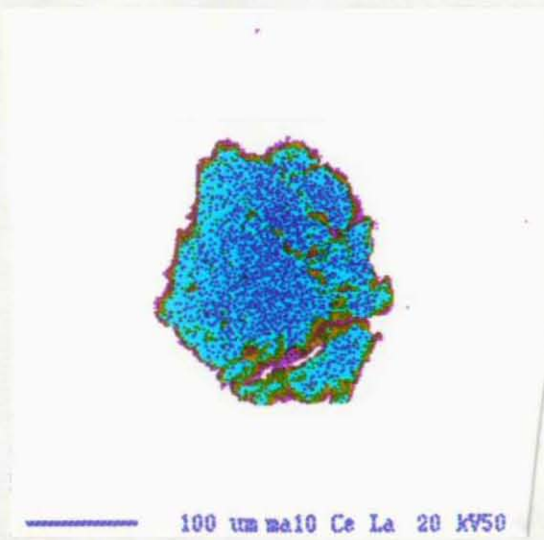

Figure 9. Element map (Cerium) of monazite grain from non-magnetic, non-conductive product of -250+125μm fraction of beach sand, Malawi.

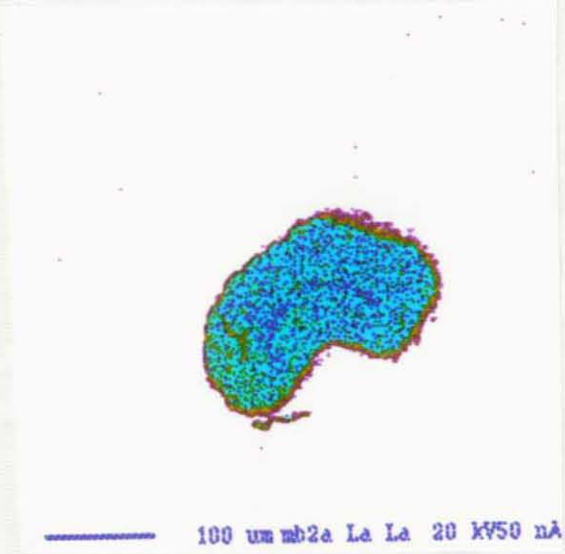

Figure 10. Element map (Lanthanum) of monazite grain from non-magnetic, conductive product of -250+125μm fraction of beach sand, Malawi.

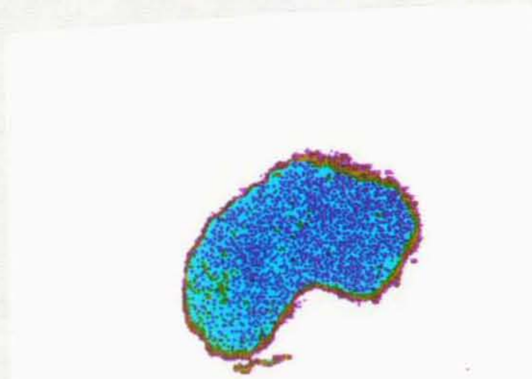

Figure 11. Element map (Cerium) of monazite grain from non-magnetic,conductive product of -250+125μm fraction of beach sand, Malawi.

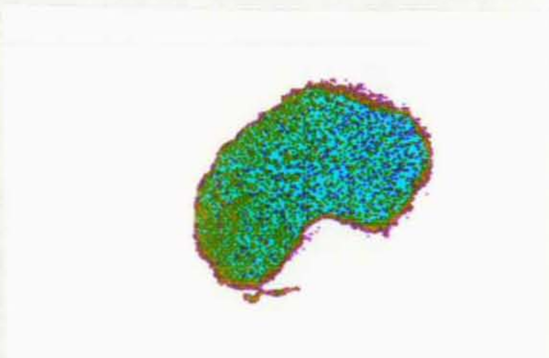

Figure 12. Element map (Neodymium) of monazite grain from non-magnetic, conductive product of -250+125μm fraction of beach sand, Malawi.

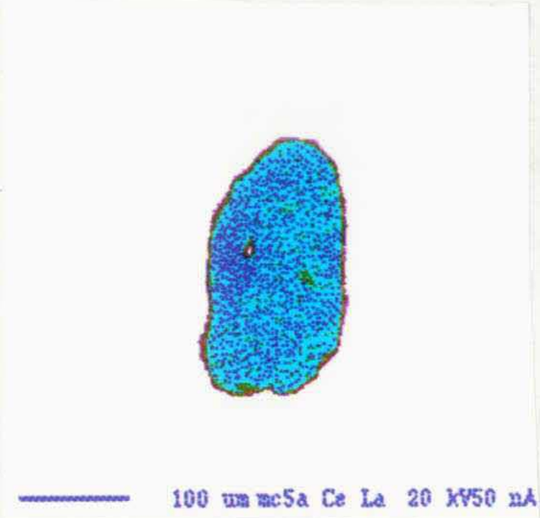

Figure 13. Element map (Cerium) of monazite grain from magnetic, non-conductive product of -250+125μm fraction of beach sand, Malawi.

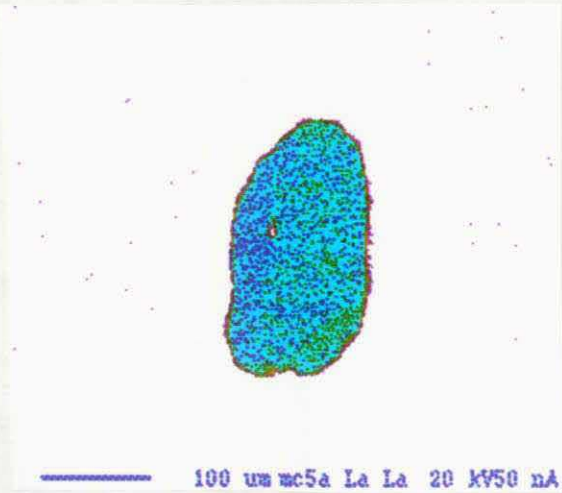

Figure 14. Element map (Lanthanum) of monazite grain from magnetic, conductive product of -250+125μm fraction of beach sand, Malawi.

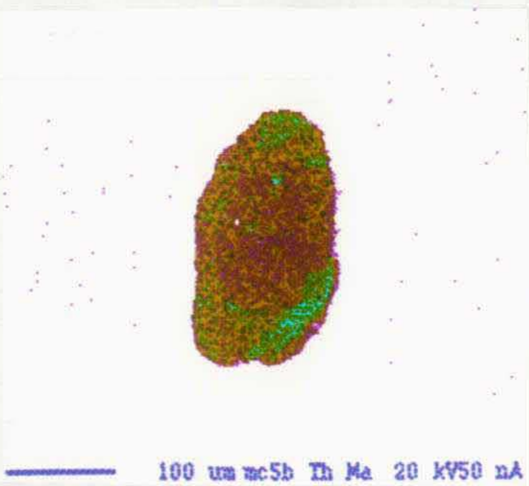

Figure 15. Element map (Thorium) of monazite grain from magnetic, conductive product of -250+125μm fraction of beach sand, Malawi.

Appendix A. Mineralogical composition of the Basement rocks, Cape Maclear peninsula, Malawi (from Dawson and Kirkpatrick, 1968).

Biotite granite (medium grained, leucocratic, massive)

Microcline feldspar (phenocrysts), quartz, biotite mica (occassional muscovite, hornblende and riebeckite). Accessories include sphene, titano-magnetite, apatite, zircon and rutile.

Syenite (medium grained, light grey-green, massive)

Microcline feldspar (phenocrysts), quartz, hornblende, clinopyroxene, biotite mica (+ amphibole?). Accessories include titano-magnetite, sphene, apatite and zircon.

Charnockitic granulites and gneisses (medium grained, greyish-green, rare gneissic banding)

Hypersthene (up to 30%), diopside, augite, hornblende, biotite mica, plagioclase (andesine-labradorite) feldspar, orthoclase (occassionally), quartz. Accessories include apatite, magnetite, pyrite, zircon and deep red garnets (locally conspicuous in banded varieties).

Biotite gneiss (finely banded, alternating felsic and mafic layers on a cm scale)

Almandine garnet (up to 5 mm and often in clusters), quartz, oligoclase, biotite (up to 25%). Accessories include apatite, titano-magnetite and zircon.

Marble

Calcite, dolomite, spinel, phlogopite, diopside, antigorite, scapolite, sphene and forsterite.

Calc-silicate granulite (saccharoidal, light grey-green to dark green)

Diopside, scapolite, calcite, garnet, quartz, oligoclase, andesine. Accessory sphene.

Appendix B Malawi beach sand mineral processing data

Product	Head yield Wt %	Product yield Wt %	Ilmenite grade Wt %	Ilmenite recovery Wt %	Zircon grade Wt %	Zircon recovery Wt %	Rutile grade Wt %	Rutile recovery Wt %	Monazite grade Wt %	Monazite recovery Wt %
Raw material	100	-	35	100	4.1	100	0.5	100	0.6	100
Dry screening										
+2mm	0.1	0.1	-	-	-	-	-	-	-	-
-2 +1mm	4.7	4.7	-	-	-	-	-	-	-	-
-1mm +500 µm	24.8	24.8	4.5	3.1	0.3	1.8	0.8	38.4	1.3	52
-500 +250 µm	38	38	14.5	15.7	1.1	10.2	0.9	68.4	0.3	19
-250 +125 µm	32	32	76.2	69.7	6.3	49.2	0.4	25.6	1.2	64
-125 +63 µm	0.4	0.4	-	-	-	-	-	-	-	-
-63 µm	0.1	0.1	-	-	-	-	-	-	-	-
Gravity separation										
-1mm +500 µm										
Heavy product	5.5	22.2	18	2.7	1.1	2.4	2.9	30.7	0	0
Light product	19.3	77.8	0	-	0	0	0	0	0	0
-500 +250 µm										
Heavy product	30.7	80.9	48	41.6	2.2	16.3	0.8	48.5	0.3	15.2
Light product	7.3	19.1	1	0.2	0	0	0	0	0	0
Magnetic separation										
-500 +250 µm										
Heavy magnetic	10	32.4	83.9	21.5	0	0	0	0	0	0
Heavy middling	16.8	54.7	34.2	14.8	0	0	0.4	12.1	0	0
Heavy non-magnetic	3.9	12.9	3	0	19.4	16.9	5	35.8	3.3	19.7
-250 +125 µm										
Magnetic product	27.2	85.1	49.9	38.8	0	0	0	0	0.2	8.1
Middling product	2.8	8.8	51.4	4.1	11.8	8.1	1.1	6.2	7.9	37.1
Non-magnetic product	2	6.1	0.4	0	72.4	34.5	5.6	21.9	7	22.8
Electrostatic separation										
-1mm +500 µm										
Heavy cond	0.9	16.5	94.6	1.9	0	0	0	0	0	0
Heavy non-cond	4.6	83.5	1.9	0.2	2.4	2.1	0	0	0	0
-500+250 µm										0
Heavy mag cond	9	89.9	90.8	20.9	0	0	0	0	0	0
Heavy mag non-cond	1	10.1	66.4	1.7	0	0	0	0	0	0
-250 +125 µm										
Mag cond	24.3	89.4	70.4	49	0	0	0	0	0	0
Mag non-cond	2.9	10.6	45.5	3.8	3.7	2.6	0	0	0.2	1
Non-mag cond	0.03	1.3	28.6	0	16.9	0.1	40	1.9	2	0.1
Non-mag non-cond	1.97	98.7	0	0	73.4	34.5	5.1	19.7	7.1	22.8

N.B. Head yield is the proportion of the total weight of the raw material contained in the product.
Product yield is the proportion of the total weight of the processing feed material contained in the product

Appendix B Malawi beach sand mineral processing data cont/d

Product	Quartz Wt %	Feldspar Wt %	Garnet Wt %	Sphene Wt %	Iron oxide Wt %	Apatite Wt %	Staurolite Wt %	Spinel Wt %	Epidote Wt %
Raw material	25.3	4.9	19.1	1.5	7.8	0.06	0.1	0.3	0.08
Dry screening									
+2mm	-	-	-	-	-	-	-	-	-
-2 +1mm	-	-	-	-	-	-	-	-	-
-1mm +500 µm	51.3	3.5	31.1	0.9	3.8	0	0	0.2	0.9
-500 +250 µm	20.9	15.1	28.3	11.8	3.8	0.7	0.3	0.8	0.3
-250 +125 µm	0.3	0.3	4.3	6.2	4.2	0.4	0	0	0
-125 +63 µm	-	-	-	-	-	-	-	-	-
-63 µm	-	-	-	-	-	-	-	-	-
Gravity separation									
-1mm +500 µm									
Heavy product	6.3	0	50.9	2.5	12.3	0	0	0.9	3.2
Light product	83.2	10.8	4.8	0	0	0	0	0	0
-500 +250 µm									
Heavy product	1.3	1.2	41.2	0	3.6	0	0.3	0.7	0.2
Light product	57.6	31.6	6.2	0.8	1.1	0	0	0	0
Magnetic separation									
-500 +250 µm									
Heavy magnetic	0	0	10.9	0	4.4	0	0.8	0	0
Heavy middling	0.2	0	60.8	0	3.5	0	0	0.3	0.3
Heavy non-magnetic	10.2	10.9	36.5	0	2	0.8	0	5.1	0.9
-250 +125 µm									
Magnetic product	0	0	38.7	2.3	8.7	0	0	0	0
Middling product	0.7	0.7	18.9	3.8	2.9	0.8	0	0	0
Non-magnetic produc	6.6	2.6	4.6	0.3	0	0.2	0	0	0
Electrostatic separation									
-1mm +500 µm									
Heavy cond	0	0	0	5.4	0	0	0	0	0
Heavy non-cond	2.7	0.2	81.2	0.6	9.9	0	0	1.1	0
-500+250 µm									
Heavy mag cond	0	0	3.9	5.3	0	0	0	0	0
Heavy mag non-cond	0.3	0	32.3	0.4	0.6	0	0	0	0
-250 +125 µm									
Mag cond	0	0	0.1	3.1	26.4	0	0	0	0
Mag non-cond	0	0	42.1	2.1	6.2	0	0	0	0
Non-mag cond	3.4	1.7	2.2	4.2	0	0	0	0	0
Non-mag non-cond	6.7	2.6	4.7	0.2	0	0.2	0	0	0

Appendix B Malawi beach sand mineral processing data cont/d

Product	Corundum Wt %	Olivine Wt %	Columbite Wt %	Wollast-onite Wt%	Pyroxene Wt %	Cassiterite Wt %	Andalusite Wt %	Total Wt %
Raw material	0.07	0.2	0.001	0.003	0.1	0.07	0.2	100.0
Dry screening								
+2mm	-	-	-	-	-	-	-	-
-2 +1mm	-	-	-	-	-	-	-	-
-1mm +500 μm	0.3	0.3	0	0	0	0	0.8	100.0
-500 +250 μm	0	0.2	0	0	0.7	0.3	0	100.0
-250 +125 μm	0	0.2	0	0	0	0	0	100.0
-125 +63 μm	-	-	-	-	-	-	-	-
-63 μm	-	-	-	-	-	-	-	-
Gravity separation								
-1mm +500 μm								
Heavy product	0.9	1	0	0	0	0	0	100.0
Light product	0	0	0	0	0	0	1.2	100.0
-500 +250 μm								
Heavy product	0	0	0	0	0.2	0	0	100.0
Light product	0	0.9	0	0	0.8	0	0	100.0
Magnetic separation								
-500 +250 μm								
Heavy magnetic	0	0	0	0	0	0	0	100.0
Heavy middling	0	0	0	0	0.3	0	0	100.0
Heavy non-magnetic	0	1.1	0	0	0	1.8	0	100.0
-250 +125 μm								
Magnetic product	0	0.2	0	0	0	0	0	100.0
Middling product	0	0	0	0	0	0	0	100.0
Non-magnetic product	0	0.2	0	0.1	0	0	0	100.0
Electrostatic separation								
-1mm +500 μm								
Heavy cond	0	0	0	0	0	0	0	100.0
Heavy non-cond	0	0	0	0	0	0	0	100.0
-500+250 μm								
Heavy mag cond	0	0	0	0	0	0	0	100.0
Heavy mag non-cond	0	0	0	0	0	0	0	100.0
-250 +125 μm								
Mag cond	0	0	0	0	0	0	0	100.0
Mag non-cond	0	0.2	0	0	0	0	0	100.0
Non-mag cond	0	0	1	0	0	0	0	100.0
Non-mag non-cond	0	0	0	0	0	0	0	100.0

Appendix C Malaysian 'amang' sand mineral processing data

Product	Head yield Wt %	Product yield Wt %	Ilmenite grade Wt %	Ilmenite recovery Wt %	Zircon grade Wt %	Zircon recovery Wt %	Rutile grade Wt %	Rutile recovery Wt %	Monazite grade Wt %	Monazite recovery Wt %
Raw material	100	-	90.5	100	0.5	100	0.5	100	0.7	100
Dry screening										
+2mm	0.05	0.05	-	-	-	-	-	-	-	-
-2 +1mm	0.05	0.05	-	-	-	-	-	-	-	-
-1mm +500 µm	1.4	1.4	41.7	0.6	0	0	0	0	0	0
-500 +250 µm	44.6	44.6	85.9	42.3	0	0	0	0	0	0
-250 +125 µm	50.5	50.5	86.4	48.2	0.4	40.4	0.4	40.4	0.4	28.9
-125 +63 µm	3.3	3.3	-	-	-	-	-	-	-	-
-63 µm	0.1	0.1	-	-	-	-	-	-	-	-
Magnetic separation										
-500 +250 µm										
Magnetic	40.9	91.6	96.5	41.7	0	0	0	0	0	0
Non-magnetic	3.7	8.4	42.7	1.7	0	0	0.9	6.5	0	0
-250 +125 µm										
Magnetic	44.3	87.8	85.9	29.9	0.2	12.6	0	0	4.8	E
Non-magnetic	6.2	12.2	52.7	2.5	6	52.3	3.3	28.8	3.5	21.8
Electrostatic separation										
-500+250 µm										
Mag cond	36.2	88.4	97.7	36.9	0	0	0	0	0	0
Mag non-cond	4.7	11.6	90.3	4.5	0.2	1.8	0	0	0	0
Non-mag conductive	2.6	69.1	76.4	2	0	0	0.5	2.3	0	0
Non-mag non-cond	1.1	30.9	11.6	0.1	10.3	21.3	0	0	3	4.4
-250 +125 µm										
Mag cond	36.4	82.2	96.6	27.2	0	0	3.2	E	0	0
Mag non-cond	7.9	17.8	83.1	5.1	0.3	3.3	0	0	5.9	46.4

N.B. Head yield is the proportion of the total weight of the raw material contained in the product.
Product yield is the proportion of the total weight of the processing feed material contained in the product

Appendix C Malaysian 'amang' sand mineral processing data cont'd

Product	Quartz Wt %	Feldspar Wt %	Garnet Wt %	Sphene Wt %	Iron oxide Wt %	Apatite Wt %	Olivine Wt %	Columbite Wt %
Raw material	1.9	0.1	0.1	2.6	0.9	0	0	0
Dry screening								
+2mm	-	-	-	-	-	-	-	-
-2 +1mm	-	-	-	-	-	-	-	-
-1mm +500 μm	20.6	0	0.7	26.6	6.9	0	0	0
-500 +250 μm	2.5	0	0	10.9	0.7	0	0	0
-250 +125 μm	2.2	0.2	0	6.6	1	0	0	0
-125 +63 μm	-	-	-	-	-	-	-	-
-63 μm	-	-	-	-	-	-	-	-
Magnetic separation								
-500 +250 μm								
Magnetic	0.4	0	0	2.6	0.6	0	0	0
Non-magnetic	35.2	0	0	10.8	0	0	0	0
-250 +125 μm								
Magnetic	0.1	0	0	3.2	5.3	0	0	0
Non-magnetic	13.5	0.4	0.7	6.7	0.9	0.5	0	0
Electrostatic separation								
-500+250 μm								
Mag cond	0	0	0	2.3	0	0	0	0
Mag non-cond	0	0	0	4.6	4.8	0	0	0
Non-mag conductive	0.2	0	0	5.9	0.5	0	0	0.5
Non-mag non-cond	59	2	0	12	0	0	1.7	0
-250 +125 μm								
Mag cond	0	0	0	0.2	0	0	0	0
Mag non-cond	0	0	0	3.9	6.4	0	0	0

Appendix C Malaysian 'amang' sand mineral processing data cont'd

Product	Cassiterite Wt %	Andalusite Wt %	Xenotime Wt %	Total Wt %
Raw material	1.2	0.1	0	100.0
Dry screening				
+2mm	-	-	-	-
-2 +1mm	-	-	-	-
-1mm +500 µm	0	3.4	0	100.0
-500 +250 µm	0	0	0	100.0
-250 +125 µm	2.4	0	0	100.0
-125 +63 µm	-	-	-	-
-63 µm	-	-	-	-
Magnetic separation				
-500 +250 µm				
Magnetic	0	0	0	100.0
Non-magnetic	0	1.4	0	100.0
-250 +125 µm				
Magnetic	0.3	0	0.2	100.0
Non-magnetic	11.2	0.6	0	100.0
Electrostatic separation				
-500+250 µm				
Mag cond	0	0	0	100.0
Mag non-cond	0	0	0.2	100.0
Non-mag conductive	16	0	0	100.0
Non-mag non-cond	0	0.5	0	100.0
-250 +125 µm				
Mag cond	0	0	0	100.0
Mag non-cond	0	0	0.3	100.0

Appendix D Magnetic intensity generated by Carpco induced-roll high-intensity magnetic separator as a function of electromagnet current

Percentage of maximum current (Equivalent cuurent in amps in brackets)	**Magnetic field intensity** 4 mm separating gap (gauss)	2 mm separating gap (gauss)
10 (0.35)	2533	4125
20 (0.69)	5375	8000
30 (1.04)	7625	11000
40 (1.38)	9500	12750
50 (1.73)	11000	13875
60 (2.07)	12000	14625
70 (2.42)	12625	15125
80 (2.76)	13125	15375
90 (3.11)	13375	15625
100 (3.45)	13625	15688

Appendix E Magnetic field intensities (and electromagnet current) required for magnetic separation

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Malawi beach sand

-500 +250 μm

Magnetic ←|→ Middling ←|→ Non-magnetic

10,000 (4 mm / 1.5 A) — 15,700 (2 mm / 3.45 A)

-250 +125 μm

Magnetic ←|→ Middling ←|→ Non-magnetic

13,300 (4 mm / 3 A) — 15,700 (2 mm / 3.45 A)

Malaysian 'amang' sand

-500 +250μm and -250 +125μm

Magnetic ←|→ Non-magnetic

15,700 (2 mm / 3.45 A)

N.B. The magnetic field intensities are in gauss with the corresponding separating gap and electromagnet current, in amps, in brackets below.

Appendix F Electron microprobe analysis data for Malawi beach sand

Non-magnetic non-conductive product of -250 +125 μm fraction

Grain	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Total
ZIRCON													
32	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	66.63	98.19
33	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	67.31	98.60
34	31.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	65.96	97.03
37	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	67.04	98.33
38	31.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.90	98.40
40	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.23	97.51
41	31.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.23	97.30
42	31.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	65.96	97.46
43	31.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.50	98.00
50	31.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	67.31	99.51
Average	31.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	66.61	98.03
RUTILE													
31	0.21	93.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	0.27	94.76
35	1.50	91.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00	93.79
39	0.43	90.93	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	1.03	0.00	92.82
44	0.21	91.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	0.41	93.54
45	0.00	89.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.47	0.27	91.50
46	0.43	90.60	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	1.32	0.27	93.05
47	0.21	91.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.27	93.30
48	0.21	90.76	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.88	0.00	92.29
49	0.21	91.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	0.00	92.97
51	0.21	91.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.27	93.11
52	0.21	91.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	0.27	93.26
53	0.21	89.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	0.00	91.32
54	0.43	90.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	0.41	93.09
55	0.21	91.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.47	0.00	93.28
56	0.43	92.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00	93.89
57	0.43	91.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.62	0.41	94.05
Average	0.35	91.32	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	1.20	0.18	93.13

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Non-magnetic conductive product of -250 +125 μm fraction

Grain	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Total
ZIRCON													
40	31.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.36	97.86
42	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.90	98.19
44	31.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.50	98.21
45	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	65.96	97.24
46	31.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.36	97.86
47	30.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.23	97.09
48	31.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.23	97.73
49	31.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	67.04	98.11
50	31.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.77	97.84
51	31.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.36	97.65
Average	31.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.47	97.78
RUTILE													
35	0.21	91.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00	92.68
36	0.21	89.43	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.00	1.32	0.00	91.54
37	0.21	89.93	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.00	91.32
38	0.21	90.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	0.00	91.99
39	0.21	90.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.41	92.41
43	0.43	90.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.00	92.24
52	0.21	91.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.00	92.36
54	0.21	90.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	0.00	91.63
56	0.21	90.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	0.00	91.80
57	0.43	91.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	91.69
58	0.21	90.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	0.41	92.39
60	0.21	88.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	0.27	90.40
Average	0.25	90.43	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	1.03	0.09	91.87
ILMENITE													
34	0.21	52.32	0.00	0.00	36.60	0.79	0.33	0.00	0.00	0.00	0.44	0.00	90.70
41	0.21	52.49	0.00	0.00	38.17	0.79	0.83	0.00	0.00	0.00	0.00	0.00	92.49
53	0.43	52.99	0.00	0.00	35.31	1.42	0.17	0.00	0.00	0.00	0.59	0.00	90.91
55	0.43	60.17	0.57	0.00	27.45	0.00	1.16	0.00	0.00	0.00	0.88	0.00	90.66
59	0.43	53.82	0.38	0.00	34.88	0.63	0.99	0.14	0.00	0.00	0.59	0.00	91.87
Average	0.34	54.36	0.19	0.00	34.48	0.73	0.70	0.03	0.00	0.00	0.50	0.00	91.33

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Magnetic non-conductive product of -250+125μm fraction

Grain	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Nb2O5	SnO2	Ta2O5	Total
ZIRCON																
16	29.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	65.28	0.00	0.00	3.30	97.94
29	30.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.36	0.00	0.00	0.00	97.01
32	28.71	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	64.20	0.86	0.00	0.00	94.20
33	28.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.74	0.00	0.00	2.93	96.39
36	33.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	55.28	4.15	0.00	0.00	92.70
37	33.86	0.00	0.00	0.29	0.29	0.00	0.00	0.00	0.00	0.00	0.00	56.90	3.72	0.00	0.00	95.06
38	32.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	56.36	3.58	0.00	0.00	92.72
39	32.57	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	54.06	3.29	0.00	0.00	90.21
40	32.79	0.00	0.00	0.00	0.29	0.00	0.17	0.00	0.27	0.00	0.00	54.87	3.43	0.00	0.00	91.82
16C	34.29	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	56.77	3.43	0.00	0.00	94.65
16R	33.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	56.90	3.58	0.00	0.00	93.81
Av.	31.8	0.03	0	0.027	0.117	0	0.03	0	0.05	0	0	59.2	2.3668	0	0.566	94.23
ILMENITE																
10	0.00	48.97	0.00	0.00	45.61	3.17	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	98.19
11	0.00	45.97	0.00	0.00	45.46	2.53	0.33	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	94.70
12	0.00	53.82	0.00	0.00	38.89	0.63	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	93.67
13	1.29	41.95	0.57	0.00	46.32	1.74	0.83	0.28	0.27	0.00	0.44	0.00	0.00	0.00	0.00	93.69
14	0.00	48.14	0.00	0.00	47.61	3.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	98.76
15	0.00	46.63	0.00	0.00	46.89	2.69	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	96.62
17	0.00	46.47	0.00	0.00	46.18	3.17	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	96.08
18	0.64	45.63	0.00	0.00	48.47	0.63	0.33	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	96.29
19	1.50	37.44	1.14	0.00	30.45	0.79	1.49	1.82	0.00	0.12	0.00	0.00	0.00	0.00	0.00	74.75
20	0.00	47.14	0.00	0.00	45.46	2.37	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	95.31
21	0.00	48.14	0.00	0.00	45.61	1.58	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	95.66
22	0.00	52.32	0.38	0.29	36.03	0.63	0.50	0.14	0.00	0.00	0.44	0.00	0.00	0.00	0.00	90.73
23	0.00	45.80	0.00	0.00	48.75	0.79	0.50	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	96.28
24	0.00	36.27	0.00	0.00	56.47	1.11	0.33	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	94.63
25	0.00	46.97	0.00	0.00	48.75	3.17	0.33	0.00	0.27	0.00	0.59	0.00	0.00	0.00	0.00	100.08
26	0.64	47.30	0.00	0.00	45.18	3.96	0.33	0.00	0.27	0.00	0.00	0.00	0.29	0.00	0.00	97.97
27	0.86	51.48	0.00	0.00	39.03	0.95	0.33	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	93.06
28	0.00	45.46	0.00	0.00	51.18	0.79	0.33	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	98.21
30	0.00	46.47	0.00	0.00	48.18	2.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	97.18
31	0.00	46.47	0.00	0.00	48.32	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	97.64
Av.	0.25	46.4	0.104	0.015	45.44	1.95	0.33	0.1	0.11	0.01	0.19	0	0.0143	0	0	94.98

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data fro Malawi beach sand

Magnetic conductive product of -250+125μm fraction

Grain	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	V2O3	ZrO2	Nb2O5	SnO2	Ta2O5	Total
ILMENITE																
1	0.21	46.63	0.00	0.00	50.90	1.27	0.50	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.00	100.25
2	0.21	50.48	0.19	0.00	35.17	2.37	0.66	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	89.53
3	0.43	51.65	0.00	0.00	40.17	0.63	0.50	0.00	0.27	0.00	0.74	0.00	0.00	0.00	0.00	94.39
4	0.21	49.31	0.00	0.00	44.61	1.11	0.99	0.00	0.27	0.00	0.44	0.00	0.00	0.00	0.00	96.94
5	0.21	50.65	0.00	0.00	48.04	1.58	0.33	0.00	0.27	0.00	0.44	0.00	0.00	0.00	0.00	101.52
6	0.21	46.30	0.00	0.00	47.32	2.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	96.53
7	0.00	48.14	0.00	0.00	51.18	0.63	0.50	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	101.04
8	0.21	41.45	0.00	0.00	53.90	1.27	0.33	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	97.75
9	0.21	46.63	0.00	0.00	46.32	1.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	94.28
10	0.21	48.14	0.00	0.00	47.75	0.79	0.50	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	97.80
11	0.21	49.98	0.00	0.00	45.89	1.27	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	97.52
12	0.21	49.31	0.00	0.00	47.75	2.69	0.66	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	101.07
13	0.43	46.80	0.00	0.00	49.90	3.32	0.00	0.00	0.40	0.00	0.44	0.00	0.00	0.00	0.00	101.30
13a	0.00	47.47	0.00	0.00	48.90	3.64	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	100.45
14	0.00	53.99	0.00	0.00	32.17	2.37	0.17	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	89.14
15	0.86	0.33	0.00	0.00	95.08	0.00	0.17	0.00	0.27	0.00	0.29	0.00	0.00	0.00	0.00	97.00
16	0.00	45.13	0.00	0.00	51.61	1.11	0.83	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.00	99.42
17	0.86	49.31	0.19	0.00	43.03	1.90	0.66	0.00	0.27	0.00	0.44	0.00	0.00	0.00	0.00	96.66
18	0.00	48.81	0.00	0.00	47.32	3.80	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	100.20
19	0.00	50.15	0.00	0.00	46.89	1.74	0.00	0.00	0.27	0.00	0.59	0.00	0.00	0.00	0.00	99.64
20	0.00	52.82	0.00	0.00	38.60	1.11	0.33	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	93.30
21	0.00	47.97	0.00	0.00	48.47	2.85	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	99.88
Av.	0.21	46.43	0.02	0.00	48.23	1.78	0.33	0.00	0.12	0.00	0.40	0.00	0.00	0.00	0.00	97.53

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Non-magnetic non-conductive product of -250+125 μm fraction

Grain	CaO	P2O5	La2O3	CeO2	Pr6O11	Nd2O3	Sm2O3	Eu2O3	Gd2O3	Dy2O3	Ho2O3	Er2O3	Y2O3	SiO2	Al2O3	ThO2	UO2	Total
MONAZITE (rims)																		
1	0.70	28.87	15.48	31.07	2.30	11.08	1.86	0.00	1.38	0.00	0.00	0.00	0.00	0.64	0.00	5.92	0.00	99.30
2	0.70	28.64	16.18	30.71	2.66	10.26	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.74	0.00	99.45
3	0.70	27.50	15.48	29.97	1.69	8.75	1.62	0.00	1.38	0.00	0.00	0.00	0.00	1.50	0.00	9.10	0.00	97.70
4	1.68	28.41	12.67	28.00	3.62	12.13	1.74	0.00	1.73	0.00	0.00	0.00	0.00	0.86	0.00	10.58	0.00	101.43
5	0.84	25.43	13.37	26.90	1.57	8.40	0.00	1.16	2.19	0.00	0.00	0.00	0.00	1.71	0.00	9.33	0.00	90.90
6	0.98	27.27	15.48	28.00	2.42	8.98	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	12.06	0.00	98.41
7	0.56	27.96	15.48	30.71	3.02	10.03	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	6.60	0.00	97.15
8	0.70	27.50	17.47	30.95	2.78	9.45	1.16	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.37	0.00	97.45
9	1.40	27.73	13.96	27.27	2.54	9.80	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	12.86	0.00	98.33
10	0.98	28.64	16.54	30.95	3.38	10.26	1.39	0.00	1.38	0.00	0.00	0.00	0.00	0.43	0.00	5.80	0.00	99.76
11	0.84	21.08	12.08	24.20	2.30	7.58	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	6.94	0.00	78.02
11a	0.84	27.04	15.01	30.58	3.26	9.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	8.99	0.00	97.02
12	1.26	25.66	9.97	23.83	2.42	9.33	1.62	0.00	1.27	0.00	0.00	0.00	2.16	2.57	3.22	15.93	0.00	99.24
13	0.98	28.64	15.72	29.60	1.81	9.68	1.74	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	7.40	0.00	96.64
14	0.70	28.18	16.30	30.83	2.66	9.68	1.86	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.85	0.00	99.35
15	1.54	26.35	12.43	25.30	1.81	8.28	1.28	0.00	0.00	0.00	0.00	0.00	0.51	2.14	0.76	16.50	0.00	96.90
16	0.56	27.27	15.95	31.56	3.02	10.03	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	9.56	0.00	101.06
17	0.70	27.50	14.43	30.09	3.38	10.96	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	8.19	0.00	98.26
18	0.28	28.64	14.54	30.34	1.81	12.01	1.62	0.00	0.00	0.00	0.00	0.00	0.64	0.86	0.95	4.10	0.00	95.79
19	0.70	28.18	12.31	28.62	3.62	12.13	2.32	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	5.69	0.00	94.44
20	1.12	25.89	15.83	28.49	0.00	8.40	1.04	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	7.85	0.00	90.35
21	1.68	28.41	12.08	26.53	2.42	11.78	2.20	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	10.01	0.00	95.76
22	0.84	26.81	13.25	28.99	3.26	11.55	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	10.81	0.00	98.61
23	1.54	27.96	12.31	27.76	3.14	11.31	1.97	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	10.70	0.00	97.55
24	0.84	27.04	13.60	27.51	2.66	10.15	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	10.92	0.00	95.62
25	0.84	27.27	15.13	29.85	2.66	10.38	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.74	0.00	96.65
26	0.28	28.41	20.05	31.20	2.30	8.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	5.23	0.00	97.06
27	0.70	28.64	15.25	30.34	2.17	11.55	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	4.78	0.00	95.71
28	0.42	29.79	16.18	32.18	3.38	11.66	2.32	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	1.37	0.00	97.52
29	1.12	26.12	11.85	26.16	2.30	11.31	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	4.89	0.00	86.21
30	2.24	27.96	14.54	27.27	2.78	9.80	1.51	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	10.81	0.00	97.76
Av	0.94	27.45	14.55	28.89	2.55	10.16	1.45	0.04	0.30	0.00	0.00	0.00	0.11	1.23	0.16	8.47	0.00	96.30

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Non-magnetic non-conductive product of -250+125 μm fraction

Grain	CaO	P2O5	La2 O3	Ce O2	Pr6 O11	Nd2 O3	Sm2 O3	Eu2 O3	Gd2 O3	Dy2 O3	Ho2 O3	Er2 O3	Y2 O3	SiO2	Al2 O3	ThO2	UO2	Total
MONAZITE (cores)																		
1	0.56	28.64	15.60	33.53	3.50	11.31	1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	5.12	0.00	100.65
2	0.70	27.27	14.89	29.85	3.26	10.38	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	9.44	0.00	98.69
3	0.56	27.27	15.95	30.46	3.26	10.03	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	9.56	0.00	100.31
4	1.82	28.87	12.90	27.88	2.66	11.31	1.51	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	10.58	0.00	98.18
5	1.40	28.18	13.49	28.49	2.17	9.91	1.97	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	10.01	0.00	96.71
6	1.12	28.64	17.01	28.86	3.02	9.10	1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	8.19	0.00	98.54
7	0.70	27.96	15.48	30.58	3.02	10.26	1.04	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	8.76	0.00	99.09
8	0.70	27.27	17.01	30.58	2.05	8.75	1.62	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	7.40	0.00	96.88
9	1.40	27.73	12.67	26.16	2.78	10.15	1.97	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	14.00	0.00	98.13
10	0.70	28.64	17.71	31.69	2.66	9.33	1.39	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	5.23	0.00	98.00
11	0.84	27.73	14.07	29.60	3.02	10.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	9.10	0.00	96.03
12	0.84	26.35	11.96	28.00	3.02	10.26	1.39	0.00	0.00	0.00	0.00	0.00	0.64	2.14	0.95	13.31	0.00	98.87
13	0.56	28.18	14.89	29.72	2.90	10.85	1.74	0.00	0.00	0.00	1.61	1.26	0.00	1.07	0.00	8.53	0.00	101.32
14	0.56	27.73	15.60	30.09	2.78	9.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	9.44	0.00	97.71
15	1.54	26.35	12.67	26.28	2.30	8.16	1.74	0.00	0.00	0.00	0.00	0.00	0.64	2.36	0.95	16.39	0.00	99.36
16	0.56	27.04	15.60	29.97	1.93	9.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.93	0.00	10.47	0.00	97.06
17	0.56	27.50	14.19	28.99	1.57	10.96	1.62	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	8.53	0.00	95.43
18	0.00	29.10	14.31	30.58	3.87	12.48	2.09	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	3.76	0.00	97.04
19	0.84	27.27	13.14	27.88	2.42	11.43	2.20	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	8.08	0.00	94.32
20	1.26	25.66	15.95	29.23	2.54	9.10	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	8.88	0.00	95.61
21	1.40	28.87	12.67	28.62	3.87	12.01	2.20	0.00	1.38	0.00	0.00	0.00	0.00	0.64	0.00	9.33	0.00	101.00
22	0.98	28.18	14.54	28.99	3.38	11.08	2.20	0.00	1.73	0.00	0.00	0.00	0.00	0.86	0.00	7.74	0.00	99.68
23	1.12	29.33	13.60	28.25	3.38	10.85	2.20	0.00	2.31	0.00	0.00	0.00	1.52	0.00	2.27	4.32	0.00	99.16
24	0.98	25.66	13.84	24.81	0.00	8.28	1.62	0.00	0.00	0.00	0.00	0.00	0.64	2.14	0.95	12.63	0.00	91.55
25	0.84	27.73	15.48	29.23	2.05	10.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	7.51	0.00	94.31
26	4.34	22.23	9.15	16.21	0.00	5.72	0.00	2.20	3.00	0.00	0.00	0.00	0.64	2.36	0.95	8.08	0.00	74.86
27	1.12	29.10	13.60	28.86	2.90	11.08	1.28	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.95	5.12	1.13	95.78
28	0.00	29.56	18.53	35.49	3.26	10.03	1.86	1.27	1.73	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	101.95
29	1.26	29.33	13.72	31.32	3.99	12.71	2.90	1.62	1.50	0.00	0.00	0.00	0.00	0.43	0.00	6.37	0.00	105.15
30	2.24	28.41	13.60	28.13	2.54	10.85	1.62	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	8.53	0.00	96.57
Av.	1.05	27.73	14.46	28.94	2.67	10.23	1.46	0.17	0.39	0.00	0.05	0.04	0.16	1.16	0.23	8.48	0.04	97.26
Overall average																		
	1.00	27.58	14.50	28.92	2.61	10.19	1.46	0.10	0.34	0.00	0.03	0.02	0.13	1.20	0.20	8.48	0.02	96.78
Average of analysis over 95%																		
	0.95	27.94	14.76	29.45	2.79	10.35	1.51	0.06	0.30	0.00	0.03	0.02	0.13	1.15	0.19	8.58	0.02	98.24

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Non-magnetic conductive product of -250+125 μm fraction

Grain	CaO	P2O5	La2O3	CeO2	Pr6O11	Nd2O3	Sm2O3	Eu2O3	Gd2O3	Dy2O3	Ho2O3	Er2O3	Y2O3	SiO2	Al2O3	ThO2	UO2	Total
MONAZITE (rims)																		
1	0.56	26.81	15.13	29.97	2.30	9.10	1.62	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	10.13	0.00	97.33
2	0.28	19.02	8.21	18.18	1.57	6.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.93	0.76	5.12	0.00	61.71
2a	0.84	25.21	12.55	27.63	2.42	9.45	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.71	1.89	6.60	0.00	89.81
3	0.70	27.27	15.83	29.60	2.78	9.21	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	8.42	0.00	96.71
4	0.98	27.73	13.49	27.76	2.54	10.15	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	8.65	0.00	94.00
5	0.56	27.50	15.95	30.58	3.02	8.98	1.74	1.39	1.38	0.00	0.00	0.00	0.00	1.07	0.00	6.37	0.00	98.55
6	0.70	26.58	14.66	29.97	3.38	10.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	8.19	0.00	95.38
7	0.84	28.41	11.38	25.79	3.02	11.31	2.55	0.00	2.07	1.49	0.00	0.00	1.91	0.86	0.00	6.71	0.00	96.35
8	1.26	27.04	15.13	30.09	3.26	10.15	1.51	0.00	0.00	0.00	0.00	0.00	0.89	1.29	0.00	3.41	0.00	94.02
9	0.70	26.81	14.07	29.60	3.14	10.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	10.24	0.00	96.45
10	1.26	28.18	11.85	26.77	3.02	10.85	1.16	0.00	1.38	0.00	0.00	0.00	0.64	1.29	0.19	10.01	0.00	96.60
11	0.42	27.96	15.01	29.85	3.26	10.96	1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	7.05	0.00	97.11
12	0.42	28.18	15.95	30.58	2.78	9.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	5.46	0.00	93.78
13	0.84	26.58	12.43	27.88	3.50	10.85	1.74	0.00	1.50	0.00	0.00	0.00	0.89	1.71	0.76	6.26	0.00	94.94
15	0.28	25.21	17.01	29.23	1.93	8.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.93	0.00	10.35	0.00	94.34
16	0.42	24.98	11.85	27.14	2.90	10.26	1.97	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	4.55	0.00	85.36
16a	1.12	20.62	10.09	20.76	0.00	6.18	0.00	1.16	0.00	0.00	0.00	0.00	0.00	2.57	3.60	4.89	0.00	70.98
16b	0.98	20.85	9.50	20.88	1.93	7.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.57	3.03	4.21	0.00	71.30
17	0.84	27.73	15.72	29.35	2.30	8.98	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	7.05	0.00	93.98
18	0.56	27.73	15.95	30.83	3.02	10.15	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.49	0.00	97.07
19	0.70	27.96	15.01	30.21	3.26	11.08	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	7.17	0.00	97.74
20	0.98	24.98	13.37	25.79	3.02	8.75	1.39	0.00	0.00	0.00	0.00	0.00	0.89	1.93	1.14	12.52	0.00	94.75
21	0.70	28.18	15.60	29.48	2.54	9.68	2.20	0.00	1.50	0.00	0.00	0.00	0.00	0.64	0.00	5.80	0.00	96.33
22	0.56	24.98	14.54	28.13	2.66	8.98	1.51	1.27	1.73	0.00	0.00	0.00	0.00	1.50	0.38	8.31	0.00	94.54
23	0.56	27.73	15.60	30.58	2.78	9.33	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.28	0.00	96.65
24	0.70	27.27	15.60	30.58	4.11	10.15	0.00	0.00	0.00	0.00	0.00	1.14	0.00	1.29	0.00	7.97	0.00	98.80
25	0.84	26.12	12.90	28.62	3.62	10.26	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	10.58	0.00	95.84
26	0.70	26.58	14.54	29.85	2.90	9.45	1.97	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	10.13	0.00	97.83
27	1.40	28.87	10.79	26.77	3.87	12.01	2.32	0.00	1.38	0.00	0.00	0.00	0.00	0.43	0.00	8.42	0.00	96.27
28	0.42	27.27	16.77	30.46	2.54	8.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.71	0.00	93.87
30	1.12	28.41	13.60	28.86	2.54	10.26	1.39	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	7.85	0.00	94.69
31	0.42	27.50	16.65	30.71	2.42	9.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.14	0.00	94.01
32	0.42	26.12	15.25	28.74	2.17	9.45	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	9.33	0.00	94.59
33	3.78	19.48	8.91	6.51	1.21	9.10	0.00	4.05	5.19	0.00	0.00	0.00	1.02	6.43	5.11	3.76	0.00	74.53
Av	0.82	26.23	13.85	27.58	2.70	9.57	1.11	0.23	0.47	0.04	0.00	0.03	0.18	1.51	0.50	7.42	0.00	92.24

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Non-magnetic conductive product of -250+125 μm fraction

Grain	CaO	P2O5	La2 O3	Ce O2	Pr6 O11	Nd2 O3	Sm2 O3	Eu2 O3	Gd2 O3	Dy2 O3	Ho2 O3	Er2 O3	Y2 O3	SiO2	Al2 O3	ThO2	UO2	Total
MONAZITE (cores)																		
1	0.70	26.81	15.25	29.97	2.90	9.10	1.04	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	9.79	0.00	97.05
2	0.56	27.73	15.25	30.58	3.62	10.03	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.17	0.00	97.50
3	0.70	27.73	15.48	29.97	2.54	8.98	1.16	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	8.88	0.00	96.50
4	1.12	27.50	14.43	28.62	2.90	10.03	1.97	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	9.22	0.00	96.85
5	0.56	27.73	15.60	28.13	0.00	8.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	7.74	0.00	89.45
5a	0.70	27.96	15.36	29.97	3.14	9.68	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	7.28	0.00	96.55
6	0.70	27.04	15.48	30.95	2.66	9.56	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	7.28	0.00	96.02
7	1.12	28.41	13.60	28.49	2.66	11.43	3.01	1.27	1.50	0.00	0.00	0.00	0.00	0.64	0.00	7.05	0.00	99.21
8	1.54	26.35	15.13	30.58	3.62	10.96	2.09	0.00	1.84	0.00	0.00	0.00	1.02	1.07	0.00	3.07	0.00	97.28
9	0.84	26.35	13.84	27.88	2.30	9.80	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.93	0.00	12.63	0.00	96.95
10	1.26	27.50	13.02	28.00	3.14	11.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	10.24	0.00	95.76
11	0.56	26.81	16.07	30.46	2.78	10.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	8.31	0.00	96.65
12	0.56	28.18	16.77	31.56	3.26	9.45	1.86	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	5.69	0.00	98.41
13	0.84	27.50	13.02	28.74	2.90	10.96	1.97	0.00	1.61	0.00	0.00	0.00	1.02	1.29	0.00	6.49	0.00	96.33
14	0.00	0.00	26.15	31.56	2.17	5.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	65.47
15	0.56	28.18	17.01	31.56	3.14	10.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	4.32	0.00	95.92
16	0.42	27.73	15.48	30.58	2.42	10.26	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	5.23	0.00	94.47
17	0.84	28.41	15.60	28.62	2.30	9.56	1.28	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	7.85	0.00	95.31
18	0.42	27.73	15.72	29.60	3.02	10.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.71	0.00	95.00
19	0.70	27.73	13.02	28.13	2.54	10.50	1.97	0.00	1.38	0.00	0.00	0.00	0.00	1.07	0.00	7.51	0.00	94.54
20	0.98	25.66	12.90	25.79	2.54	8.51	0.00	0.00	0.00	0.00	0.00	0.00	1.14	1.93	0.00	12.52	0.00	91.98
21	0.56	28.41	15.60	30.21	3.02	10.50	1.28	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	5.12	0.00	95.56
22	0.56	26.81	16.07	30.71	2.90	9.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.97	0.00	95.97
23	0.56	27.73	14.78	29.48	2.54	11.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.83	0.00	94.52
24	0.56	27.27	15.36	29.60	3.26	10.38	1.74	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	7.40	0.00	96.64
25	0.70	25.89	13.25	27.51	2.78	9.91	1.86	0.00	0.00	0.00	0.00	0.00	0.00	1.71	0.00	11.27	0.00	94.89
26	0.70	26.58	14.54	29.97	2.66	8.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	8.99	0.00	93.80
27	1.26	28.87	11.96	26.65	2.78	12.01	2.55	0.00	1.50	0.00	0.00	0.00	0.00	0.43	0.00	8.76	0.00	96.78
28	0.56	26.81	15.95	29.72	2.42	9.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.00	7.51	0.00	93.47
29	0.98	27.96	14.43	28.49	2.54	10.38	1.51	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	9.10	0.00	96.24
30	0.98	27.50	13.14	28.74	3.26	10.50	1.97	0.00	1.50	0.00	0.00	0.00	0.00	0.86	0.00	7.97	0.00	96.40
31	0.56	27.96	15.95	29.97	2.54	10.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.14	0.00	94.45
32	0.42	26.35	13.96	28.37	2.78	10.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.93	0.00	9.44	0.00	93.75
33	0.98	23.83	14.07	24.20	2.54	7.70	1.04	0.00	0.00	0.00	0.00	0.00	0.00	3.21	0.00	18.55	0.00	96.12
Av.	0.74	26.50	15.09	29.22	2.72	9.92	1.03	0.04	0.27	0.00	0.00	0.00	0.09	1.20	0.00	7.94	0.00	94.76
Overall averages																		
	0.78	26.36	14.47	28.40	2.71	9.75	1.07	0.13	0.37	0.02	0.00	0.02	0.14	1.35	0.25	7.68	0.00	93.50
Average of analyses over 95%																		
	0.79	27.46	14.65	29.31	3.01	10.18	1.33	0.07	0.40	0.04	0.00	0.03	0.12	1.18	0.00	8.15	0.00	96.72

N.B. Data are weight percentages as determined by EPMA.

Appendix F Electron microprobe analysis data for Malawi beach sand

Magnetic non-conductive product of -250+125 μm fraction

Grain	CaO	P2O5	La2O3	CeO2	Pr6O11	Nd2O3	Sm2O3	Eu2O3	Gd2O3	Dy2O3	Ho2O3	Er2O3	Y2O3	SiO2	Al2O3	ThO2	UO2	Total
MONAZITE (rims)																		
1	0.56	20.62	10.79	20.88	1.81	6.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	1.32	4.44	0.00	67.99
2	1.40	24.98	11.96	25.18	2.54	9.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.71	1.14	7.51	0.00	86.33
3	0.70	27.96	15.13	29.97	2.30	9.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	6.94	0.00	92.94
4	1.40	29.10	11.96	26.65	2.30	11.43	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.28	0.00	91.98
5	1.26	29.10	12.43	27.88	3.62	11.78	2.09	0.00	1.38	0.00	0.00	0.00	0.00	0.64	0.00	8.65	0.00	98.84
6	0.28	26.12	12.55	25.79	3.02	10.26	1.28	0.00	1.73	0.00	0.00	0.00	0.64	1.07	0.00	5.23	0.00	87.97
6a	0.56	27.27	14.07	28.62	2.54	10.73	1.62	0.00	0.00	0.00	0.00	0.00	1.27	1.07	0.00	5.23	0.00	92.99
8	0.98	28.18	15.25	28.37	2.17	9.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	9.22	0.00	94.58
7	0.84	28.41	13.37	28.62	2.90	11.78	2.32	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	4.89	0.00	93.78
9	1.12	26.35	10.20	23.34	2.42	9.56	1.97	0.00	0.00	0.00	0.00	0.00	1.52	1.29	0.00	10.13	0.00	87.90
Av.	0.91	26.81	12.77	26.53	2.56	10.00	1.11	0.00	0.31	0.00	0.00	0.00	0.34	0.99	0.25	6.95	0.00	89.53
MONAZITE (cores)																		
1	0.42	26.12	13.49	25.55	1.57	8.28	1.28	0.00	1.38	0.00	0.00	0.00	0.00	0.86	0.00	5.69	0.00	84.63
1a	0.42	25.66	13.84	26.16	1.93	7.81	1.28	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	5.23	0.00	83.41
1b	0.56	25.43	12.78	26.28	2.54	9.21	1.39	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	6.49	0.00	85.76
2	0.70	27.50	13.25	26.41	2.42	10.85	2.32	0.00	0.00	0.00	1.26	0.00	0.00	0.43	0.00	4.55	0.00	89.68
2a	0.84	27.04	13.72	25.55	1.81	10.26	1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	5.23	0.00	86.63
3	0.70	27.73	15.36	29.97	2.66	10.15	1.28	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	6.94	0.00	95.64
4	1.12	28.41	13.60	27.27	2.54	10.96	1.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.92	0.00	91.79
5	0.98	29.79	14.43	28.37	3.14	11.31	1.97	0.00	1.50	0.00	0.00	0.00	0.64	0.00	0.00	3.98	0.00	96.11
6	0.98	28.18	12.43	26.90	3.75	11.55	1.51	0.00	1.50	0.00	0.00	0.00	0.76	0.43	0.00	4.78	0.91	93.67
7	0.70	28.64	14.43	29.23	2.54	11.31	1.28	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	3.64	0.00	92.20
8	0.84	27.50	14.78	27.88	2.30	9.21	1.51	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	9.10	0.00	94.19
9	1.26	25.89	9.38	22.84	2.78	9.10	1.74	0.00	1.84	0.00	0.00	0.00	1.78	1.50	0.00	11.61	1.13	90.86
Av.	0.79	27.32	13.46	26.87	2.50	10.00	1.60	0.00	0.52	0.00	0.11	0.00	0.26	0.68	0.00	6.10	0.17	90.38
Average of analsyses over 95%																		
	0.98	28.87	14.07	28.74	3.14	11.08	1.78	0.00	0.96	0.00	0.00	0.00	0.21	0.50	0.00	6.52	0.00	96.86

N.B. Data are weight percentages as determined by EPMA.

Appendix G Rare earth element normalization values

Rare earth element	Chondrite value
La	0.310
Ce	0.808
Pr	0.122
Nd	0.600
Sm	0.195
Eu	0.0735
Gd	0.259
Tb	0.0474
Dy	0.322
Ho	0.0718
Er	0.210
Tm	0.0324
Yb	0.209
Lu	0.0322

N.B. Chondrite normalization values recommended by Boynton (1984). To normalize divide rock value by chondrite value.

Appendix H Average REE composition (atomic percent) of monazite

REE	A	B	C	D	E	F	G	H	I	J
La	21.2	24.2	25.2	29.7	28.3	20.5	21.5	25.5	25.4	24.1
Ce	45.4	48.1	43.5	51.8	49.3	46.0	48.2	48.5	48.5	46.9
Pr	5.8	5.3	8.5	4.3	4.8	5.4	5.3	4.7	5.1	5.2
Nd	19.3	17.5	20.2	12.5	1.2	22.0	21.0	18.0	17.7	19.1
Sm	5.1	2.7	2.1	1.3	1.7	3.5	2.0	2.7	2.4	3.1
Eu	-	-	0.1	-	-	0.6	-	0.1	0.1	-
Gd	2.5	1.4	0.2	0.1	0.4	1.9	0.8	0.5	0.7	1.7
Tb	0.1	0.1	0.1	-	-	-	-	-	-	-
Dy	0.4	0.5	0.1	-	0.1	0.1	0.3	-	-	-
Ho	-	-	-	-	0.1	-	-	-	-	-
Er	0.1	0.1	-	0.3	0.1	-	-	-	-	-
Tm	-	-	-	-	-	-	-	-	-	-
Yb	0.1	0.1	-	-	-	-	-	-	-	-
Lu	-	-	-	-	-	-	-	-	-	-
100 Y / (Y+Ln)	(3.8)	(3.3)	(2.6)	(4.4)	(0.8)	(1.55)	(4.0)	(0.2)	(0.2)	(0.2)
Σ = La+Ce+Pr	72.4	77.6	77.2	85.8	82.4	71.9	75.0	78.7	79.0	76.2
La-Nd	91.7	95.1	97.4	98.3	97.6	93.9	96.0	96.7	96.7	95.3
Sm-Ho	8.1	4.7	2.6	1.4	2.3	6.1	4.0	3.3	3.2	4.8
Er-Lu	0.2	0.2	-	0.3	0.1	-	-	-	-	-
RE_2O_3, wt.%	58.9	56.5	55.3	-	-	61.6	-	59.3	59.0	59.8
ThO_2, wt.%	9.0	6.3	6.0	-	2.1	0.9	7.9	8.6	8.2	6.5
U_3O_8, wt.%	1.18	0.62	-	-	-	-	1.16	0.02	-	-

N.B. The REE compositions listed are in atomic percent (except where stated), ie the La figures are the percentage that they represent of the total Lanthanides (Ln) present. The samples are as follows: A= av. granitic pegmatite, B= av. granites, granodiorites and quartz monzonites, C= av. gneiss, D= av. alkalic rocks and alkalic pegmatites, E= av. carbonatites, F= av. dark monazites, G=av. placers, H= av. non-conductive, non-magnetic Malawi beach sand (MBS), I= av. conductive , non-magnetic MBS and J= av. non-conductive, magnetic MBS. Data from Fleischer et al, 1991.