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Mineral Reconnaissance Programme

Industrial mineral potential of andalusite and garnet in the Scottish Highlands

Department of Trade and Industry

MRP Report 142

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BRITISH GEOLOGICAL SURVEY

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CONTENTS

FIGURES

TABLES

SUMMARY

Following the completion of a desk review of andalusite and garnet occurrences in the Scottish Highlands, a programme of field sampling, laboratory characterisation and mineral processing was undertaken to identify their potential for use as industrial raw materials. Bulk samples were collected from selected occurrences of andalusite schists in the Dalradian metasedimentary rocks of north-east Scotland, and from garnetiferous Lewisian, Moine and Dalradian rocks and beach sands at sites throughout the Highlands.

Petrographic studies of the andalusite samples showed that andalusite mostly occurs as large or small, euhedral or anhedral grains. The euhedral grains have a well developed crystal structure and contain few inclusions, and it is these characteristics which influence their quality and suitability for mineral processing. Petrographic analyses of the garnet samples showed that garnets occur in a range of grain size, form and colour and contain variable amounts of inclusions. Some garnet samples were relatively free of inclusions, whereas others were so full of inclusions that they have a honeycomb appearance. The former type are the preferred raw material.

Following petrographical analysis, five andalusite samples and nine garnet samples were chosen for laboratory mineral processing trials whose aim was to produce concentrates of the target minerals with high grades and recoveries. A range of techniques was employed on both andalusite and garnet samples using a combination of magnetic and gravity separation. The results enabled the most promising samples to be identified and these were subject to pilot-scale mineral processing trials using a mineral spiral to produce mineral concentrates.

The andalusite concentrates produced by laboratory mineral processing showed that concentrates with high andalusite contents and moderate recoveries could be obtained from some samples. The results produced by pilot-scale processing were mostly not encouraging, yielding concentrates with low andalusite contents and recoveries. The concentrates produced by both laboratory and pilot-scale mineral processing do not match the chemical specifications required for industrial grade andalusite. The Al_2O_3 and Fe_2O_3 contents, which are particularly critical, are respectively too low and too high. The andalusite-bearing rocks of north-east Scotland are therefore considered to have a low potential and do not warrant further investigation.

The garnet concentrates produced by laboratory mineral processing trials mostly contained high garnet contents and high recoveries. Pilot-scale processing also resulted in concentrates with high garnet contents and recoveries. Concentrates produced by both laboratory and pilot-scale processing gave densities of 4 g/cm^3, indicating their suitability as industrial-grade garnet products. The more promising samples were collected from garnet-mica schists of Dalradian age at locations from near Huntly in north-east Scotland to Loch Fyne in the south-west Highlands. Further investigations are recommended to prove the scale of resources and to carry out more detailed mineral processing and quality assessments.

INTRODUCTION

The presence of industrial minerals such as talc, andalusite, garnet and graphite in the Scottish Highlands is well known, but there is little published information on their quality or quantity. The objective of this work was to increase knowledge of the industrial mineral potential of the Highlands by evaluating selected occurrences of andalusite and garnet from a determination of their mineralogical character, their grade (mineral content) and their potential for beneficiation to meet specifications for new and existing markets.

Previous Studies

Information on the occurrence of andalusite and garnet in the Scottish Highlands is given in the memoirs and maps of the British Geological Survey (BGS), and additional information is held in the Survey's records and archives. Some information on the garnet potential of several areas of western Scotland is contained within regional reconnaissance studies carried out between 1969 and 1971 by Robertson Research Co. Ltd. for the Highlands and Islands Development Board (Robertson Research Co. Ltd., 1969; Chatten et al., 1971; McKenzie and Pattrick, 1971).

Minerals planning and development framework

The central and north-west parts of the Scottish Highlands contain a number of National Scenic Areas and Forest Parks, but the eastern part is largely free of these designations. Appropriate development is encouraged by Highlands and Islands Enterprise in parts of the region, to counteract depopulation and lack of employment opportunities. Agriculture is the principal land-use on the lower ground with upland areas given over to rough grazing, forestry, grouse moor and deer forest. Road and rail communications are generally better in the east than the west. Access by sea is possible at numerous points.

Andalusite

Andalusite is a member of the sillimanite group of minerals which also includes kyanite and sillimanite. The three minerals are polymorphs of Al_2SiO_5 and have slightly different physical properties. The most important use of andalusite is in the manufacture of high alumina refractories. Mullite is formed by the calcination of andalusite at high temperatures (1350–1550^{0}C) and combines high strength at high temperatures with resistance to physical and chemical erosion. Andalusite bricks have a range of applications in blast furnaces, in steel transfer ladles and in cement kilns and incinerators. Conversion of andalusite to mullite is accompanied by a small volume increase, resulting in the sealing of joints between refractory bricks and improved resistance to slag and metal penetration.

Andalusite has an ideal composition of 62.9% Al_2O_3 and 37.1% SiO_2 but inclusions within the crystal structure are commonly a major source of contamination. Impurities include iron oxides, ilmenite and carbon in the crystal lattice and micaceous impurities and quartz intimately associated with the andalusite. All these impurities are difficult to remove. It is therefore essential that andalusite raw materials should be relatively pure and free of inclusions. Enquiries with UK consumers of andalusite indicate that typical specifications require >59% Al_20_3 and <0.9% Fe_20_3, although specifications are not always exact and there are generally agreements with individual suppliers.

UK imports of aluminosilicate minerals appear under the trade heading 'andalusite, kyanite and sillimanite'. Total imports under this heading were 56,702 tonnes in 1995, valued at £7,487,000. Large producers of andalusite are South Africa (by far the largest source) and France. Most UK imports of 'sillimanite minerals' are believed to be andalusite. Extraction of andalusite is usually by normal hard rock quarrying methods and liberation of the andalusite involves crushing, screening and sophisticated processing techniques including dense-media separation and magnetic separation.

Andalusite is formed by regional or thermal metamorphism of aluminous shales. Andalusite schists are widely recorded in the Dalradian metasedimentary rocks of north-east Scotland (Huntly-Aberdeen-Banff area). Most occurrences are in rocks of the Southern Highlands Group (Upper Dalradian).

Garnet

Garnets are a group of complex silicate minerals; the most common garnet species are almandine ($Fe_3Al_2Si_3O_{12}$) and pyrope ($Mg_3Al_2Si_3O_{12}$). They occur chiefly in metamorphic rocks although they can also occur as detrital grains in sediments due to their resistance to mechanical abrasion and chemical attack. Garnets contain variable amounts of elements such as Al, Ca, Cr, Fe, Mg, Mn and Ti which may affect their density, hardness and colour. Density ranges between 3.2 and 4.3, depending on chemical composition.

As a commercial product garnet is hard, chemically inert and non-carcinogenic. These properties make garnet very useful as an abrasive, although modest quantities are also used in water filtration. Garnet is currently more expensive (garnet price: £140–£160 tonne ex-UK works) than alternative blasting abrasive media (e.g. copper slag and coal slag) and its use is presently confined to applications where the superior technical qualities of garnet are required. Increasing usage of garnet as a blasting abrasive will be dependent on a reduction in the relative price differential between garnet and alternative abrasives. Specifications for garnet focus upon particle-size distribution, density (4 g/cm^3, ideally), particle shape and hardness (6.5 to 7.5 Mohs).

Hard-rock garnet deposits are generally blasted, crushed and screened before processing, whilst alluvial and placer deposits are usually extracted by dredging or by drag-lines followed by screening. Garnet is recovered using processing techniques such as gravity separation, froth flotation, magnetic separation and air classification.

Garnet is a relatively common mineral in the metamorphic rocks of the Scottish Highlands, and garnet-rich rocks are developed locally in Lewisian gneisses and amphibolites, Moine schists and Dalradian schists, notably the Ben Lui Schist and its equivalents and in parts of the Southern Highland Group. Garnet also occurs in certain beach sands, particularly where the coastal exposures are garnetiferous.

SAMPLE COLLECTION

Potential sites for sampling andalusite and garnet in the Scottish Highlands were identified from maps, memoirs, reports and files held in the BGS archives together with the results of recent field mapping (Tables 1 and 2). Sample collection was divided into two phases. During the first phase andalusite occurrences in north-east Scotland considered to have the greatest potential were visited and sampled. The second phase involved the sampling of garnet-bearing rocks from the more promising sites in the Highlands and the collection of bulk samples of andalusite at the two sites selected for pilot-scale mineral processing in north-east Scotland. In addition, two samples were taken from drillcore of garnet-bearing anorthosite from Harris and further bulk samples collected from five sites for pilot-scale mineral processing of garnet.

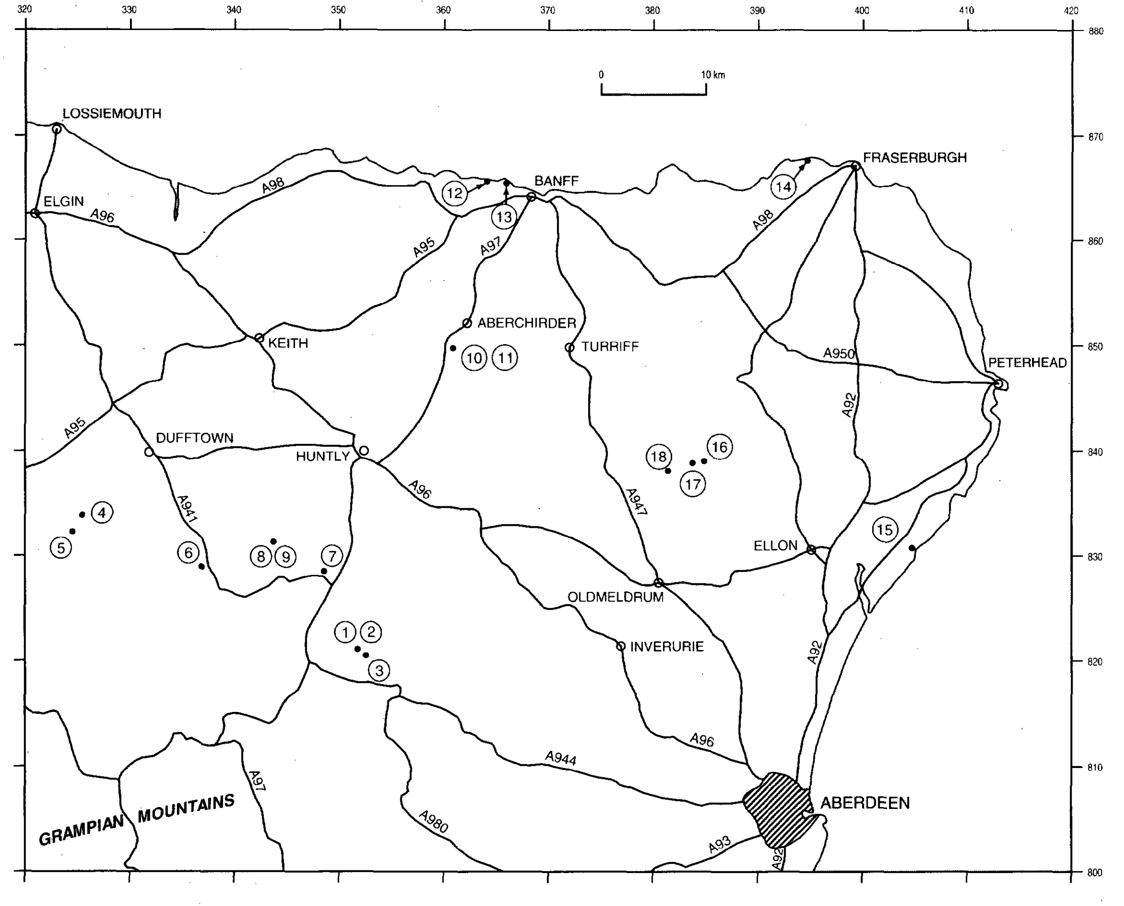

Figure 1 Location of andalusite samples in north-east Scotland

Eighteen samples (Figure 1) of andalusite-bearing rock (from 25 localities visited) and nineteen samples (Figure 2) of garnet-bearing rock (from 28 localities visited) were collected. Due to financial constraints, not all sites identified as potential targets for andalusite were sampled, although the most promising localities (sites 1–20, Table 1) were all visited. Each sample weighed approximately 25 kg and consisted of rock lumps, 75–250 mm in diameter. A further 25–50 kg was collected for those samples identified for pilot scale mineral processing (Figures 3, 4 and 5). Andalusite samples were numbered with the prefix 'AND' and garnet samples were separately numbered with the prefix 'GAR'.

The samples are not necessarily representative of the rocks at each location, as care was taken to avoid weathered strata and rocks with low concentrations of the target minerals. Each sample was therefore selective and represents zones of significant enrichment of the target mineral. Several sites were visited where significant enrichment, although recorded, was not observed and, therefore, no sample was collected. Sites which were remote from roads or tracks were not sampled as their inaccessibility significantly reduced their potential (Table 1).

Andalusite proved relatively easy to recognise in the field, particularly where it occurs as dark-coloured, coarse-grained, 'spots' or 'knots' in the schists. However, at several localities, concentrations of andalusite were low or the andalusite crystals were fine grained or intergrown with the rock matrix and identification was more difficult. Most occurrences were in the mica schists of the Southern Highland Group (Dalradian Supergroup), although a few localities occurred in hornfels.

Garnet occurrences are widespread in the Scottish Highlands and rocks enriched in garnet were easily recognised. The garnets seen in the field were mostly dark red to pale pink in colour and ranged in size from 5 cm or more to less than 1 mm in diameter. In most cases, the coarsest crystals and aggregates are obviously fractured and contained a great number of inclusions.

Figure 2 Sampling sites for garnet in the Scottish Highlands

Table 1 Andalusite localities

Principal targets

Location	National Grid Reference	1:50K (Geol.)	1:50K (Topo.)	Stratigraphy and comments	Sample Number
Correen Quarry	NJ 522 213	76W	37	Dalradian, Suie Hill Formation.	AND 1/2
The Carbouies	NJ 494 179	76W	37	Dalradian, Suie Hill Formation.	No exposure
Ford below Hillock of Terpersie	NJ 536 205	76W	37	Dalradian, Suie Hill Formation.	AND 3
Tap O'Noth	NJ 483 291	76W	37	Dalradian, Suie Hill Formation. 'Massive mica schist rich in andalusite'.	AND 7
Black Hillock	NJ 373 292	85	37	Dalradian, Blackwater Formation. 'Black slate with perfect crystals'.	AND 6
Tervie Burn	NJ 249 326	85	36	Dalradian, Mortlach Graphitic Schist, 'Large crystals of andalusite'.	AND 5
Corbie Craig	NJ 263 338	85	28	Dalradian, Mortlach Graphitic Schist Formation. 'Large crystals'.	AND 4
Bridgend	NJ 515 361	86	29	Dalradian, Boyndie Bay Group.	No exposure
Burncruinach	NJ 503 351	86	29	Dalradian, Boyndie Bay Group. Ness Bogie, north-west bank.	No exposure
Falaiche Burn	NJ 434 316 to NJ 438 315	86	37	Dalradian, Boyndie Bay Group. Possibly from thermal metamorphism.	AND 8/9
Mill of Kinnairdy	NJ 611 501	86	29	Dalradian, Boyndie Bay Group. Good exposure at weir.	AND 10
River Deveron, east bank	NJ 611 495	86	29	Dalradian, Boyndie Bay Group.	AND 11
Black Law, Aberchirder	NJ 638 543	86	29	Dalradian, Boyndie Bay Group. Old quarry c. 240 m south of summit.	No exposure
Whitehills, shore west of harbour	NJ 651 656	96	29	Dalradian, Whitehills Group.	AND 12
Whitehills, west side of Boyndie Bay	NJ 663 652	96	29	Dalradian, Whitehills Group.	AND 13
Pittulie shore	NJ 950 679	97	30	Dalradian, Rosehearty Group.	AND 14
Mill of Ardo, Methlick	NJ 850 384	87	30	Dalradian, Methlick Division.	AND 16
River Ythan, Methlick	NJ 841 392 to NJ 856 376	87	30	Dalradian, Methlick Division. Southern part of section hornfelsed.	AND 17
River Ythan, Fetterletter	NJ 806 388	86	29	Dalradian, Fyvie Schist Formation.	AND 18
Slains Castle to Crincle Den, shore section	NK 054 300 to NJ 062 312	87	30	Dalradian, Collieston Formation.	AND 15
Howmill Quarry	NJ 490 186	76W	37	Dalradian, Suie Hill Formation. Roadside quarry.	No exposure

Table 1 Andalusite localities (continued)

Secondary targets

Location	National Grid Reference	1:50K (Geol.)	1:50K (Topo.)	Stratigraphy and comments	Sample Number
Ardhuncart Hill	NJ 48 18	76W	37	Dalradian, Suie Hill Formation. Angular blocks on south slopes of hill.	No exposure
Mossat Burn	NJ 430 200 to NJ 449 194	76W	37	Dalradian, Craigievar Formation.	Not sampled
Muchie Burn, Mid Clova	NJ 448 212 to NJ 451 209	76W	37	Dalradian, Craigievar Formation.	No exposure
Cattens	NJ 510 166	76W	37	Dalradian, Suie Hill Formation. Section on south bank of Don.	No exposure
Bithnie	NJ 513 172	76W	37	Dalradian, Suie Hill Formation. Loose blocks.	Not sampled
Mains of Mayen	NJ 570 480	86	29	Dalradian, Boyndie Bay Group. Old roadside quarry.	Low concentration
Haickburn to Corniehaugh Road	NJ 562 478 to NJ 580 465	86	29	Dalradian, Boyndie Bay Group. Roadside exposure.	Not sampled
Shield Burn, Gartly	NJ 488 355	86	29	Dalradian, Boyndie Bay Group.	Not sampled
Clashmach Hill, north part	NJ 498 385	86	29	Dalradian, Boyndie Bay Group.	Not sampled
Nether Kirton	NJ 809 346	86	30	Dalradian, Fyvie Schist Formation.	Not sampled
Little Barthol, west of Chapel	NJ 804 341	86	30	Dalradian, Fyvie Schist Formation.	Not sampled
Burn of Rothes	NJ 242 481	85	28	Dalradian, Grampian Group. Andalusite and cordierite hornfels.	Not sampled
Shenval, Blackwater	NJ 366 304	85	37	Dalradian, Blackwater Formation.	Not sampled
Uppermill of Hatton	NJ 059 375	87	30	Dalradian, Collieston Formation.	Not sampled
Cove	NO 947 987	77	38	Dalradian, Aberdeen Formation.	Not sampled
Maryculter	NO 856 990	77	38	Dalradian, Aberdeen Formation.	Not sampled
Cove	NJ 957 013	77	38	Dalradian, Aberdeen Formation.	Not sampled
Inverharroch	NJ 382 312	85	37	Dalradian, Blackwater Formation.	Not sampled
Buck of the Cabrach	NJ 412 234	75	37	Dalradian, Suie Hill Formation.	Not sampled
Creag an Sgor Hill	NJ 370 190	75	37	Dalradian, Craigievar Formation.	Not sampled
Scad Hill	NJ 422 228	75	37	Dalradian, Suie Hill Formation.	Not sampled
Meikle Firbriggs	NJ 359 287	75	37	Dalradian, Blackwater Formation.	Not sampled
Wester Corskie	NJ 631 531 to NJ 631 533	86	29	Dalradian, Boyndie Bay Group. Old quarries.	Not sampled

Principal sources listed in the references. Additional information from BGS staff.

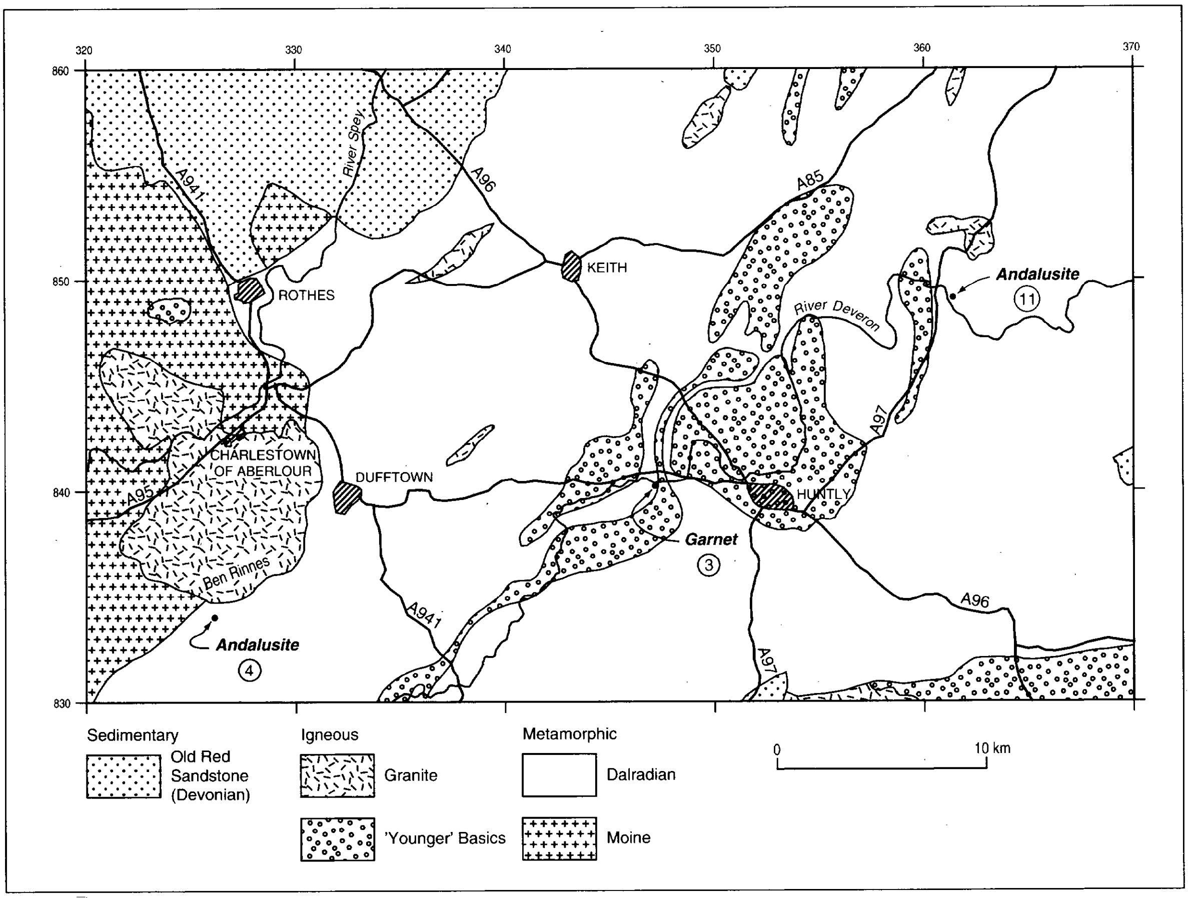

Figure 3 Location of selected andalusite (AND 4 and 11) and garnet samples (GAR 3) in the Huntly area, north-east Scotland

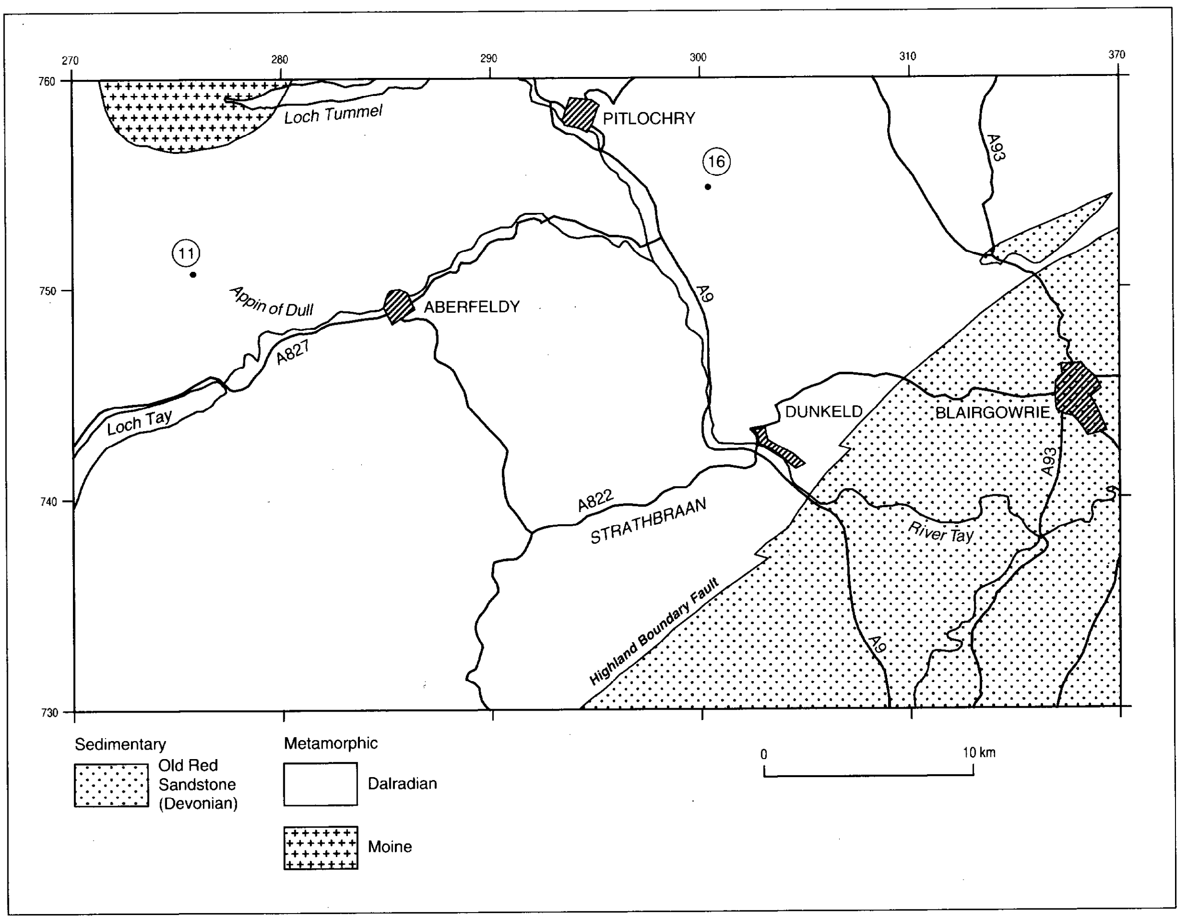

Figure 4 Location of selected garnet samples (GAR 11 and 16) in the Aberfeldy area

Table 2 Garnet localities

Location	National Grid Reference	1:50K (Geol.)	1:50K (Topo.)	Stratigraphy and comments	Sample Number
Rodel, South Harris	NF 028 881	1:10000	18	Lewisian, South Harris Igneous Complex. Metagabbro, few inclusions.	GAR 18/19
River Deveron, south bank	NJ4720 4041	86	28	Dalradian. Coarse garnet rock.	GAR 3
Cairnie, A96 road cutting	NJ 482 446	86	28	Dalradian. Coarse garnet schist.	GAR 2
Ardtoe	NM 627 709	52W	40	Moine. Pelite with ≤ 20% garnet.	GAR 9
Carn Mor	NM 62 71	52W	40	Moine. Northerly continuation of above horizon.	GAR 10
Tulliemet	NO 005 546	56W	53	Dalradian, Southern Highland Group. Garnet common in semipelite.	GAR 16
Meall Reamhar	NO 029 577	56W	53	Dalradian, Southern Highland Group. Psammite - semipelitic schists.	GAR 17
Scourie More, Scourie	NC 142 446	107	9	Lewisian.	GAR 7
Carn a Mhadaidh, Tongue	NC 532 511	114	10	Lewisian. Average 50% garnet over 8 m by 180 m, lots of inclusions.	Inaccessible
Garbh Chnoc, Tongue	NC 575 545	114	10	Lewisian. 50-80% garnet, lots of inclusions.	GAR 6
Achiltibuie	NC 025 085	101	15	Lewisian. Garnet-amphibolite few inclusions.	GAR 8
Kirkton Farm, Tyndrum	NN 361 285	46	50	Dalradian. Ben Lui Schist Formation.	GAR 13
Ceann Garbh, Glen Fyne	NN 226 192	45	50	Dalradian, Ben Lui Schist Formation.	Inaccessible
Shore SW of Rubha Bathaich Bhain, Loch Fyne	NN 164 099	37	56	Dalradian, Ben Lui Schist Formation.	GAR 15
Burn SE of Leanach	NS 048 972	37	56	Dalradian. Ben Lui Schist Formation.	Low concentration
Allt Coire Phelginn	NN 762 504	55W	51	Dalradian, Pitlochry Schist Formation.	GAR 11
Strathan Cove	NC 574 650	114	10	Recent. Beach sand containing garnet.	GAR 5
Glen Glass	NH 485 736 to NH 544 688	93	20/21	Moine. Traverse across pelite.	GAR 4
Cuil to Drishaig, north shore Loch Fyne	NN 179 118 to NN 159 106	37	56	Dalradian, Ben Lui Schist Formation.	GAR 14
Stream NNW of Cruach nan Capull	NN 14 06	37	56	Dalradian, Ben Lui Schist Formation.	No exposure

Table 2 Garnet localities (continued)

Location	National Grid Reference	1:50K (Geol.)	1:50K (Topo.)	Comments	Sample Number
Allt Bhorland, Killin	NN 555 350	46	51	Dalradian, Ben Lui Schist Formation.	GAR 12
Lower part of Ear Dubh	NN 100 018	37	56	Dalradian, Ben Lui Schist Formation.	No exposure
Sgurr a'Ghlas Leathaid	NH 245 564	82	25	Moine. Bands ≤ 8 cm in amphibolites, remote location.	Inaccessible
Carr Brae, Dornie	NG 90 24	72W	33	Lewisan. Specimen from BGS collection.	Inaccessible
Chadh Bhuidhe Lodge, Loch Fannich	NH 157 674	92	20	Moine. Probably submerged by enlarged Loch Fannich.	Inaccessible
Knock of Lawsie, Crathie	NO 2651 9689	65E	44	Dalradian. Iron-rich garnet amphibolite.	Low concentration
St Cyrus beach	NO 756 647	57	45	Recent. Garnet-bearing beach sand.	GAR 1
Monifieth/Buddon beach	NO 49 31 to NO 54 36	49	54	Recent. Garnet-bearing beach sand.	Low concentration

Principal sources listed in the references. Additional information from BGS staff.

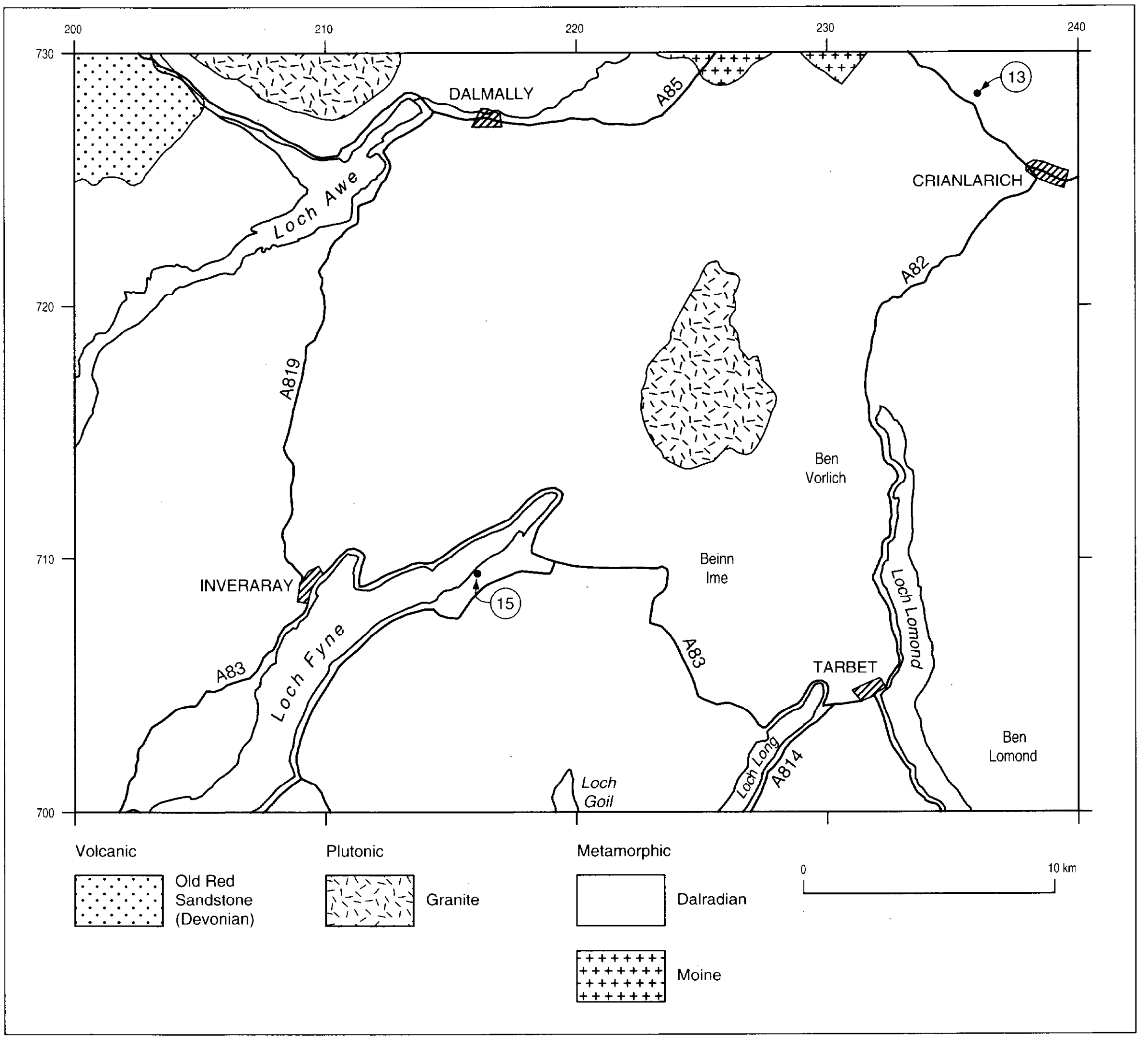

Figure 5 Location of selected garnet samples (GAR 13 and 15) in Argyll and Bute

LABORATORY METHODOLOGY

The andalusite and garnet samples collected during fieldwork were investigated by a range of laboratory procedures (Figures 6 and 7) to determine their mineralogical character and their suitability for mineral processing.

Petrographic analysis

Petrographic studies of the samples enabled determination of mineralogy, texture and fabrics, and also indicated their potential suitability for mineral processing.

Standard thin sections (3 x 1 inch with a 30 µm rock slice and glass cover slip) were prepared from representative rock fragments selected from each sample. Repeat thin sections were made where necessary from several samples, particularly those which were lithologically variable. The thin sections were examined using a Zeiss binocular microscope (with a camera attachment) and the mineralogy and texture of each sample was determined. Particular attention was given to the size distribution of the main mineral phases, the presence of mineral inclusions, the crystal form of the target minerals (andalusite and garnet) and their textural relationships with associated minerals.

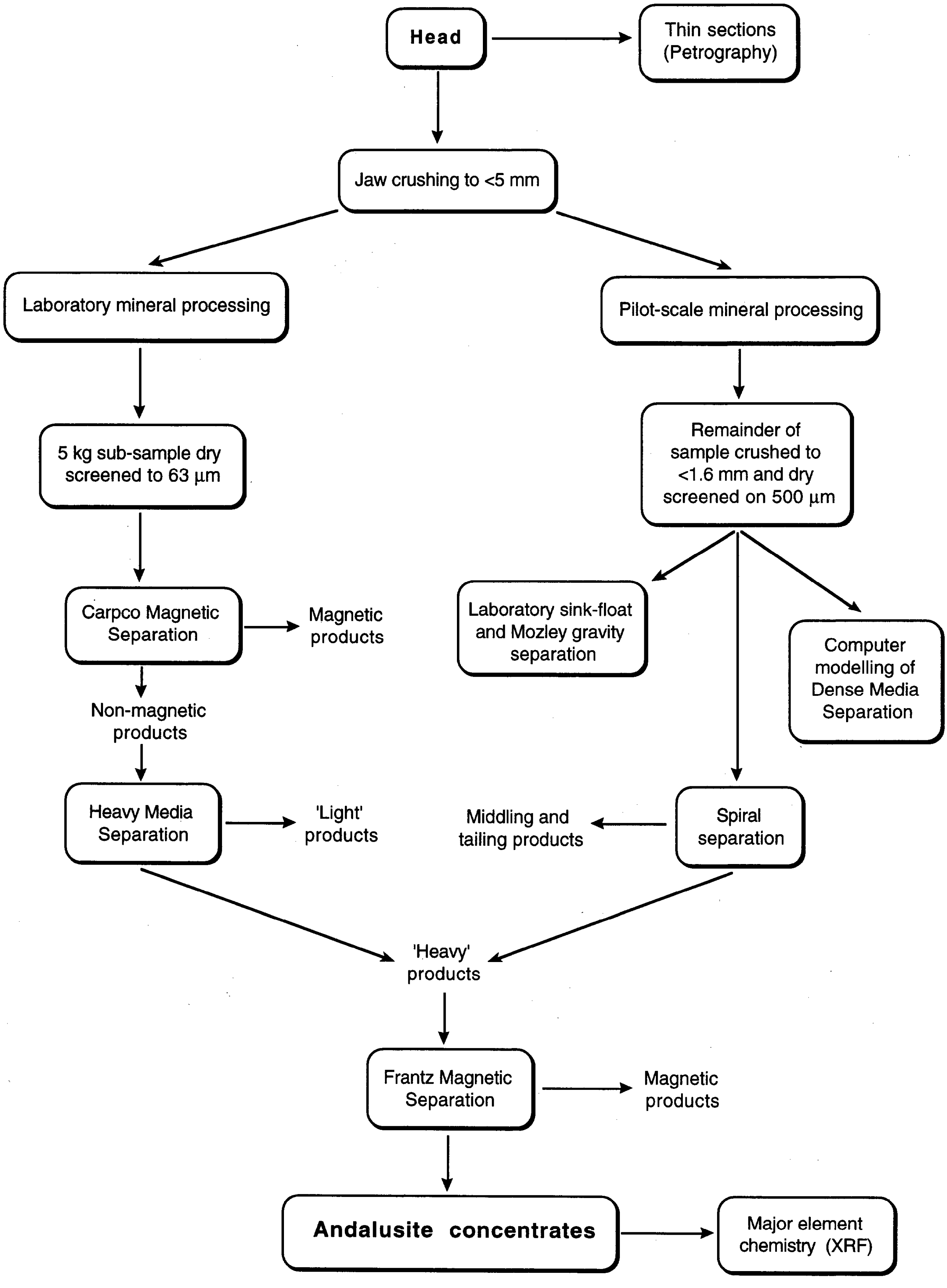

Figure 6 Flow diagram for mineral processing of andalusite

Measurement of the crystal size of the andalusite and garnet was determined using the integral microscope graticule (calibrated with a 2 mm scale for each magnification). Using these size data the particle-size range and mean were calculated. Photomicrographs were taken of representative andalusite and garnet crystals from each sample.

The petrographic analysis was used to select those samples most suitable for mineral processing trials. The criteria used for selection were: target mineral content, proportion of mineral inclusions, texture, crystal form and size, presence of alteration and the likely liberation characteristics.

Sample preparation

In order to achieve efficient mineral processing, the feed material must contain well liberated target mineral particles with a size distribution appropriate to the separation techniques employed. The samples were therefore prepared for processing using a combination of jaw crushing, roller milling and screening.

Each sample was initially jaw crushed to <10 mm size and a representative 5 kg sub-sample of the crushed material was taken for further jaw crushing and roller milling. The degree of crushing depended upon the calculated liberation size of the target mineral present in the sample. The samples were screened using the following sieve series: 4 mm, 2 mm, 1 mm, 500 μm, 250 μm, 125 μm and 63 μm. Each sample was crushed to a size coarser than the calculated liberation size in an attempt to maximise the particle-size of the liberated target mineral. However, this resulted in a large proportion of middling grains, which could be reground to improve the overall recovery of the target mineral.

A second selection process was undertaken at this stage in order to confirm that those samples chosen following petrographic analysis were suitable for mineral processing trials. This was carried out because sub-samples of the crushed material are more representative of the bulk sample than the rock fragments chosen for preparation of thin sections and petrographic analysis. The size fractions were examined as loose grains using a Nikon binocular microscope. The criteria used for selection were an estimated target mineral content and the degree of liberation of the target mineral(s).

Laboratory mineral processing

Laboratory mineral processing of the selected samples aimed to produce concentrates of the target mineral(s) with a high grade and recovery (see glossary in Appendix 1). The following techniques were employed on both the andalusite- and garnet-bearing samples.

Carpco high-intensity induced-roll magnetic separator

Magnetic separators are used to separate minerals with different magnetic susceptibilities. The Carpco high-intensity induced-roll magnetic separator (Model MIH (13) 111-5) consists of a laminated roll, composed of alternating layers of phosphored steel of different diameter giving the roll a serrated surface (Wills, 1992). A magnetic field is generated by a large electromagnet suspended above the roll surface. Magnetic flux concentrates on the raised parts of the serrated surface giving a high magnetic intensity. This ensures that the magnetic field gradient increases towards the roll surface. Mineral grains are fed onto the rotating roll via a vibratory hopper. Depending upon the magnetic intensity at the roll surface, minerals having a magnetic susceptibility greater than a particular value will be attracted to the roll surface. These minerals are collected in the 'magnetics' bin. Those minerals with a lower magnetic susceptibility with be thrown from the drum surface, due to the rotational momentum and are collected in the 'non-magnetics' bin.

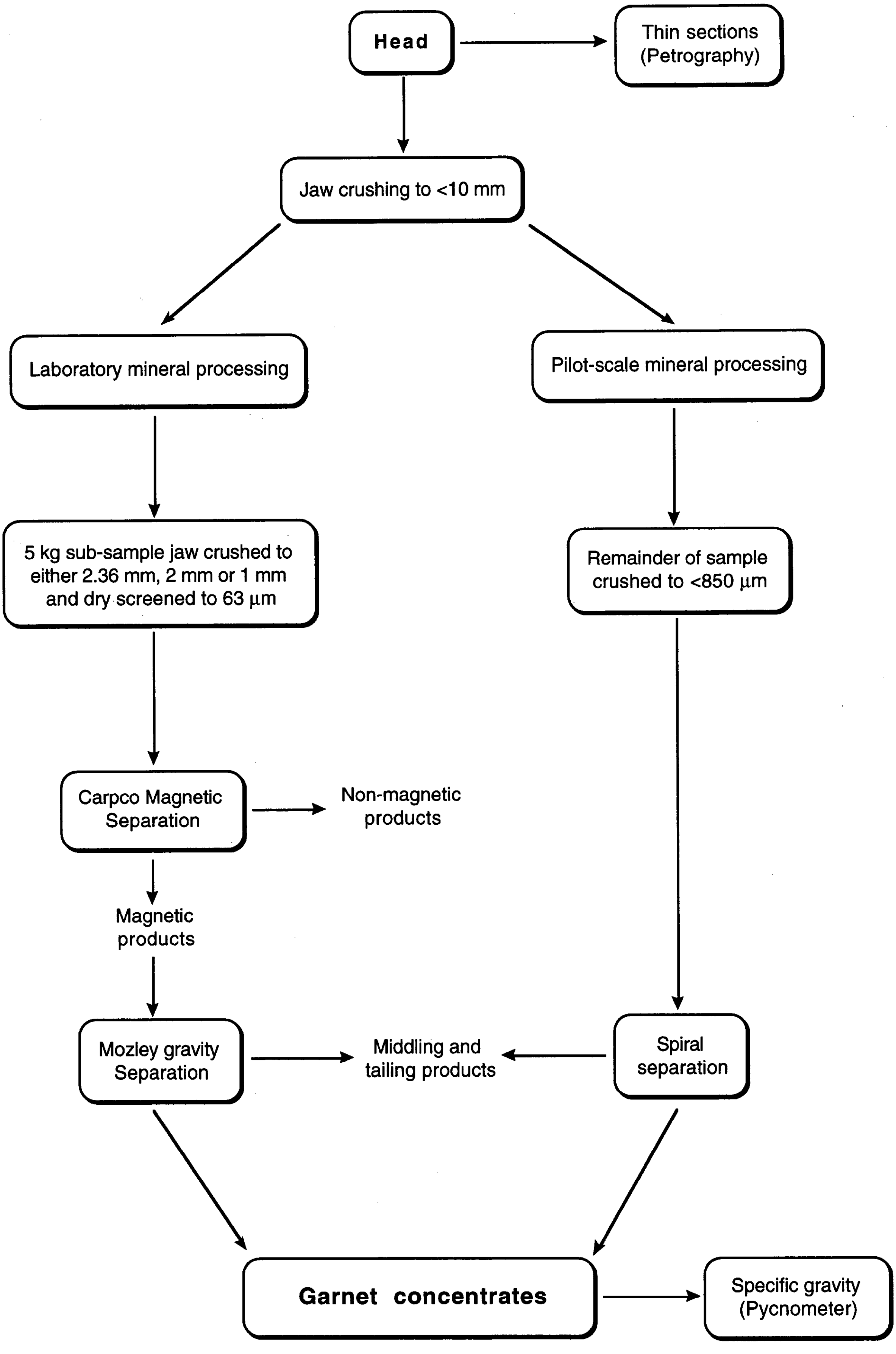

Figure 7 Flow diagram for mineral processing of garnet

Samples processed by magnetic separation have an upper size limit of 2 mm and a lower size limit of 63 μm, with an optimum size range of 500 and 125 μm. The size fractions processed for this work included those between -2 +1 mm and -125 +63 μm. The processing of large particles, >1 mm is heavily influenced by mass whereas the processing of fine particles, <125 μm is influenced by the effect of air currents and the electrostatic attraction between particles. The material was processed using the current series (magnetic intensity in gauss in brackets) 0.3A (4 100), 1A (11 000), 2A (14 00), 3A (15 500) and 3.45A (15 700). The 'non-magnetic' product from the first separation (0.3A) being used as the feed for the next separation and so on. The products removed at low intensity are strongly magnetic, such as magnetite; medium intensity are moderately magnetic, such as garnet; and highest intensity are weakly magnetic, such as biotite mica.

The variables influencing magnetic separation include: roll speed (optimum 180 rpm), feed hopper vibration (optimum 30–50% of maximum), gap between roll surface and electromagnet (2–4 mm depending upon the particle-size of the sample), and the position of the product splitter plates. The splitter plate can be used to 'scalp' further valuable mineral from the process stream that would otherwise report to the non-magnetic bin.

Mozley laboratory mineral separator mk II

Gravity separators are used to separate minerals with different densities, for example 'heavy' minerals (>3 g/cm^3) such as garnet and andalusite from less dense minerals such as quartz and feldspar (2.6–2.8 g/cm^3).

The Mozley laboratory mineral separator is a shaking table type of gravity separator. Shaking tables use a flowing film of water over a flat inclined surface to separate less dense and heavy minerals (Wills, 1992). Water velocity decreases towards the surface of the table. Fine grained and relatively dense particles become entrained in the slow moving lower layer of water whereas larger and less dense particles are caught up in the faster moving upper layer of water. There is therefore a displacement of material. The table is oscillated in the horizontal plane, with an additional 'knock' at the upslope end. The oscillation helps to stratify the minerals. The 'end-knock' encourages the heavy minerals resting on the table surface to migrate upslope, enhancing the displacement between heavy and light minerals. The Mozley laboratory separator closely simulates the performance of commercial shaking tables.

Samples processed by the Mozley laboratory separator have an upper size limit of 2 mm and a lower size limit of approximately 20 μm, with an optimum size range between 500 and 63 μm. Size fractions processed for this work include those between -2 +1 mm and -125 +63 μm. As a separation progresses the less dense minerals such as quartz and feldspar are washed downslope, followed by minerals of intermediate density. The heavy minerals concentrate toward the upslope end of the table. Therefore the process stream will gradually be segregated into less-dense and dense minerals and can quite easily be separated into products, normally a concentrate, middling and tailing. For material coarser than 100 μm a V-profile table is used and for material finer than 100 μm a flat table is used.

The variables influencing gravity separation include: the horizontal oscillation amplitude and speed (typically 2.5 inches and 70 rpm respectively), the slope of the table (typically 1–2°), wash water rate (0.5–2.5 litres per minute) and sample mass (up to 200 g maximum).

Frantz isodynamic magnetic separator

The Frantz isodynamic magnetic separator consists of an inclined channel, tilted to one side, which splits into two at the downslope end. The channel is encased in an electromagnet which exerts a magnetic attraction along the raised length of the channel. The sample was fed into the channel via a vibratory hopper, which also causes the channel to vibrate. Minerals with a high magnetic susceptibility are attracted to the raised length of the channel and report to the 'magnetics' bin at the downslope end. The remaining minerals report to the 'non-magnetics' bin at the downslope end.

The samples are processed in a similar fashion to those on the Carpco high-intensity induced-roll magnetic separator. The main difference being the feed rate, the Carpco being capable of up to 50 kg per hour and the Frantz up to 50 g per hour. The variables that influence efficiency of magnetic separation include the slope and tilt of the channel, and the feed hopper vibration.

Heavy Media Separation (HMS)

Heavy media separation is a type of gravity separation. The heavy media used were organic liquids, bromoform (density of 2.9 g/cm^3) and di-iodomethane (density of 3.3 g/cm^3). The sample was placed into a separating funnel filled with heavy liquid, minerals denser than the liquid sink and those lighter than the liquid float. The products were separated using a tap at the base of the funnel.

The separating funnel can be used with an upper size limit of approximately 1 mm. The material, however, does not need to be sized for an effective separation. Particles coarser than 1 mm were separated using heavy liquid in a glass beaker. The density of the heavy liquid can be lowered with a diluent (for example triethyl orthophosphate which has a density of 1 g/cm^3). This technique can either be employed as a separation method or as part of the characterisation of a product (i.e. in order to determine the heavy mineral content of a product).

Laboratory processing of andalusite

The following processing methodology was developed and utilised for andalusite-bearing samples.

Stage 1. Magnetic separation (Carpco) was carried out on those size fractions between 1 mm and 250 μm.

Stage 2. Heavy media separation was carried out on those fractions betweeen 4 mm and 1 mm that contained well liberated andalusite and also on the non-magnetic products of Stage 1.

Stage 3. Magnetic separation (Frantz) was carried out on the heavy products from Stage 2, except for the -4 +2 mm products.

Laboratory processing of garnet

The following processing methodology was developed and utilised for garnet bearing samples.

Stage 1. Magnetic separation (Carpco) was carried out on those size fractions with well liberated garnet grains.

Stage 2. Gravity separation (Mozley shaking table) was carried out on the magnetic products (including selected middling and non-magnetic products) from Stage 1.

Stage 3. Repeat gravity separation was carried out on selected middling products from Stage 2.

Selection of samples for pilot-scale mineral processing

The selection of samples for pilot-scale mineral processing was based on the results of the laboratory mineral processing trials. The products were examined as loose grains using a Nikon binocular microscope. The criteria used for selection included the grade and recovery of target mineral(s) present in the processed products.

Pilot-scale mineral processing

Pilot-scale mineral processing was carried upon the most promising samples following laboratory processing. The aim was to produce concentrates of the target mineral(s) with a high grade and recovery. The following techniques were employed in the pilot-scale processing of both andalusite- and garnet-bearing samples.

Sample preparation

Large bulk samples were prepared for the pilot-scale processing. The andalusite (approximately 35 kg per sample) samples were jaw crushed in closed circuit to <1.6 mm and screened at 500 µm and 75 µm. The garnet samples (approximately 85 kg per sample) were jaw crushed and roller milled in closed circuit to <850 µm.

Dense Media Cyclone

The Dense Media Cyclone is a centrifugal type of heavy media gravity separator which is operationally very similar to a hydrocyclone. It consists of an inverted cone into which a heavy media, usually a suspension of finely ground magnetite or ferrosilicon in water, is introduced tangentially under pressure (Wills, 1992). The sized sample is introduced into the separator along with the heavy media. A primary vortex, moving from base to apex, is created in the cyclone by the tangential feed of the suspension. Dense minerals migrate to the inside wall of the cyclone and are discharged via the apex, or spigot, as an underflow product. Less-dense minerals are swept up in a central secondary vortex, moving from apex to base and are discharged via a vortex finder as an overflow product.

Due to the large bulk samples required (50–100 kg) no pilot-scale dense media separation work was physically carried out but using "sink-float" data the separation was simulated using a computer model. The sink-float data were derived from the separation of sub-samples using a series of heavy liquids ranging from 2.9 to 3.2 g/cm^3, increasing in 0.05 g/cm^3 increments. The sink product from the 2.9 g/cm^3 separation was used as the feed for the 2.95 g/cm^3 separation and so on. The products were examined by binocular microscopy and the grade and recovery of the target minerals were determined. These data were used to simulate a dense media cyclone separation using a specially developed spreadsheet model based on the model: "GRAVITY - evaluation of heavy liquid data" (Wills, 1992).

Mineral spiral

The spiral is a type of flowing film gravity separator. The spiral consists of a helical conduit of modified semi-circular cross-section, usually with between 3 and 5 complete 'turns' (Wills, 1992). The particle-size range effectively separated is between 1.6 mm and 75 µm. The sample is fed onto the top of the spiral as a pulp with between 25 and 30% solids by weight. As the pulp flows spirally downwards the particles stratify due to factors such as centrifugal force, differential settling, hindered settling and reverse classification. There is usually a density gradation across the profile of the spiral with heavy minerals concentrating next to the axis and minerals of lower density being swept to the outer edge. Concentrate, middling and tailing products are collected with the use of adjustable splitter plates to divert the process streams into collection bins.

The main operator controlled variables were the solids concentration of the pulp and its feed rate onto the spiral. Both of these have an influence on the depth of sample flowing over the spiral surface, which influences the separation efficiency and the placement of the target mineral across the spiral profile.

Pilot-scale mineral processing of andalusite

The following processing methodology was developed and utilised for two selected andalusite-bearing samples (AND 4 and 11).

Stage 1. Spiral processing of -1 mm +500 µm fractions for both samples and also -500 +75 µm fraction for AND 4.

Stage 2. Magnetic separation (Frantz) of spiral concentrates.

Pilot-scale mineral processing of garne

The following processing methodology was developed and utilised for two selected garnet-bearing samples (GAR 3 and 16).

Stage 1 only. Spiral processing of -850 µm fractions for both samples. Three trial separations for each sample.

Evaluation of products

The laboratory and pilot-scale mineral processing products were assessed to determine their target mineral(s) grade and recovery. The products were examined as loose grains using a Nikon binocular microscope. The major element chemistry of the andalusite concentrates was determined using X-ray fluorescence spectrometry (XRFS). The specific gravity (or relative density) of the garnet concentrates was determined using a pycnometer. These data were compared with the properties of commercially available andalusite and garnet products in order to assess the potential for industrial use.

RESULTS: ANDALUSITE

Petrography (Detailed petrographic descriptions are given in Appendix 2).

Generally the samples collected were pelitic schists, slightly to highly weathered, with abundant andalusite (and/or cordierite, plus garnet in a few samples) porphyroblasts in a quartz-mica matrix. The presence of andalusite porphyroblasts was usually identified correctly in the field, aided by the presence of a 'spotted' or 'knotted' surface texture, although cordierite was occasionally confused with andalusite. Quartz and mica form the dominant components of the matrix, and also form porphyroblast inclusions. They range in size up to 1 mm and 600 µm respectively. Fine-grained opaque minerals, probably iron and titanium oxides, also occur disseminated throughout the matrix.

Andalusite occurs in most of the samples as one, or both, of two distinct types of porphyroblast:

i) Euhedral (AND 1, 4, 5, 6 and 8). The andalusite occurs as large (up to 5 mm) pseudohexagonal or small (up to 2 mm) square porphyroblasts which often display well developed cross-cutting cleavage. Inclusions are rare, and are mainly fine grained quartz. 'Chiastolite' cross texture is common with fine black inclusions often defining the cleavage. The porphyroblasts characteristically have a well developed crystal form and crystal boundaries.

ii) Anhedral (AND 2, 3, 9, 10, 11, 16 and 18). The andalusite occurs as large (up to 6.5 mm), irregular, poikiloblastic or heavily included (up to 50%) porphyroblasts (Figure 4), often with a 'fragmented' appearance. The inclusions are mainly quartz, mica and opaque minerals. Often the andalusite occurs closely associated with cordierite porphyroblasts, often as a 'mantle' around a cordierite 'spot'. The andalusite has a poorly developed crystal form and its boundaries are often hard to distinguish from the matrix.

In some samples (AND 13, 14, 15 and 17) the andalusite is almost totally replaced by sericite and often only an outline or 'relict' remains.

Cordierite porphyroblasts occur in about half of the samples, in close association with andalusite. It generally occurs as large (up to 5 mm) irregular to rounded prismatic porphyroblasts often with a poikiloblastic or heavily included texture. The inclusions are mainly quartz, mica and opaque minerals. The cordierite often has a poorly defined crystal boundary, and can only be distinguished from the matrix by its yellowish-brown colour.

Garnet porphyroblasts occur in three samples (AND 4, 5 and 10). The garnet, almandine in composition, occurs as euhedral (trapezoidal or dodecahedral) crystals, up to 1 mm in diameter, with well defined crystal boundaries. They are relatively free of inclusions and may have a fractured and/or fragmented appearance.

Based on the petrographic analysis the following samples were selected for sample preparation : AND 1, 4, 5, 6, 8, 10, 11, 16 and 18.

Sample preparation

The particle-size distribution data, and andalusite grade and recovery data for the prepared samples are given in Appendix 3. A summary of andalusite grade, particle-size and liberation size is given in Table 3.

All the samples were crushed through 5 mm, except for AND 1 which was crushed through 2 mm. In most cases the largest weight proportions occur in the coarsest size fractions. The andalusite grade for most of the head materials ranges from 2 to 10% andalusite, whereas AND 6 contains only 1.5% andalusite and AND 18 contains 16.6%. Most of the samples showed little variation in andalusite content with particle-size. A few samples exhibited an increase in andalusite with decreasing particle-size (AND 1 and 18) and one (AND 10) showed an increase with increasing particle-size. AND 4 and 5 exhibited a concentration of andalusite in the -2 + 1 mm fraction, which is probably due to the nature of the andalusite present in these two samples. The euhedral porphyroblasts have probably 'popped' out of the rock as intact, totally liberated crystals during jaw crushing. This is supported by the presence of andalusite shaped 'pits' in many of the rock fragments examined following crushing. These liberated porphyroblasts tend to concentrate into a single size fraction.

The andalusite present in the crushed rock material occurred as two separate types of porphyroblasts, similar to the petrographic distinction:

i) Euhedral (AND 1, 4, 5 and 6). The andalusite has a dark-red to reddish-brown colour, a vitreous lustre and is translucent to opaque. The andalusite displays preferential grain boundary breakage. It occurs as elongate crystals often with striated faces and a hexagonal cross-section. Surfaces are usually clean, often with rusty brown material defining the cleavage.

ii) Anhedral (AND 8, 10, 11, 16 and 18). The andalusite has a pinkish-grey, brownish-grey or grey colour, with a sub-vitreous lustre and is opaque to translucent. The andalusite usually does not liberate along crystal boundaries and often occurs as middling grains. It occurs as rounded or irregular crystals often with a 'sugary' surface coating of quartz and mica.

The garnet also present in some samples is easily identified as euhedral (trapezoidal or dodecahedral) crystals with a deep-red to brownish-red colour and a vitreous lustre. It usually occurs at a low grade, 1 to 2%. The grade does not vary significantly with particle-size, although there is a slight increase in garnet content between 2 mm and 500 μm. This is also possibly due to the garnet 'popping' out of the rock, as with the andalusite in AND 4 and 5.

Table 3 Grade, particle-size and liberation size of andalusite

Sample (AND)	Andalusite content (%)	Andalusite size (mm)		
		Range	Average	Liberation
1	5.3	1.7 – 0.4	0.9	1
4	7.5	4.6 – 0.8	2.4	1
5	9.8	2.7	nd	1 – 2
6	1.5	3.6 – 0.6	2.1	1 – 0.5
8	2.9	nd	nd	1 – 0.5
10	3.1	nd	nd	0.5 – 0.25
11	7.0	6.5 – 1	2.4	1 – 2
16	2.6	3.6 – 1.5	2.2	1 – 2
18	16.7	4.8 – 0.6	2.6	1 – 2

nd = not determined

The samples chosen for laboratory mineral processing were:

AND 4: 8% andalusite and 3% garnet, with well formed andalusite crystals.
AND 5: 10% andalusite and 1% garnet, with well formed andalusite crystals.
AND 10: 3% andalusite (irregular form) and 1% garnet.
AND 11: 7% andalusite (irregular form).
AND 16: 3% andalusite (irregular form).

Laboratory mineral processing

The results of the laboratory mineral processing are given in Appendix 4 and are summarised in Table 4. The Carpco magnetic separation directed the andalusite into 'non-magnetic' products and a proportion of the mica, garnet and other magnetically susceptible minerals into 'magnetic' products. This resulted in a minor increase in the total andalusite content (<0.5%). A small proportion (<0.5%) of the andalusite was, however, lost, typically as middling grains with garnet.

The heavy media separation concentrated the andalusite into sink or 'heavy' products. The less-dense minerals, such as quartz, feldspar and mica were removed in 'float' products. This resulted in a significant increase in the andalusite content. Most of the 'heavy' products contained between 50 and 100% andalusite, although the heavy products of AND 16 contained less than 10% andalusite, due to incomplete liberation. The non-andalusite component of the heavy products of AND 4 and 5 was mainly garnet (between 4 and 60%). AND 10 also contained garnet but with a high proportion of biotite mica. A proportion of andalusite was lost into the 'float' products as middling grains with quartz, feldspar and mica. This loss was small in AND 4, 5 and 16 (<5% of andalusite recovery) but large in AND 10 and 11 (40 and 55% of andalusite recovery respectively). In each case most of the loss was in the coarsest fraction processed, especially in the -4 +2 mm size fraction. The loss decreased with decreasing particle-size: in AND 4 and 5 there was no loss finer than 1 mm; in AND 10 and 11 there was no loss finer than 500 μm; but in AND 16 andalusite was lost in all fractions.

Table 4 Laboratory mineral processing of andalusite

	Andalusite		
Sample (AND)	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
4	3.4	99	45
5	4.0	99	40
10	0.3	83	8
11	0.2	96	3
16	3.9	9	13

The Frantz magnetic separation upgraded the 'heavy' products and concentrated the andalusite into 'non-magnetic' products (andalusite concentrates). Garnet and other magnetically susceptible minerals were removed at this stage as 'magnetic' products. The andalusite concentrates of AND 4 and 5 contained up to 100% andalusite. The concentrates of AND 10 and 11 contained up to 85% and 98% andalusite respectively, the remainder being a coating of fine grained quartz and mica around the andalusite porphyroblasts. The concentrates of AND 16, however, contained less than 10% andalusite, as the andalusite remains unliberated (even to less than 500 μm). The andalusite in AND 16 did not separate preferentially along grain boundaries and generally fractured across the crystal. This is due partly to its poorly defined crystal nature. It is also partly due to the presence of inclusions which cut across the crystal boundary welding the andalusite to the matrix. Therefore most of the andalusite was 'locked' up in middling grains.

Andalusite was lost in the coarse-grained 'magnetic' products, mainly due to incomplete liberation, for example the -2 +1 mm 'magnetic' product of AND 4 contained 12% andalusite. The proportion of andalusite lost into the 'magnetic' products dropped dramatically below 1 mm (< 1%). The highest loss occured as unliberated material in the +2 mm fractions, and may represent up to 75% of the recoverable andalusite.

Based on the results of the laboratory mineral processing the overall andalusite grade and recovery for combined andalusite concentrates can be calculated (Table 4). AND 4 and 5 produced concentrates grading 99% with recoveries up to 45%. AND 10 and 11 produced concentrates grading up to 96% with recoveries up to 8%. AND 16 produced a concentrate grading 9% with a recovery of 13%. Further size reduction of the unprocessed coarse size fractions to less than 2 mm would further liberate the andalusite present. Assuming this andalusite would have a similar processing performance to the -2 mm fractions already processed, overall andalusite grade and recoveries can be calculated. AND 4 could, therefore produce a concentrate grading 99% with a 70% recovery and AND 5 a concentrate grading 99% with a 90% recovery.

Based on the results of the laboratory mineral processing the following samples were chosen for pilot-scale mineral processing trials:

AND 4: High andalusite grade and recovery, with euhedral andalusite and garnet porphyroblasts.

AND 11: High andalusite grade, with less well-formed andalusite porphyroblasts.

The two samples represent the best examples of the two distinctly contrasting types of andalusite encountered during the investigation.

Pilot-scale mineral processing

The results of the pilot-scale mineral processing are given in Appendix 5 and are summarised in Table 5.

Dense Media Cyclone

Sink-float trials indicated that for AND 4 and AND 11 concentrates containing up to 90% andalusite could be produced. AND 4 has a distinct separation between less-dense minerals, such as quartz, feldspar and mica and the heavy minerals, andalusite and garnet. AND 11 does not have a distinct separation and a significant proportion of the andalusite reports to the less-dense products. This is due to insufficient liberation.

Table 5 Pilot-scale mineral processing of andalusite

	Andalusite		
Sample	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
AND 4			
Dense Media Cyclone	16.0	79.5	88.2
Mineral Spiral	5.6	36.6	45.6
AND 11			
Dense Media Cyclone	2.3	50.1	18.1
Mineral Spiral	2.3	35.0	14.0

The modelling of the dense media cyclone separation indicated that for AND 4 products containing up to 80% andalusite with recoveries up to 88% could be produced (Table 5). The andalusite grade could be further improved by subsequent processing of the concentrate using gravity, magnetic and/or electrostatic methods. AND 11 had a much poorer performance, mainly due to insufficient liberation of the andalusite. Products only containing up to 50% andalusite, with recoveries up to 50% could be produced. Further grinding, i.e. to finer than 500 μm, would probably liberate the andalusite. However, this size would be too fine for dense media cyclone separation to be effective.

Mineral Spiral

Mozley tabling indicated that for AND 4 a concentrate containing 80% andalusite at 67% recovery, as well as 10% garnet at a recovery of 95%, could be produced. AND 11 produced a concentrate with only 55% andalusite at a recovery of 74%. These results indicate that a simple gravity separation method could be used to effectively separate andalusite, even though it has a density close to the gangue.

The spiral test work was not as successful as anticipated. This is probably due to the small difference in density between the andalusite and the non-target minerals. Gravity separation only works effectively if there is a difference of at least 1 g/cm^3 between the target and non-target minerals. AND 4 produced concentrates with a combined grade of 37% andalusite with a recovery of 46%, and 12% garnet with a recovery of 34%. AND 11 produced a concentrate containing 35% andalusite with a 14% recovery. This was recovery of andalusite present in the -1 mm +500 μm fraction only.

Evaluation of andalusite

Commercial andalusite should contain a minimum of 54% Al_2O_3 and 42% SiO_2, with a maximum of 1% Fe_2O_3, 2% TiO_2, 0.1% CaO and 0.1% MgO. The composition of the andalusite concentrates and commercially available andalusite is given in Appendix 6. The andalusite concentrates all have lower alumina and higher iron contents than the typical chemical specifications of commercial andalusites. Therefore they are not suitable for use as industrial raw materials

RESULTS: GARNET

Petrography

The samples collected were mainly mica schists, although garnet-rich samples of gneiss, anorthosite, amphibolite and beach sand were also collected. Petrographic descriptions of the samples are given in Appendix 7.

Mica schist

The schist samples (GAR 2, 3, 4, 6, 11, 12, 13, 14, 15, 16 & 17) contained garnet porphyroblasts in a quartz (+/- feldspar) - mica rich matrix, with some opaque minerals (+/- chlorite). The matrix is typically dominated by quartz and mica, although mica-rich matrix occurs in several samples. Quartz (+/- feldspar) ranged in size from 60 μm to 1.8 mm, typically 0.1 to 1 mm. In some samples it forms an interlocking mosaic. Biotite mica often occurred disseminated throughout the matrix, ranging in size from 30 μm to 2.7 mm, typically 0.1 to 0.3 mm. Opaque minerals ranged in size from 60 μm to 0.9 mm, typically 0.1 to 0.3 mm. Cordierite occurred in GAR 17 as tabular porphyroblasts.

Garnet occurs as two types of porphyroblast (often with mica or chlorite sheaths and quartz or chlorite infilled 'pressure shadows'):

i) Inclusion-free (GAR 2, 3, 4, 11, 12, 13, 14, 15, 16 and 17). Garnet porphyroblasts in these samples were relatively free of inclusions, any occurring are mainly composed of quartz and/or opaques. They have euhedral (trapezoidal or dodecahedral) to rounded hexagonal crystal form with distinct crystal boundaries, ranging in size from 0.1 to 5.7 mm, typically 0.3 to 2.7 mm in diameter.

ii) Inclusion-rich (GAR 2, 6, 11 & 14). Garnet porphyroblasts in these samples contained up to 40% inclusions, mainly quartz, feldspar and mica, plus some opaques. Some porphyroblasts were so heavily included that they have a 'honeycomb' appearance. Rotational deformation was defined in some garnets by the presence of sinusoidal inclusion trails. These garnets have an irregular to sub-hexagonal crystal form, often with a fragmented appearance. They ranged in size from 0.3 to 10 mm, typically 0.7 to 5.8 mm in diameter.

Gneiss

The gneiss samples (GAR 7, 9 & 10) contained garnet (+/- pyroxene) porphyroblasts in a quartz-feldspar (+/- mica) matrix. Quartz and alkali feldspar ranged in size from 60 μm to 0.9 mm, typically 0.1 to 0.6 mm. Mica ranged in size from 0.15 to 0.9 mm, typically 0.2 to 0.8 mm. Opaques ranged in size up to 0.3 mm. Pyroxene (enstatite ?) occured in GAR 7 as pseudohexagonal porphyroblasts up to 1.5 mm in diameter.

Garnet occurred as rounded pseudohexagonal to irregular porphyroblasts, ranging in size from 0.3 to 3 mm, typically 0.5 to 2.5 mm in diameter. They were relatively inclusion free, although heavily included rims may be present in some (GAR 9) crystals. Inclusions that do occur are mainly quartz, feldspar and mica. Chlorite filled fractures and quartz filled 'pressure shadows' also occurred.

Anorthosite

The anorthosite drill core samples (GAR 18 & 19) contained garnet (+/-amphibole) porphyroblasts in a plagioclase feldspar dominated matrix. The feldspar occurred as a coarse-grained, closely interlocking mosaic of crystals, ranging in size from 30 μm to 3 mm. Opaques occured up to 1 mm in size. Amphibole hornblende occurs in GAR 18 as prismatic porphyroblasts. Garnet occurred as anhedral to irregular porphyroblasts, 0.3 to 4.5 mm in diameter. In GAR 18 they were heavily fractured and inclusion-rich, with a 'honeycomb' texture. The garnets in GAR 19 were relatively free of inclusions.

Beach sands

The samples of beach sand (GAR 1 & 5) contained quartz, shell and rock fragments, garnet, opaques, ?pyroxene and mica. Quartz, shell and rock fragments dominated the medium to very coarse sand fractions (>250 μm) and garnet and opaques occured mainly in the medium to very fine sand fractions (<250 μm). The garnet ranged in size from 1 mm to 63 μm.

Amphibolite

The amphibolite sample (GAR 8) contained garnet, pyroxene and amphibole porphyroblasts in a quartz-feldspar matrix. Quartz and alkali feldspar ranged in size from 0.3 to 1.5 mm and opaques up to 0.2 mm. Amphibole hornblende ranged in size from 0.1 to 1.5 mm and pyroxene from 0.3 to 1.8 mm. Chlorite was also present . Garnet occurred as irregular porphyroblasts with relatively few inclusions (mainly coarse quartz, feldspar, pyroxene and amphibole). Garnet ranged in size from 0.3 to 4.5 mm in diameter.

Based on the petrographic analyses the following samples were selected for sample preparation: GAR 1, 3, 5, 7, 8, 11, 12, 13, 14, 15, 16 and 19.

Sample preparation

The particle-size distribution, and garnet grade and recovery data for the prepared samples are given in Appendix 8. A summary of garnet grade, particle-size and liberation size is given in Table 6.

After initial crushing the sub-samples were milled through either 2.36 mm (GAR 13), 2 mm (GAR 3, 7, 8, 11, 14, 15 and 19) or 1 mm (GAR 12 and 16). GAR 1 and 5 did not require crushing as they are beach sands. The crushed samples retained the largest weight proportions in the coarsest size fractions. The beach sands have a natural closely sized particle-size distribution, with most particles occurring between 500 and 125 μm.

Table 6 Grade, particle-size and liberation size of garnet

Sample (GAR)	Garnet content (%)	Garnet size (mm)		
		Range	Average	Liberation
1	11.1	0.5 – 0.063	0.25 - 0.125	na
3	10.0	3 – 0.15	1.4	1 – 0.5
5	24.3	1 – 0.063	0.5 - 0.25	na
7	21.4	3 – 0.3	1.2	0.5 – 0.25
8	3.8	4.5 – 0.3	1.7	0.5 – 0.25
11	11.0	4.2 – 0.6	2	1 – 0.5
12	12.5	1.8 – 0.15	0.8	11 – 0.5
13	10.0	4.8 – 0.9	2.7	1 – 0.5
14	7.0	2.7 – 0.3	1.2	0.5 – 0.25
15	9.4	2.7 – 0.45	1.3	0.5 – 0.25
16	14.5	1.8 – 0.3	1.1	1 – 0.5
19	2.2	4.5 – 0.15	1.1	0.25 – 0.125

na = Not applicable

The garnet content of the head material generally ranged from 5 to 25%, GAR 8 and 19 both contained less than 4%. There is a small variation in garnet content with particle-size; in some samples garnet content increased and in others it decreased with decreasing particle-size. A degree of garnet concentration, up to 4 times the head grade, can often be seen in the fractions between 1 mm and 125 µm. This concentration is possibly caused by the preferential liberation of garnet from coarse rock fragments (>1 mm). The garnet 'pops' out of the rock due to the stresses caused by crushing and milling and reports to finer fractions.

The liberation size of the garnet was found to be mainly in the range 1 mm to 250 µm. The degree of liberation increases with decreasing particle-size. Ranging up to 75% for >2 mm, up to 90% for -2 +1 mm and up to 100% for -1 mm +500 µm.

The garnet generally has a consistent appearance in all samples. Dark red, orange red to reddish pink, angular to euhedral (trapezoidal or dodecahedral) crystals, vitreous lustre, translucent to opaque, with generally few visible inclusions and relatively clean surfaces.

The samples chosen for laboratory mineral processing trials were:

- GAR 1: 11% garnet, with well liberated and closely sized crystals.
- GAR 3: 10% garnet, large euhedral crystals free of inclusions.
- GAR 5: 24% garnet, with well liberated and closely sized crystals.
- GAR 7: 21% garnet, large crystals free of inclusions.
- GAR 8: 4% garnet, large crystals free of inclusions.
- GAR 11: 11% garnet, large euhedral crystals free of inclusions.
- GAR 13: 10% garnet, very large euhedral crystals free of inclusions.
- GAR 15: 9% garnet, large euhedral crystals free of inclusions.
- GAR 16: 15% garnet, large euhedral crystals free of inclusions.

Laboratory mineral processing

The results of the laboratory mineral processing are given in Appendix 9 and are summarised in Table 7.

The Carpco magnetic separation concentrated the garnet into 'magnetic' products and a significant proportion of the quartz, feldspar and mica was removed in 'non-magnetic' products. This resulted in an increase in the garnet content. Most of the 'magnetic' products contained between 25% and 60% garnet, although GAR 8 and GAR 15 contained less than 20%, due to the presence of pyroxene and amphibole, and chlorite respectively. GAR 5 contained 81% garnet. This high concentration is possibly due to the well liberated and clean nature of the garnet. A small proportion of garnet was lost in the magnetic middling and non-magnetic products. However, the non-magnetic -2 +1 mm product of GAR 13 contains nearly 30% of all the recoverable garnet. This was due to incomplete liberation.

Table 7 Laboratory mineral processing of garnet

Sample (GAR)	Garnet		
	Yield (wt %)	**Grade (wt %)**	**Recovery (wt %)**
1	3.8	80.0	27.6
3	14.4	86.7	60.8
5	8.6	90.0	31.7
7	9.1	77.3	32.9
8	5.5	15.2	22.0
11	2.4	74.6	15.9
13	7.1	80.4	59.5
15	1.7	70.0	12.4
16	11.2	84.0	62.7

The gravity separation successfully upgraded the garnet content of the 'magnetic' products and produced garnet 'concentrates'. Less-dense minerals such as quartz, feldspar and mica were removed in middling and tailing products. The concentrates generally contained between 70% and 95% garnet. GAR 8 contained less than 20% garnet, mainly due to the presence of pyroxene and amphibole.

The middling products generally contained up to 75% garnet and the tailings up to 20% garnet. This represents, respectively, up to 36% and up to 12% of the recoverable garnet present. The small losses to tailings are acceptable, however the higher losses to the middlings are not. Therefore the middling products of several samples were reprocessed by gravity separation in an attempt to recover this 'lost' garnet. Products with garnet contents comparable to the original concentrates were produced. In most cases over 50% of the 'lost' garnet was recovered. The unliberated garnet in some coarse-grained size fractions and middling products could be liberated by regrinding, preferably to less than 1 mm.

Based on the results of the laboratory mineral processing, the grade and recovery for combined garnet concentrates were calculated. They typically grade between 70% and 90%, with recoveries up to 63%. GAR 8 has a low grade due to the presence of amphibole and pyroxene. GAR 15 has a low recovery due to incomplete liberation.

Based on the laboratory mineral processing results the following samples were chosen for pilot-scale mineral processing trials:

GAR 3: A high head grade (21%). Concentrate with high garnet grade (87%) and recovery (61%). Relatively coarse crystals (up to 2.7 mm) free of inclusions.

GAR 16: A relatively high head grade (15%). Concentrate with high garnet grade (84%) and recovery (63%). Relatively coarse crystals (up to 1.8 mm), with euhedral form and free of inclusions.

Pilot-scale mineral processing

The results of the pilot-scale mineral processing are given in Appendix 10 and are summarised in Table 8.

Table 8 Pilot-scale mineral processing of garnet

	Garnet		
Sample	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
GAR 4			
Concentrate	3.2	99	12
Conc. and middling	25.9	77	76
GAR 11			
Concentrate	6.0	99	27
Conc. and middling	29.5	62	83

The mineral spiral test work produced garnet concentrates, containing between 69% and 85% garnet. The concentrates were dry screened on 300 µm, 150 µm and 75 µm sieves. The +300 µm fraction of the concentrates contained up to 99% garnet with a small amount of biotite mica inclusions visibly present in the garnet. The recoveries are low, up to 36% for the +300 µm concentrates. The remaining garnet mainly occurs in the +300 µm fraction of the middling products, which contain up to 90% garnet with up to 78% recovery. A significant proportion of this garnet is partially unliberated. The small amount of garnet unaccounted for mainly occurs in the -300 +150 µm fractions of the concentrate and middling products. Reprocessing of these products would recover a significant proportion of 'lost' garnet, although the +300 µm fractions would probably have to be reground to less than 600 µm to liberate the garnet.

Combined concentrate and middling +300 µm fractions yields concentrates grading up to 87% garnet with up to 84% recovery for GAR 3, and up to 75% garnet with up to 86% recovery for GAR 16.

Evaluation of products

The important applications of garnet include sand blasting, water jet cutting, water filtration, abrasives, polishing and lapping, and anti-skid surfaces. The specifications for garnet include particle-size distribution, garnet content, free silica content, specific gravity, hardness and particle-shape. The specific gravity of the garnet concentrates is given in Appendix 11. Commercial garnet products have specific gravities of at least 4 g/cm^3 (Harben, 1995). The garnet concentrates have specific gravities in the range 3.3 to 4 g/cm^3. GAR 3 and 16 produced high grade products with specific gravities of 4 g/cm^3.

CONCLUSIONS

Andalusite

1. The andalusite samples from north-east Scotland were generally Dalradian pelitic schists, containing between 2 and 10% andalusite in a quartz-mica matrix. The andalusite occurs as two forms of porphyroblast (up to 6.5 mm in length): i) euhedral crystals with relatively few inclusions and often displaying 'chiastolite cross' texture; and ii) irregular crystals, with poikiloblastic texture and/or heavily included, often closely associated with cordierite. Some andalusite is totally replaced by sericite. In addition garnet occurs as porphyroblasts, up to 1 mm in diameter, in several samples.

2. Five samples (AND 4, 5, 10, 11 and 16) were chosen for laboratory mineral processing trials and a combination of magnetic and gravity separation was used to produce andalusite concentrates. AND 4 and 5 produced concentrates containing 99% andalusite with recoveries up to 45%. AND 10 and 11 produced concentrates containing up to 96% andalusite but with low recoveries. AND 16 produced concentrates with low andalusite contents and poor recoveries.

3. Two samples (AND 4 and 11) were selected for pilot-scale mineral processing trials. A computer model was used to simulate dense media cyclone separations and showed that AND 4 would produce concentrates containing up to 80% andalusite with recoveries up to 95% and AND 11 would produce concentrates with low andalusite contents and poor recoveries. A mineral spiral was used to produce andalusite concentrates. Both AND 4 and 11 produced concentrates with low andalusite contents and poor recoveries. The poor results are partly due to the limited nature of the pilot scale processing. Further trials, to optimise the separation conditions, may produce better results. The small density difference between the andalusite and the gangue minerals may also partly account for the poor processing performance.

4. The andalusite concentrates produced, by the laboratory and pilot-scale mineral processing, do not match the chemical specifications required for industrial grade andalusite. The Al_2O_3 and Fe_2O_3 contents, which are especially critical, are, respectively, too low and too high, making them unsuitable for use as industrial raw materials.

Garnet

5. The garnet samples collected from the Scottish Highlands comprised mainly schists with some gneiss, anorthosite, amphibolite and beach sand. They mostly contain between 5 and 25% garnet porphyroblasts in a quartz-mica or feldspar matrix. The garnet in these samples occurs in two forms up to 10 mm in diameter: i) inclusion-free, euhedral to rounded crystals; and ii) inclusion-rich, irregular to sub-hexagonal crystals.

6. Nine samples (GAR 1, 3, 5, 7, 8, 11, 13, 15 and 16) were chosen for laboratory mineral processing trials and a combination of magnetic and gravity separation was used to produce garnet concentrates. Typically, concentrates containing up to 90% garnet with up to 63% recovery were produced. Poor separation efficiency or incomplete liberation resulted in some concentrates with low garnet contents and/or poor recoveries.

7. Two samples (GAR 3 and 16) were chosen for pilot-scale mineral processing trials. A mineral spiral was used to produce garnet concentrates. Both samples produced concentrates containing up to 99% garnet with poor recoveries. The remaining garnet occurs in the middling products. Combination

of the concentrates and middlings would produce products containing up to 87% garnet with recoveries up to 86%.

8. The garnet concentrates produced, by both the laboratory and pilot-scale mineral processing, have densities up to 4 g/cm^3. This indicates that they (especially GAR 3 and 16) may be suitable for use as industrial grade garnet, although further end-use specific testing will be required for confirmation.

The more promising samples were collected from garnet-mica-schist host-rocks of Dalradian age at locations from near Huntly in north-east Scotland to Loch Fyne in the south-west Highlands.

RECOMMENDATIONS

1. The study has shown that the andalusite-bearing rocks of north-east Scotland have a low resource potential and no further work is recommended.

2. The garnet-bearing rocks of the Scottish Highlands at some localities are potential sources of commercial garnet and it is recommended that further investigations should be undertaken to test this potential, particularly further pilot-scale mineral processing involving:

   (i) collection of larger bulk samples (GAR 3 and 16) for mineral spiral processing;

   (ii) collection of bulk samples from other sites (GAR 11, 13 and 15) for mineral spiral processing;

   (iii) reprocessing mineral spiral products to improve garnet recovery, including grinding of middling products to liberate garnet;

   (iv) detailed evaluation of spiral processing products, including garnet content, specific gravity, chemistry, particle-size and shape.

3. This study has considered only garnet and andalusite. It is recommended that possible sources of other industrial minerals in the Scottish Highlands, including feldspar, silica sand, graphite and talc should be investigated.

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APPENDIX 1 Glossary

Closed circuit Applied to crushing and grinding. The crushed/ground product is screened and oversize material is fed back into the crusher/grinder. This reduces the amount of fine material produced.

Concentrate A processed product containing the highest proportion of the valuable mineral.

Degree of liberation The percentage of the valuable mineral occurring as liberated particles in the sample in relation to the total content.

Feed The raw material, or head.

Gangue The non-valuable minerals, or waste.

Grade The valuable mineral content.

Head See feed.

Heavy liquid Liquids used for heavy media seperation, usually bromoform (2.9 g/cm^3) and/or Di-iodomethane (3.3 g/cm^3).

Heavy minerals Minerals with a specific gravity greater than 3 g/cm^3.

HMS Heavy Media Separation. The separation of minerals based on their density using a heavy liquid.

Jaw crusher Crusher with two plates that open and shut like animal jaws. One jaw is fixed and the other is pivoted to close onto the fixed jaw at set distances. Material fed into the crusher is alternately squeezed and released. As the material is broken down it progresses to the aperture and is released once finer than a set particle-size.

Liberation Release of the valuable mineral from the host rock.

Magnetic field gradient The rate at which the magnetic field intensity increases toward the magnet surface.

Magnetic flux The strength of a magnetic field through an area. The S.I. unit for magnetic flux density is the tesla (c.g.s unit is the gauss).

Magnetic susceptibility The ratio of the magnetisation produced in a substance to the magnetic field strength. Ferromagnetic materials have a high magnetic susceptibility.

Middling i) Particles containing valuable and non-valuable minerals.

ii) Processing products with valuable mineral contents lower than the concentrate but higher than the tailings. They do not necessarily contain middling particles.

Pulp A suspension of solids in a fluid (generally water).

APPENDIX 1 Glossary (continued)

Quality The physico-chemical properties of the target, or useful, mineral which determine its suitability for specific end uses.

Recovery The proportion of valuable mineral from the head that reports to the processing product.

Roller mill Crusher with two cylindrical rolls which rotate toward each other. Material is fed into the rolls and is broken down by pressure as it passes through.

Tailing Processing product with the lowest valuable mineral content.

Target mineral The valuable mineral.

Valuable mineral The target mineral.

Yield Proportion of the head mass that the processing product represents.

APPENDIX 2 Petrography of andalusite samples

Detailed petrographic descriptions are given for those samples selected for sample preparation and processing studies. Other samples are more briefly described.

AND 1 Correen Quarry NJ 522 213

A weathered pelitic schist with large andalusite porphyroblasts in a quartz-mica rich matrix. The quartz occurs as elongated subhedral crystals, 30 to 600 µm long, parallel to the foliation, often in alternating fine- and coarse-grained bands. Mica, 30 to 400 µm long, occurs interlayered with the quartz, often defining the foliation. Occasional opaque grains, 10 to 400 µm in diameter also occur. Two types of porphyroblast are recognised. Large, irregular to rounded prismatic cordierite porphyroblasts, ranging in size from 1.5 to 4.5 mm which generally contain a high proportion of inclusions (quartz, mica and opaques). These porphyroblasts have indistinct crystal boundaries and the low relief and the pale brown body colour are the only properties distinguishing them from the matrix. The second type of porphyroblast occurs as smaller, square crystals of andalusite, typically displaying 'chiastolite' cross texture of fine inclusions. They have weakly developed cross-cutting cleavage and range in size from 0.5 to 1.5 mm. Minor accessory minerals present include zircon (?), chlorite and staurolite.

AND 2 Correen Quarry NJ 522 213

A slightly weathered, well foliated pelitic schist with abundant cordierite porphyroblasts in a quartz-mica rich matrix. The porphyroblasts are dominated by cordierite, with only one porphyroblast of andalusite identified. This displayed a poikiloblastic texture (with inclusions of quartz, opaques and mica), an irregular shape and poorly defined crystal boundaries.

AND 3 Terpersie NJ 536 205

Highly weathered pelitic schist with abundant cordierite porphyroblasts in a coarse-grained quartz-mica matrix. Reddish-brown colouration (due to weathering?). Few andalusite porphyroblasts are present, usually closely associated with cordierite. The andalusite occurs as irregular crystals, often as a 'mantle' to a cordierite core and has many inclusions of quartz, mica and opaques. The andalusite also has poorly defined crystal boundaries.

AND 4 Creag Nearach NJ 262 339

A weathered pelitic schist with andalusite and garnet porphyroblasts in a quartz-mica matrix. The quartz occurs as an interlocking mosaic of crystals, ranging in size from 60 µm to 1 mm, often in alternating layers of coarse- and fine-grained crystals. The mica occurs as fine crystals 10 to 20 µm long, defining the foliation and is also disseminated throughout the matrix. The andalusite occurs as large, 0.8 to 4.6 mm, euhedral to pseudohexagonal porphyroblasts, displaying a cross-cutting cleavage and often mantled with a thin layer of biotite mica. Quartz inclusions (30 to 150 µm) occur. Almandine garnet occurs as roundish porphyroblasts, 0.6 to 0.9 mm in diameter, often fragmented and sheathed in fine mica. Both the andalusite and garnet have distinct crystal boundaries.

AND 5 Tervie Burn NJ 249 326

Weathered pelitic schist with andalusite and garnet porphyroblasts in a foliated mica-quartz matrix. The mica occurs as fine crystals, 10 to 20 µm long and dominates the matrix. The quartz occurs as crystals 10 to 480 µm in diameter disseminated throughout and locally as aggregates/veins. Occasional opaques (rutile?), 60 µm to 1 mm in diameter occur. Andalusite occurs as euhedral to subhedral, pseudohexagonal crystals, 1.3 to 2.7 mm in diameter. They often contain fine inclusions in the core whereas the rim is free of inclusions. Garnet occurs as euhedral, hexagonal crystals with minor inclusions, and range in size from 0.2 to 1 mm in diameter. Both the andalusite and garnet display distinct crystal boundaries.

AND 6 Black Hillock NJ 373 292

Semi-pelite with large andalusite porphyroblasts in a weakly foliated mica-quartz matrix. Biotite mica occurs as crystals 50 to 600 μm long, often defining the foliation. Quartz occurs as crystals 30 μm to 1.5 mm in diameter and opaque minerals occur sporadically. The andalusite porphyroblasts are irregular to square in shape, with cross-cutting cleavage and poorly defined crystal boundaries. They display a poikiloblastic and/or heavily included texture (inclusions mainly fine-grained quartz and opaques, and coarse-grained mica). 'Chiastolite' cross texture often occurs. The andalusite crystals range in size from 0.6 to 3.6 mm in diameter. Garnet porphyroblasts occur as irregular to pseudohexagonal shaped crystals, 0.1 to 0.6 mm in diameter.

AND 7 Tap O' Noth NJ 483 291

Weathered spotted hornfels with cordierite porphyroblasts in a quartz-mica matrix. Occasional opaques occur. The cordierite porphyroblasts occur as poorly defined crystals with a poikiloblastic texture. No andalusite present.

AND 8 Felaiche Burn NJ 434 316

Pelitic phyllite with small andalusite porphyroblasts in a fine grained quartz-mica matrix, with occasional opaques. The andalusite porphyroblasts occur as rounded to sub-hexagonal crystals with a poikiloblastic and very heavily included texture (inclusions mainly quartz, with some mica and opaques). Faint 'chiastolite' cross texture occurs in some. The andalusite has 'granulated' appearance with a poorly defined shape and crystal boundaries.

AND 9 Felaiche Burn NJ 438 315

Weathered phyllite with abundant cordierite porphyroblasts in a quartz-mica matrix with occasional opaques. Few andalusite porphyroblasts occur, as very irregular, poikiloblastic and heavily included crystals with a very poorly defined crystal form and crystal boundaries.

AND 10 Mill of Kinnairdy NJ 611 501

Weathered semi-pelite with abundant coarse andalusite porphyroblasts in a relatively coarse grained quartz-mica matrix, with occasional opaques. Andalusite occurs as large, irregular to rounded porphyroblasts with poorly defined crystal boundaries and abundant inclusions (quartz and mica). Garnet occurs as small euhedral porphyroblasts, 120 to 240 μm in diameter.

AND 11 River Deveron NJ 611 495

Weathered semi-pelite with abundant coarse andalusite porphyroblasts in a quartz-mica matrix. Biotite mica occurs disseminated throughout, defining the foliation and ranging in size from 20 to 300 μm. The quartz ranges in size from 20 to 250 μm. Opaques are finely disseminated throughout the matrix. The andalusite occurs as large porphyroblasts from 0.5 to 6.5 mm in size with a rectangular outline and poorly defined crystal boundaries. Heavily included (inclusions, mainly quartz and mica, forming up to 50% of the crystal) texture giving the crystals a 'fragmented' appearance.

AND 12 Whitehills NJ 651 656

A 'knotted' weathered schist with abundant cordierite porphyroblasts in a quartz-mica matrix, with occasional opaques. No andalusite seen.

AND 13 Whitehills NJ 663 652

Highly weathered schist with abundant coarse andalusite porphyroblasts in a quartz-mica matrix with occasional opaques. The andalusite porphyroblasts are rounded with poorly defined crystal boundaries and are heavily sericitised.

AND 14 Pittulie NJ 950 679

Slightly weathered semi-pelite with abundant andalusite porphyroblasts in a quartz-mica matrix, with occasional opaques. The andalusite has poorly defined crystal form and boundaries, and is heavily sericitised.

AND 15 Broad Haven NK 053 302

Slightly weathered semi-pelitic schist with abundant andalusite porphyroblasts in a quartz-mica matrix, with occasional opaques. The andalusite is heavily sericitised.

AND 16 Mill of Ardo NJ 850 384

Slightly weathered semi-pelitic schist with abundant andalusite and cordierite porphyroblasts in a mica-quartz matrix, with occasional opaques. Biotite mica, 30 to 350 μm in size and quartz, 30 to 150 μm in size. Andalusite occurs as poikiloblastic porphyroblasts, 0.6 to 3.6 mm in size, with an irregular fragmented appearance. It occurs as a 'mantle' to cordierite porphyroblasts lined with biotite mica. It does not have a definite crystal boundary, and is therefore difficult to distinguish from the matrix. The cordierite occurs as poikiloblastic and included (inclusions mainly mica, plus quartz and opaques) porphyroblasts with a rounded, 'lozenge' shape. The cordierite has a yellowish colour.

AND 17 River Ythan NJ 846 385

Slightly weathered semi-pelitic schist with abundant andalusite porphyroblasts in a quartz-mica matrix with occasional opaques. The andalusite is heavily sericitised.

AND 18 River Ythan NJ 806 388

Slightly weathered hornfels/semi-pelitic schist with abundant andalusite and cordierite porphyroblasts in a quartz-mica matrix with occasional opaques. Biotite mica, 50 to 500 μm in size and quartz, 10 to 200 μm in size. Andalusite occurs as poikiloblastic and included (inclusions mainly quartz, opaques and mica) porphyroblasts with a rounded shape and an irregular, fragmented appearance. Ranging in size from 0.5 to 4.8 mm. Cordierite occurs as poikiloblastic and included porphyroblasts (inclusions mainly mica, quartz and opaques) with an irregular, rounded shape. They often occur as 'spots' surrounded by mica and andalusite and range in size 0.8 to 4.8 mm.

APPENDIX 3 Particle-size distribution, grade and recovery of andalusite

Size fraction	AND 1			AND 4					AND 5				
		Andalusite			Andalusite		Garnet			Andalusite		Garnet	
	Yield	Grade	Recovery	Yield	Grade	Recovery	Grade	Recovery	Yield	Grade	Recovery	Grade	Recovery
+4 mm	0.0	0.0	0.0	21.3	5.0	19.9	2.0	14.2	24.2	1.0	16.6	1.0	24.2
-4 +2 mm	0.0	0.0	0.0	30.5	5.0	28.5	2.0	20.2	30.5	2.0	42.0	1.0	30.5
-2 +1 mm	34.0	5.0	32.4	16.2	5.0	30.3	2.0	21.6	14.8	2.0	20.3	1.0	14.8
-1 mm +500 µm	17.5	10.0	33.3	10.0	10.0	9.4	10.0	33.3	9.4	1.0	6.5	1.0	9.4
-500 +250 µm	10.4	10.0	19.8	6.8	5.0	6.3	3.0	6.7	6.1	1.0	4.2	1.0	6.1
-250 µm	38.1	2.0	14.5	15.2	2.0	5.7	2.0	4.0	15.1	1.0	10.4	1.0	15.1
Total	100.0	5.2	100.0	100.0	5.4	100.0	2.8	100.0	100.0	1.5	100.0	1.0	100.0

Size fraction	AND 6					AND 8			AND 10				
		Andalusite		Garnet			Andalusite			Andalusite		Garnet	
	Yield	Grade	Recovery	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery	Grade	Recovery
+4 mm	27.4	2.0	35.8	1.0	41.1	25.4	1.0	8.7	22.8	10.0	36.7	1.0	36.2
-4 +2 mm	25.6	2.0	33.5	1.0	38.4	32.7	5.0	56.0	25.1	10.0	40.3	1.0	39.8
-2 +1 mm	12.2	1.0	8.0	1.0	9.2	13.6	5.0	23.3	8.0	10.0	12.9	1.0	12.8
-1 mm +500 µm	8.4	1.0	5.5	1.0	6.3	6.7	2.0	4.6	3.7	5.0	3.0	1.0	2.9
-500 +250 µm	6.6	1.0	4.3	1.0	5.0	3.3	1.0	1.1	3.9	2.0	1.3	2.0	2.5
-250 µm	19.8	1.0	12.9	0.0	0.0	18.4	1.0	6.3	36.5	1.0	5.9	1.0	5.8
Total	100.0	1.5	100.0	0.9	100.0	100.0	2.9	100.0	100.0	6.2	100.0	1.0	100.0

Size fraction	AND 11			AND 16			AND 18		
		Andalusite			Andalusite			Andalusite	
	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery
+4 mm	24.2	10.0	27.2	28.0	2.0	21.8	26.2	15.0	23.6
-4 +2 mm	29.8	10.0	33.6	30.7	2.0	23.9	31.5	15.0	28.4
-2 +1 mm	13.0	10.0	14.6	12.5	5.0	24.2	14.1	20.0	17.0
-1 mm +500 µm	6.8	10.0	7.7	6.7	5.0	13.0	8.2	30.0	14.8
-500 +250 µm	3.8	10.0	4.3	4.6	2.0	3.6	4.9	40.0	11.8
-250 µm	22.3	5.0	12.6	17.5	2.0	13.6	15.0	5.0	4.5
Total	100.0	8.9	100.0	100.0	2.6	100.0	100.0	16.7	100.0

APPENDIX 4 Laboratory mineral processing of andalusite

Sample AND 4

Product	Yield (wt %)	Andalusite Grade (wt %)	Andalusite Recovery (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
+4 mm *	21.3	5.0	14.2	2.0	15.7
-4 +2 mm *	30.5	5.0	20.3	2.0	22.5
-2 +1 mm	16.2	18.2	39.2	4.8	28.4
HMS					
Light product *	12.8	1.0	1.7	1.0	4.7
Heavy product	3.5	81.2	37.5	18.5	23.7
Magnetic separation of heavy product					
Magnetic product *	1.6	60.0	12.4	40.0	23.0
Non-magnetic product *	1.9	99.0	25.0	1.0	0.7
-1 mm +500 µm	10.0	12.8	17.0	5.4	20.1
Magnetic separation					
Magnetic product *	0.2	2.0	0.0	15.0	0.9
Non-magnetic product	9.9	13.0	17.0	5.3	19.2
HMS of non-magnetic product					
Light product *	8.0	0.0	0.0	0.0	0.0
Heavy product	1.8	71.0	17.0	29.0	19.2
Magnetic separation of heavy product					
Magnetic product *	0.6	15.0	1.2	85.0	18.8
Non-magnetic product *	1.2	99.0	15.8	1.0	0.4
-500 +250 µm	6.8	5.9	5.3	0.8	2.1
Magnetic separation					
Magnetic product *	1.2	1.0	0.2	2.0	0.9
Non-magnetic product	5.6	7.0	5.2	0.6	1.2
HMS of non-magnetic product					
Light product *	5.1	0.0	0.0	0.0	0.0
Heavy product	0.4	92.4	5.2	7.6	1.2
Magnetic separation of heavy product					
Magnetic product *	0.1	60.0	0.6	40.0	1.2
Non-magnetic product *	0.3	100.0	4.5	0.0	0.0
-250 µm *	15.2	2.0	4.0	2.0	11.2
Total (products with *)	100.0	7.5	100.0	2.7	100.0

APPENDIX 4 Laboratory mineral processing of andalusite (continued)

Sample AND 5

Product	Yield (wt %)	Andalusite Grade (wt %)	Andalusite Recovery (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
+4 mm *	24.2	10.0	24.6	1.0	17.5
-4 +2 mm *	30.5	10.0	31.2	1.4	31.1
HMS					
Light product *	27.4	1.0	2.8	1.0	19.8
Heavy product	3.1	90.0	28.4	5.0	11.2
-2 +1 mm	14.8	21.7	32.6	1.5	16.4
HMS					
Light product *	11.6	1.0	1.2	1.0	8.4
Heavy product	3.2	97.8	31.5	3.5	8.0
Magnetic separation of heavy product					
Magnetic product *	0.2	50.0	0.8	50.0	5.8
Non-magnetic product *	3.0	99.0	30.6	1.0	2.2
-1 mm +500 μm	9.4	6.4	6.1	2.3	15.5
Magnetic separation					
Magnetic product *	0.1	1.0	0.0	20.0	1.7
Non-magnetic product	9.3	6.5	6.1	2.0	13.7
HMS of non-magnetic product					
Light product *	8.5	0.0	0.0	0.0	0.0
Heavy product	0.8	76.0	6.1	24.0	13.7
Magnetic separation of heavy product					
Magnetic product *	0.2	20.0	0.5	80.0	13.3
Non-magnetic product *	0.6	99.0	5.6	1.0	0.4
-500 +250 μm	6.1	6.2	3.9	1.9	8.6
Magnetic separation					
Magnetic product *	0.4	2.0	0.1	15.0	4.6
Non-magnetic product	5.7	6.6	3.8	1.0	4.1
HMS of non-magnetic product					
Light product *	5.3	0.0	0.0	0.0	0.0
Heavy product	0.4	87.0	3.8	13.0	4.1
Magnetic separation of heavy product					
Magnetic product *	0.1	20.0	0.1	80.0	4.1
Non-magnetic product *	0.4	100.0	3.7	0.0	0.0
-250 μm *	15.1	1.0	1.5	1.0	10.9
Total (products with *)	100.0	9.8	100.0	1.4	100.0

APPENDIX 4 Laboratory mineral processing of andalusite (continued)

Sample AND 10

Product	Yield	Andalusite		Garnet	
		Grade	Recovery	Grade	Recovery
	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)
+4 mm *	22.8	5.0	36.2	1.0	22.9
-4 +2 mm *	25.1	5.1	40.4	0.0	0.0
HMS					
Light product *	25.0	5.0	36.8	0.0	0.0
Heavy product	0.0	100.0	3.6	2.0	0.0
-2 +1 mm	8.0	2.4	6.1	2.1	16.8
HMS					
Light product *	7.9	1.0	2.5	2.0	15.8
Heavy product	0.2	63.3	3.6	5.6	1.0
Magnetic separation of heavy product					
Magnetic product *	0.0	5.0	0.1	25.0	1.0
Non-magnetic product *	0.1	80.0	3.6	0.0	0.0
-1 mm +500 µm	3.7	3.3	3.9	2.1	7.9
Magnetic separation					
Magnetic product *	0.2	1.0	0.1	5.0	0.8
Non-magnetic product	3.5	3.4	3.8	2.0	7.1
HMS of non-magnetic product					
Light product *	3.4	1.0	1.1	1.0	3.4
Heavy product	0.2	50.8	2.7	21.8	3.7
Magnetic separation of heavy product					
Magnetic product *	0.1	2.0	0.0	50.0	3.5
Non-magnetic product *	0.1	85.0	2.7	2.0	0.2
-500 +250 µm	3.9	1.5	1.8	3.9	15.6
Magnetic separation					
Magnetic product *	0.9	1.0	0.3	5.0	4.3
Non-magnetic product	3.1	1.6	1.6	3.6	11.3
HMS of non-magnetic product					
Light product *	2.9	0.0	0.0	0.0	0.0
Heavy product	0.2	26.1	1.6	58.9	11.3
Magnetic separation of heavy product					
Magnetic product *	0.1	5.0	0.2	80.0	11.3
Non-magnetic product *	0.1	85.0	1.3	0.0	0.0
-250 µm *	36.5	1.0	11.6	1.0	36.7
Total (products with *)	100.0	3.1	100.0	1.0	100.0

APPENDIX 4 Laboratory mineral processing of andalusite (continued)

Sample AND 11

Product	**Yield** (wt %)	**Andalusite Grade** (wt %)	**Andalusite Recovery** (wt %)
+4 mm *	24.2	10.0	34.3
-4 +2 mm *	29.8	10.0	42.3
HMS			
Light product *	29.8	10.0	42.3
Heavy product	0.0	0.0	0.0
-2 +1 mm	13.0	5.6	10.4
HMS			
Light product *	12.9	5.0	9.2
Heavy product	0.1	95.0	1.2
Magnetic separation of heavy product			
Magnetic product *	0.0	0.0	0.0
Non-magnetic product *	0.1	95.0	1.2
-1 mm +500 µm	6.8	5.8	5.6
Magnetic separation			
Magnetic product *	0.3	1.0	0.0
Non-magnetic product	6.5	6.1	5.6
HMS of non-magnetic product			
Light product *	6.4	5.0	4.6
Heavy product	0.1	91.3	1.0
Magnetic separation of heavy product			
Magnetic product *	0.0	85.0	0.4
Non-magnetic product *	0.1	95.0	0.7
-500 +250 µm	3.9	1.7	0.9
Magnetic separation			
Magnetic product *	0.7	0.0	0.0
Non-magnetic product	3.1	2.1	0.9
HMS of non-magnetic product			
Light product *	3.1	0.0	0.0
Heavy product	0.1	94.7	0.9
Magnetic separation of heavy product			
Magnetic product *	0.0	75.0	0.1
Non-magnetic product *	0.1	98.0	0.8
-250 µm *	22.3	2.0	6.3
Total (products with *)	100.0	7.0	100.0

APPENDIX 4 Laboratory mineral processing of andalusite (continued)

Sample AND 16

Product	Yield (wt %)	Andalusite Grade (wt %)	Andalusite Recovery (wt %)
+4 mm *	28.0	2.0	21.6
-4 +2 mm *	30.7	2.0	23.7
-2 +1 mm *	12.5	5.0	24.0
-1mm +500 µm	6.7	5.2	13.3
Magnetic separation			
Magnetic product *	0.1	0.0	0.0
Non-magnetic product	6.6	5.2	13.3
HMS of non-magnetic product			
Light product *	3.0	2.0	2.3
Heavy product	3.6	7.9	11.0
Magnetic separation of heavy product			
Magnetic product *	0.9	1.0	0.3
Non-magnetic product *	2.8	10.0	10.7
-500 +250 µm	4.6	2.1	3.8
Magnetic separation			
Magnetic product *	0.8	0.0	0.0
Non-magnetic product	3.8	2.6	3.8
HMS of non-magnetic product			
Light product *	1.5	2.0	1.1
Heavy product	2.3	2.9	2.6
Magnetic separation of heavy product			
Magnetic product *	1.2	1.0	0.5
Non-magnetic product *	1.1	5.0	2.2
-250 µm *	17.5	2.0	13.5
Total (products with *)	100.0	2.6	100.0

APPENDIX 5 Pilot-scale mineral processing of andalusite

Sample GAR 4 Dense Media Cyclone (Modelling results)

Sink-float data used for modelling

Density (g/cm^3)	**Yield** (wt %)	**Andalusite Grade** (wt %)	**Andalusite Recovery** (wt %)
<2.9	80.7	0	0.0
2.9 - 2.95	1.7	10	1.2
2.95 - 3.00	0.6	30	1.3
3.00 - 3.05	1.0	50	3.6
3.05 - 3.10	0.4	80	2.5
3.10 - 3.20	1.5	90	9.6
>3.20	14.2	80	81.9

Modelling results

Ep = 0.04

Separating density (g/cm^3)	**Yield** (wt %)	**Andalusite Grade** (wt %)	**Andalusite Recovery** (wt %)
2.95	19.8	68.7	95.3
3	17.9	74.6	93.5
3.05	16.6	77.9	91.0
3.1	15.8	79.5	88.2

Ep = 0.06

Separating density (g/cm^3)	**Yield** (wt %)	**Andalusite Grade** (wt %)	**Andalusite Recovery** (wt %)
2.95	23.1	58.5	94.7
3	20.0	66.1	92.9
3.05	18.0	71.5	90.6
3.1	16.7	75.1	88.0

Separating density 3.00 g/cm^3

Ep	**Yield** (wt %)	**Andalusite Grade** (wt %)	**Andalusite Recovery** (wt %)
0.04	17.9	74.6	93.5
0.06	20.0	66.1	92.9
0.08	22.7	57.8	92.2
0.1	25.4	51.4	91.5
0.012	27.8	46.5	90.6

Separating density 3.05 g/cm^3

Ep	**Yield** (wt %)	**Andalusite Grade** (wt %)	**Andalusite Recovery** (wt %)
0.04	16.6	77.9	91.0
0.06	18.0	71.5	90.6
0.08	20.1	63.9	90.0
0.1	22.3	57.1	89.3
0.012	24.4	51.5	88.4

APPENDIX 5 Pilot-scale mineral processing of andalusite (continued)

Sample GAR 11 Dense Media Cyclone (Modelling results)

Sink-float data used for modelling

		Andalusite	
Density (g/cm^3)	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
<2.9	82.9	2	26.0
2.9 - 2.95	12.7	5	10.0
2.95 - 3.00	2.2	80	28.0
3.00 - 3.05	2.1	95	31.4
3.05 - 3.10	0.2	95	3.6
3.10 - 3.20	0.0	95	0.6
>3.20	0.0	90	0.4

Modelling results

Ep = 0.04

		Andalusite	
Separating density (g/cm^3)	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
2.9	17.6	24.2	66.6
2.95	9.8	35.5	54.3
3	5.0	46.0	36.0
3.05	2.3	50.1	18.1

Ep = 0.06

		Andalusite	
Separating density (g/cm^3)	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
2.9	21.7	18.7	66.6
2.95	13.6	24.4	51.9
3	8.2	28.9	37.0
3.05	4.7	30.6	22.5

Separating density 3.00 g/cm^3

		Andalusite	
Ep	**Yield (wt %)**	**Grade (wt %)**	**Recovery (wt %)**
0.04	5.0	46.0	36.0
0.06	8.2	28.9	37.0
0.08	11.6	20.9	38.1
0.1	14.9	16.8	39.1
0.012	17.8	14.3	40.0

N.B. Ep = Ecart probable, or the probable error of separation.

APPENDIX 5 Pilot-scale mineral processing of andalusite (continued)

Sample GAR 4 Mineral spiral results

Product	Yield (wt %)	Andalusite Grade (wt %)	Andalusite Recovery (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
-1.6 +500 µm					
Concentrate	3.7	40.0	32.9	5.0	9.5
Middling	12.7	2.0	5.6	1.0	6.5
Tailing	41.7	2.0	18.5	1.0	21.3
Total	58.1	4.4	57.1	1.3	37.3
-500 +75 µm					
Concentrate	1.9	30.0	12.7	25.0	24.3
Middling	3.4	5.0	3.8	5.0	8.7
Tailing	15.2	5.0	16.9	1.0	7.8
Total	20.5	7.3	33.4	3.9	40.8
-75 µm	21.4	2.0	9.5	2.0	21.9
Total	100.0	4.5	100.0	2.0	100.0

Sample AND 11 Mineral spiral results

Product	Yield	Andalusite Grade	Andalusite Recovery
-1.6 +500 µm			
Concentrate	2.3	35.0	14.0
Middling	19.5	5.0	17.0
Tailing	78.2	5.0	69.0
Total	100.0	6.0	100.0

APPENDIX 6 Major element chemistry of andalusite produced by laboratory and pilot-scale mineral processing and commercial products

Product	SiO_2 wt %	TiO_2 wt %	Al_2O_3 wt %	Fe_2O_3t wt %	MnO wt %	MgO wt %	CaO wt %	Na_2O wt %	K_2O wt %	P_2O_5 wt %	LOI wt %	Total wt %
AND 4 Laboratory processing												
-2 +1 mm concentrate	37.28	0.65	43.62	12.89	0.23	2.07	0.05	0.13	0.44	0.05	2.05	99.46
-1 mm +500 µm concentrate	34.62	0.84	47.09	13.20	0.17	1.97	0.04	0.07	0.29	0.06	1.05	99.40
-500 +250 µm concentrate	33.82	1.62	46.29	12.96	0.15	1.83	0.04	0.10	0.30	0.06	2.31	99.48
HMS (>3.3 g/cm^3) heavy product	35.36	0.67	46.05	12.77	0.15	1.90	0.05	0.07	0.30	0.05	1.96	99.33
Mozley shaking table concentrate	47.47	0.80	33.58	9.41	0.13	2.04	0.07	0.67	1.89	0.05	3.31	99.42
AND 4 Pilot-scale processing												
-1.6 mm +500 µm spiral concentrate	61.25	0.80	22.32	6.08	0.05	1.88	0.07	0.77	2.29	0.05	3.48	99.04
-500 +75 µm spiral concentrate	68.48	0.93	19.29	5.88	0.06	1.14	0.32	0.31	0.75	0.18	1.78	99.12
AND 5 Laboratory processing												
-4 +2 mm concentrate	42.18	0.69	39.83	11.32	0.06	2.06	0.06	0.17	0.71	0.04	2.15	99.27
-2 +1 mm concentrate	37.91	0.76	43.47	12.35	0.09	2.07	0.07	0.12	0.47	0.04	1.80	99.15
-1 mm +500 µm concentrate	36.82	2.44	43.05	11.93	0.07	1.95	0.05	0.14	0.52	0.04	2.00	99.01
-500 +250 µm concentrate	34.25	14.83	35.34	9.92	0.05	1.69	0.05	0.17	0.66	0.05	2.06	99.07
AND 10 Laboratory processing												
-2 +1 mm concentrate	49.05	0.93	33.12	8.38	0.22	1.57	1.21	1.57	1.21	0.06	1.30	98.61
-1 mm +250 µm concentrate	47.01	0.97	35.23	9.14	0.32	1.62	0.83	1.03	1.27	0.06	1.16	98.63
AND 11 Laboratory processing												
-1 mm +250 µm concentrate	39.51	1.82	50.14	3.73	0.05	0.68	0.18	0.12	0.98	0.13	1.44	98.80
HMS (>3.3 g/cm^3) heavy product	44.74	1.72	44.04	4.35	0.04	1.09	0.21	0.17	1.47	0.16	1.23	99.22
Mozley shaking table concentrate	51.42	1.30	27.13	7.37	0.04	2.66	0.29	0.77	4.60	0.12	3.16	98.86
AND 11 Pilot-scale processing												
-1.6 mm +500 µm concentrate	58.14	1.09	22.35	7.03	0.03	2.52	0.33	0.81	3.95	0.10	2.71	99.06
AND 16 Laboratory processing												
-1 mm +500 µm	53.87	1.24	23.72	9.43	0.09	2.67	0.82	1.41	3.69	0.15	1.72	98.81
-500 +250 µm	53.43	1.18	24.32	9.30	0.08	2.68	0.80	1.39	3.73	0.15	1.84	98.89
Commercial andalusite												
Purusite, South Africa	38.60	0.14	59.10	0.84	na	0.11	0.16	0.09	0.30	na	0.82	na
Andalusite KF, France	38.40	0.20	60.00	0.50	na	0.10	0.10	0.10	0.20	na	0.60	na
Andalusite Shangxi, China	31.34	2.78	51.23	4.26	na	0.71	3.28	0.16	0.91	na	1.18	na

n.a. = not available

APPENDIX 7 Petrography of garnet samples

Detailed petrographic descriptions are given for those samples selected for sample preparation processing studies. Other samples are more briefly described.

GAR 1 St. Cyrus Beach NO 756 647

Beach sand containing quartz, shell fragments, garnet, opaques (probably magnetite and ilmenite), rock fragments and ?pyroxene. The quartz, shell and rock fragments dominate the medium to very coarse sand fractions (>250 µm). The garnet and opaques occur mainly in the fine to very fine sand fractions (<250 µm). The garnet ranges in size from 250 to 63 µm.

GAR 2 Cairnie NJ 483 447

Mica schist with garnet porphyroblasts in a quartz, feldspar and mica matrix. Quartz and alkali feldspar form an interlocking mosaic of coarse crystals, 0.3 to 1.8 mm in size. Biotite mica and opaque minerals occur disseminated throughout, ranging in size from 0.3 to 2.7 mm and 0.15 to 0.9 mm respectively. Garnet occurs as small, 0.15 to 1.6 mm diameter, euhedral porphyroblasts with occasional large, up to 6.5 mm, poikiloblastic and heavily included porphyroblasts. Inclusions, up to 1 mm are mainly quartz, feldspar, plus mica and opaques. The garnet has distinct crystal boundaries.

GAR 3 Mains of Art Loch NJ 472 405

Mica schist with garnet porphyroblasts in a quartz-mica matrix. Quartz ranges in size from 0.3 to 1.8 mm, mica 0.15 to 1.8 mm and opaques 0.1 to 0.75 mm. Garnet occurs as rounded to sub-hexagonal porphyroblasts 0.1 to 2.7 mm in diameter with occasional inclusion-rich garnet (inclusions mainly quartz and mica). Distinct crystal boundaries.

GAR 4 Glen Glass NH 502 731

Schist with garnet porphyroblasts in a mica-rich matrix, with some quartz and opaques. Mica ranges in size from 0.3 to 1.2 mm, quartz 0.3 to 0.9 mm and opaques 60 µm to 0.6 mm. Garnet occurs as irregular to euhedral porphyroblasts, 0.15 to 2.2 mm in diameter, with distinct crystal boundaries. Variable amount of inclusions ranging from heavily included to inclusion-free. Often surrounded by quartz-infilled 'pressure shadows'.

GAR 5 Port Vasgo NC 574 651

Beach sand containing quartz, shell and rock fragments, garnet, opaques, ?pyroxene and mica. The quartz, shell and rock fragments dominate the coarse to very coarse sand fractions (>500 µm). The garnet and opaques occur mainly in the medium to very fine sand fractions (<500 µm). The garnet ranges in size from 1 mm to 63 µm.

GAR 6 Garbh Chnoc NC 575 545

Mica schist with very coarse garnet porphyroblasts in a quartz-mica matrix. Quartz ranges in size from 0.3 to 1.5 mm, mica 0.3 to 1.8 mm and opaques up to 0.3 mm. Garnet occurs as poikiloblastic and heavily included porphyroblasts ranging in size from 1.3 to 10 mm in diameter. Subhedral to irregular in shape. Inclusions are mainly quartz and opaques and form up to 40% of the garnet. Some garnets have a 'honeycomb' appearance.

GAR 7 Scouriemore NC 142 446

Gneiss with garnet and pyroxene porphyroblasts in a quartz-feldspar matrix. Quartz and alkali feldspar range in size from 0.2 to 0.9 mm and opaques up to 0.3 mm. Garnet occurs as rounded, inclusion-free porphyroblasts 0.3 to 3 mm in diameter. Orthopyroxene (enstatite?) occurs as pseudohexagonal porphyroblasts, 0.15 to 1.5 mm in diameter with clinopyroxene laminae.

GAR 8 Achiltibuie NC 033 078

Amphibolite with garnet, pyroxene and amphibole porphyroblasts in a quartz-feldspar matrix. Quartz and alkali feldspar range in size from 0.3 to 1.5 mm and opaques up to 0.2 mm. Amphibole (hornblende?) ranges in size from 0.1 to 1.5 mm and pyroxene from 0.3 to 1.8 mm. Chlorite also occurs. Garnet occurs as irregular porphyroblasts with relatively few inclusions (mainly coarse quartz, feldspar, pyroxene and amphibole). Garnet ranges in size from 0.3 to 4.5 mm in diameter.

GAR 9 Ardtoe NM 627 709

Gneiss with garnet porphyroblasts in a quartz, feldspar and mica matrix. Quartz and alkali feldspar range in size from 60 μm to 0.3 mm, biotite mica from 0.2 to 0.75 and opaques up to 0.3 mm. Chlorite is also present. Garnet occurs as irregular porphyroblasts often with inclusion-free core and heavily-included rim. Inclusions mainly quartz, feldspar and mica. Some porphyroblasts consist entirely of heavily-included garnet. Range in size from 0.75 to 1.8 mm.

GAR 10 Carnmore, Ardtoe NM 627 713

Gneiss with garnet porphyroblasts in a quartz, feldspar and mica matrix. Quartz and alkali feldspar range in size from 0.1 to 0.6 mm, mica 0.15 to 0.9 mm and opaques up to 0.15 mm. Chlorite is also present. Garnet occurs as poikiloblastic porphyroblasts relatively free of inclusions, with a pseudohexagonal shape ranging in size from 0.45 to 3 mm. Quartz-infilled 'pressure shadows' surround the garnet.

GAR 11 Garth Castle NN 762 504

Schist with garnet porphyroblasts in a quartz, feldspar and mica matrix. Quartz and alkali feldspar range in size from 0.1 to 0.6 mm, mica 0.15 to 0.45 mm and opaques up to 0.3 mm. Garnet occurs as two types of porphyroblast: i) irregular and heavily included, and ii) euhedral and relatively inclusion-free. Range in size from 0.6 to 4.2 mm.

GAR 12 Glen Lochay NN 555 350

Schist with garnet porphyroblasts in a quartz, feldspar and mica matrix, with occasional opaques. Quartz and alkali feldspar range in size from 60 μm to 0.45 mm, mica 0.15 to 0.75 μm and opaques up to 0.1 mm. Garnet occurs as sub-hexagonal to irregular porphyroblasts, 0.15 to 2.1 mm in diameter. Relatively inclusion-free (mainly quartz and opaques). Garnet often sheathed in mica and surrounded with a quartz-infilled 'pressure shadow'.

GAR 13 Kirkton NN 361 287

Schist with garnet porphyroblasts in a mica-rich matrix with some quartz, feldspar, chlorite and opaques. Quartz and feldspar range in size from 0.15 to 0.9 mm, mica and chlorite 0.1 to 0.45 μm and opaques up to 0.3mm. Garnets form large, 0.9 to 5.7 mm in diameter, sub-hexagonal porphyroblasts.

Relatively inclusion-free (mainly opaques and quartz). Often surrounded by chlorite infilled pressure shadows.

GAR 14 Loch Fyne NN 164 109

Schist with garnet porphyroblasts in a quartz-mica matrix, with some chlorite and opaques. All matrix minerals similar in size, 0.1 to 0.6 mm. Garnet occurs as two types of porphyroblast: i) irregular and included, and ii) sub-hexagonal and relatively inclusion-free. Range in size from 0.3 to 2.7 mm in diameter. Garnet often sheathed in mica and surrounded by chlorite infilled 'pressure shadows'. Sinusoidal inclusion trails are present indicating rotational deformation of garnet.

GAR 15 Loch Fyne NN 164 099

Schist with garnet porphyroblasts in a quartz-mica matrix, with some chlorite and opaques. Quartz and mica range in size from 0.1 to 0.45 mm and opaques up to 0.3 mm. Garnet occurs as sub-hedral to anhedral porphyroblasts, 0.2 to 2.7 mm in diameter. Relatively inclusion-free (mainly quartz and opaques). Chlorite often associated with garnet, partially as sheathing around porphyroblasts and infilling 'pressure shadows'.

GAR 16 Tulliemet NO 005 546

Schist with garnet porphyroblasts in a quartz-mica matrix with some opaques. Quartz ranges in size from 60 µm to 0.18 mm, mica 30 µm to 2 mm and opaques up to 0.3 mm. Garnet occurs as euhedral to sub-hedral porphyroblasts, 0.3 to 1.8 mm in diameter. Relatively inclusion-free (mainly quartz, plus opaques and mica).

GAR 17 Meall Reamhar NO 029 577

Schist with garnet porphyroblasts in a mica-rich matrix, with some quartz and opaques. Mica ranges in size from 30 µm to 2 mm, quartz up to 0.15 mm and opaques up to 0.45 mm. Garnet occurs as rounded, sub-hexagonal porphyroblasts, 0.15 to 1.9 mm in diameter. Relatively inclusion-free. Cordierite (?) occurs as tabular porphyroblasts ranging in size from 0.15 to 2 mm long.

GAR 18 Rodel Borehole 1 NG 054 856

Anorthosite with garnet and amphibole porphyroblasts. Matrix is composed of coarse-grained plagioclase feldspar in a closely interlocking mosaic. Range in size from 0.15 to 1 mm. Opaques range in size up to 1 mm. Garnet occurs as irregular to anhedral porphyroblasts ranging in size from 0.3 to 3.9 mm. and with an aggregated appearance. Usually heavily fractured and included. Amphibole (hornblende?) occurs as prismatic porphyroblasts ranging in size from 50 µm to 1.2 mm.

GAR 19 Rodel Borehole 5 NG 057 853

Anorthosite with garnet and hornblende porphyroblasts in a plagioclase feldspar matrix. The plagioclase feldspar is coarse-grained, 30 µm to 3 mm and has closely interlocking texture. Opaques occur up to 0.3 mm. Garnet occurs as porphyroblasts ranging in size from 0.3 to 4.5 mm in diameter, with relatively few inclusions (mainly quartz). Amphibole (hornblende?) occurs as prismatic porphyroblasts ranging in size from 30 µm to 1 mm.

APPENDIX 8 Particle-size distribution, grade and recovery of garnet

Size fraction	GAR 1 Yield	GAR 1 Garnet Grade	GAR 1 Recovery	GAR 3 Yield	GAR 3 Garnet Grade	GAR 3 Recovery	GAR 5 Yield	GAR 5 Garnet Grade	GAR 5 Recovery	GAR 7 Yield	GAR 7 Garnet Grade	GAR 7 Recovery
-2.36 +2 mm	-	-	-	-	-	-	0.05	0.00	0.00	-	-	-
-2 +1 mm	-	-	-	43.81	21.51	45.96	0.05	0.00	0.00	34.81	5.93	9.63
-1 mm +500 µm	0.08	0.00	0.00	21.93	19.23	20.57	9.13	1.00	0.38	20.90	14.70	14.34
-500 +250 µm	9.10	1.48	1.21	14.64	16.97	12.12	76.97	22.61	71.52	16.19	25.49	19.25
-250 +125 µm	84.49	9.42	71.58	9.67	21.05	9.93	13.66	50.00	28.08	12.14	39.48	22.36
-125 +63 µm	6.29	47.81	27.04	5.80	26.10	7.38	0.14	5.00	0.03	7.97	47.51	17.65
-63 µm	0.04	48.00	0.17	4.15	20.00	4.05	0.00	0.00	0.00	7.99	45.00	16.77
Total	100.00	11.12	100.00	100.00	20.51	100.00	100.00	24.33	100.00	100.00	21.44	100.00

Size fraction	GAR 8 Yield	GAR 8 Garnet Grade	GAR 8 Recovery	GAR 11 Yield	GAR 11 Garnet Grade	GAR 11 Recovery	GAR 12 Yield	GAR 12 Garnet Grade	GAR 12 Recovery	GAR 13 Yield	GAR 13 Garnet Grade	GAR 13 Recovery
-2.36 +2 mm	-	-	-	-	-	-	-	-	-	7.04	9.36	6.59
-2 +1 mm	18.56	2.26	10.98	29.36	12.78	34.04	-	-	-	34.38	12.65	43.48
-1 mm +500 µm	27.20	4.78	34.04	23.68	17.67	37.96	34.89	20.13	55.99	15.55	17.35	26.98
-500 +250 µm	20.06	3.06	16.07	14.55	9.80	12.94	22.09	14.33	25.24	12.47	9.99	12.46
-250 +125 µm	14.89	8.71	33.98	12.70	10.27	11.83	18.44	8.73	12.83	13.05	6.69	8.74
-125 +63 µm	9.65	0.95	2.40	10.17	2.56	2.36	12.78	4.91	5.00	9.85	1.00	0.99
-63 µm	9.64	1.00	2.52	9.54	1.00	0.87	11.80	1.00	0.94	7.65	1.00	0.77
Total	100.00	3.82	100.00	100.00	11.02	100.00	100.00	12.54	100.00	100.00	10.00	100.00

Size fraction	GAR 14 Yield	GAR 14 Garnet Grade	GAR 14 Recovery	GAR 15 Yield	GAR 15 Garnet Grade	GAR 15 Recovery	GAR 16 Yield	GAR 16 Garnet Grade	GAR 16 Recovery	GAR 19 Yield	GAR 19 Garnet Grade	GAR 19 Recovery
-2.36 +2 mm	-	-	-	-	-	-	-	-	-	-	-	-
-2 +1 mm	31.32	10.09	45.41	35.93	12.98	49.58	-	-	-	42.28	1.28	24.37
-1 mm +500 µm	19.88	11.06	31.59	19.73	13.90	29.15	33.37	17.76	40.91	20.30	2.02	18.47
-500 +250 µm	10.85	7.83	12.21	11.12	6.51	7.70	20.10	21.21	29.43	12.36	3.64	20.26
-250 +125 µm	12.91	3.84	7.12	11.17	6.99	8.30	13.32	18.45	16.96	9.52	6.40	27.45
-125 +63 µm	13.78	1.03	2.04	11.68	2.47	3.07	15.05	6.20	6.44	7.05	1.77	5.62
-63 µm	11.25	1.00	1.62	10.37	2.00	2.21	18.16	5.00	6.27	8.49	1.00	3.83
Total	100.00	16.66	100.00	100.00	9.41	100.00	100.00	14.49	100.00	100.00	2.22	100.00

APPENDIX 9 Laboratory mineral processing of garnet

Sample GAR 1

Product	**Yield (wt %)**	**Garnet**	
		Grade (wt %)	**Recovery (wt %)**
+500 µm	0.1	0.0	0.0
-500 +250 µm	9.1	1.5	1.2
-250 +125 µm	84.5	9.4	71.6
Magnetic separation			
Magnetic product	1.3	1.0	0.1
Garnet preconcentrate	15.5	51.1	71.5
Magnetic middling	5.6	0.0	0.0
Non-magnetic product	62.1	0.0	0.0
Gravity separation of garnet pre-concentrate			
Heavy product	0.5	50.0	2.1
Garnet concentrate	3.8	80.0	27.6
Middling	7.3	53.0	34.6
Tailing	4.0	20.0	7.2
-125 +63 µm	6.3	47.8	27.0
-63 µm	0.0	48.0	0.2
Total	100.0	11.1	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 3

Product	Yield (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
-2 +1 mm	43.8	21.5	46.0
Magnetic separation			
Garnet pre-concentrate	17.8	37.6	32.6
Non-magnetic	26.0	10.5	13.4
Gravity separation of garnet pre-concentrate			
Concentrate	3.7	95.0	17.2
Middling	1.9	70.0	6.5
Tailing	12.2	15.0	8.9
Gravity separation of non-magnetic product			
Concentrate	2.1	75.0	7.5
Middling	8.9	10.0	4.4
Tailing	15.0	2.0	1.5
-1 mm +500 µm	21.9	19.2	20.6
Magnetic separation			
Garnet pre-concentrate	7.4	54.9	19.9
Non-magnetic	14.5	1.0	0.7
Gravity separation of garnet pre-concentrate			
Concentrate	2.2	88.7	9.3
Middling	3.4	54.9	9.2
Tailing	1.8	15.0	1.3
Gravity separation of middling product			
Concentrate	1.3	80.0	5.0
Tailing	2.2	40.0	4.2
-500 +250 µm	14.6	17.0	12.1
Magnetic separation			
Garnet pre-concentrate	6.4	39.1	12.1
Non-magnetic	8.3	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.2	81.7	4.8
Middling	2.9	43.8	6.2
Tailing	2.2	10.0	1.1
Gravity separation of middling product			
Garnet concentrate	0.7	75.0	2.5
Middling	1.5	48.3	3.6
Tailing	0.7	5.0	0.2
-250 +125 µm	9.7	21.0	9.9
Magnetic separation			
Garnet pre-concentrate	4.1	49.2	9.9
Non-magnetic	5.5	0.0	0.0
Gravity seperation of garnet pre-concentrate			
Garnet concentrate	1.8	90.0	8.0
Middling	0.6	53.4	1.5
Tailing	1.7	4.9	0.4
Gravity seperation of middling product			
Garnet concentrate	0.2	70.0	0.8
Middling	0.2	50.0	0.6
Tailing	0.1	10.0	0.0
-125 +63 µm	5.8	26.1	7.4
Magnetic separation			
Garnet pre-concentrate	2.7	56.6	7.4
Non-magnetic	3.1	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.2	95.0	5.6
Middling	0.5	75.0	1.7
Tailing	1.0	0.0	0.0
-63 µm	4.1	20.0	4.0
Total	100.0	20.5	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 5

Product	**Yield (wt %)**	**Garnet Grade (wt %)**	**Garnet Recovery (wt %)**
+2 mm	0.0	0.0	0.0
-2 +1 mm	0.0	0.0	0.0
-1 mm +500 µm	9.1	1.0	0.4
-500 +250 µm	77.0	22.6	71.5
Magnetic separation			
Garnet pre-concentrate	21.2	81.1	70.7
Magnetic middling	2.0	10.0	0.8
Non-magnetic	53.7	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	8.6	90.0	31.7
Tailing	12.6	75.0	39.0
-250 +125 µm	13.7	50.0	28.1
-125 +63 µm	0.1	5.0	0.0
-63 µm	0.0	0.0	0.0
Total	100.0	24.3	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 7

Product	Yield (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
-2 +1mm	34.8	5.9	9.6
-1 mm +500 µm	20.9	14.7	14.3
Magnetic separation			
Magnetic product	8.8	9.0	3.7
Garnet pre-concentrate	5.7	32.1	8.5
Magnetic middling	2.8	10.0	1.3
Non-magnetic	3.7	5.0	0.9
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.0	80.0	3.7
Middling	0.9	50.0	2.2
Tailing	3.7	15.0	2.6
-500 +250 µm	16.2	25.5	19.2
Magnetic separation			
Magnetic product	1.4	2.0	0.1
Garnet pre-concentrate	12.7	32.2	19.1
Non-magnetic product	2.1	0.1	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	2.6	70.0	8.5
Middling	6.7	31.4	9.8
Tailing	3.4	5.0	0.8
-250 +125 µm	12.1	39.5	22.4
Magnetic separation			
Garnet pre-concentrate	9.4	50.8	22.2
Magnetic middling	1.0	4.1	0.2
Non-magnetic	1.8	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	3.6	75.0	12.6
High-garnet middling	2.4	56.2	6.2
Low-garnet middling	3.0	23.6	3.3
Tailing	0.4	1.0	0.0
-125 +63 µm	8.0	47.5	17.7
Magnetic separation			
Garnet pre-concentrate	6.3	59.8	17.6
Magnetic middling	0.3	1.0	0.0
Non-magnetic	1.3	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.9	90.0	8.1
Middling	3.3	62.2	9.6
Tailing	1.1	0.6	0.0
-63 µm	8.0	45.0	16.8
Total	100.0	21.4	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 8

Product	**Yield** (wt %)	**Garnet** **Grade** (wt %)	**Garnet** **Recovery** (wt %)
-2 +1mm	18.6	2.3	11.0
-1 mm +500 µm	27.2	4.8	34.0
-500 +250 µm	20.1	3.1	16.1
Magnetic separation			
Garnet pre-concentrate	17.3	3.6	16.1
Non-magnetic	2.8	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.7	10.0	4.5
Middling	10.8	3.6	10.3
Tailing	4.7	1.0	1.2
-250 +125 µm	14.9	8.7	34.0
Magnetic separation			
Garnet pre-concentrate	13.0	10.0	34.0
Non-magnetic	1.9	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	3.8	17.6	17.5
Middling	7.5	8.1	16.1
Tailing	1.6	1.0	0.4
-125 +63 µm	9.6	1.0	2.4
-63 µm	9.6	1.0	2.5
Total	100.0	3.8	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 11

Product	**Yield** (wt %)	**Garnet** **Grade** (wt %)	**Recovery** (wt %)
-2 +1mm	29.4	12.8	34.0
-1 mm +500 µm	23.7	17.7	38.0
-500 +250 µm	14.6	9.8	12.9
Magnetic separation			
Garnet pre-concentrate	5.9	24.1	12.9
Non-magnetic	8.6	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	0.7	70.9	4.7
High garnet middling	2.3	30.0	6.4
Low garnet middling	1.1	15.0	1.5
Tailing	1.7	2.0	0.3
Gravity separation of garnet concentrate			
Garnet concentrate	0.5	90.0	4.4
Tailing	0.2	20.0	0.4
Gravity separation of high-garnet middling			
Garnet concentrate	0.4	70.0	2.5
Middling	0.5	60.0	2.5
Tailing	1.5	10.0	1.3
-250 +125 µm	12.7	10.3	11.8
Magnetic separation			
Garnet pre-concentrate	5.6	23.3	11.8
Non-magnetic	7.1	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.4	70.0	9.0
Middling	0.5	54.5	2.5
Tailing	3.7	1.2	0.4
-125 +63 µm	10.2	2.6	2.4
Magnetic separation			
Magnetic product	0.7	1.0	0.1
Garnet pre-concentrate	2.2	10.0	2.0
Middling	3.2	1.0	0.3
Non-magnetic	4.0	0.0	0.0
-63 µm	9.5	1.0	0.9
Total	100.0	11.0	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 13

Product	Yield (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
-2.36 +2 mm	7.0	9.4	6.6
Gravity separation			
Garnet concentrate	0.8	60.0	4.6
Middling	3.4	5.0	1.7
Tailing	2.9	1.0	0.3
-2 +1 mm	34.4	12.6	43.5
Magnetic separation			
Garnet pre-concentrate	4.3	34.7	14.8
Non-magnetic	30.1	9.5	28.7
Gravity separation of garnet pre-concentrate			
Concentrate	0.9	90.0	8.5
Middling	1.0	40.0	3.9
Tailing	2.3	10.0	2.3
Gravity separation of non-magnetic product			
Garnet concentrate	2.1	75.0	16.1
Middling	8.8	10.0	8.8
Tailing	19.2	2.0	3.8
-1 mm +500 µm	15.6	17.4	27.0
Magnetic separation			
Garnet pre-concentrate	4.2	56.7	27.0
Non-magnetic	11.4	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.4	85.0	14.1
Middling	1.6	59.1	11.1
Tailing	1.1	15.0	1.9
Gravity separation of middling			
Garnet concentrate	0.6	75.0	5.1
Tailing	1.0	50.0	6.0
-500 +250 µm	12.5	10.0	12.5
Magnetic separation			
Magnetic product	0.2	0.0	0.0
Garnet pre-concentrate	4.4	28.6	12.5
Non-magnetic	7.9	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	0.9	80.0	7.4
Middling	2.0	25.1	4.9
Tailing	1.5	1.0	0.1
Gravity separation of middling			
Garnet concentrate	0.6	50.0	2.9
Middling	0.8	23.0	1.9
Tailing	0.6	2.0	0.1
-250 +125 µm	13.0	6.7	8.7
Magnetic separation			
Magnetic product	0.3	1.0	0.0
Garnet pre-concentrate	3.3	26.4	8.6
Magnetic middling	1.0	1.0	0.1
Non-magnetic	8.5	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.0	80.0	8.4
Tailing	2.2	1.0	0.2
-125 +63 µm	9.9	1.0	1.0
-63 µm	7.7	1.0	0.8
Total	100.0	10.0	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 15

Product	Yield (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
-2 +1 mm	35.9	13.0	49.6
-1 mm +500 µm	19.7	13.9	29.2
-500 +250 µm	11.1	6.5	7.7
Magnetic separation			
Garnet pre-concentrate	4.3	16.4	7.6
Magnetic middling	1.0	1.0	0.1
Non-magnetic	5.7	0.0	0.0
Gravity seperation of garnet pre-concentrate			
Garnet concentrate	0.6	70.0	4.4
Middling	2.2	12.7	3.0
Tailing	1.5	1.0	0.2
-250 +125 µm	11.2	7.0	8.3
Magnetic separation			
Garnet pre-concentrate	4.6	16.6	8.1
Magnetic middling	1.6	1.0	0.2
Non-magnetic	4.9	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.1	70.0	8.0
Middling	1.4	1.0	0.2
Tailing	2.1	0.0	0.0
-125 +63 µm	11.7	2.5	3.1
-63 µm	10.4	2.0	2.2
Total	100.0	9.4	100.0

APPENDIX 9 Laboratory mineral processing of garnet (continued)

Sample GAR 16

Product	Yield (wt %)	Garnet Grade (wt %)	Garnet Recovery (wt %)
-1 mm +500 µm	33.4	17.8	40.9
Magnetic separation			
Garnet pre-concentrate	9.8	60.6	40.9
Non-magnetic	23.6	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	2.9	80.0	16.3
Middling	4.2	60.0	17.2
Tailing	2.7	40.0	7.4
Gravity separation of middling			
Garnet concentrate	2.3	80.0	10.7
Tailing	1.9	60.0	6.5
-500 +250 µm	20.1	21.2	29.4
Magnetic separation			
Garnet pre-concentrate	7.8	54.0	29.2
Magnetic middling	1.4	2.0	0.2
Non-magnetic	10.8	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.6	90.0	10.1
Middling	3.7	72.0	18.5
Tailing	2.5	3.7	0.6
Gravity separation of middling			
Garnet concentrate	1.8	80.0	9.8
Middling	1.3	71.4	6.6
Tailing	0.6	50.0	2.1
-250 +125 µm	13.3	18.5	17.0
Magnetic separation			
Garnet pre-concentrate	5.4	45.1	16.9
Magnetic middling	1.5	1.0	0.1
Non-magnetic	6.4	0.0	0.0
Gravity separation of garnet pre-concentrate			
Garnet concentrate	1.9	95.0	12.5
Middling	0.9	61.0	3.9
Tailing	2.6	2.4	0.4
Gravity separation of middling			
Garnet concentrate	0.6	80.0	3.2
Middling	0.3	34.9	0.7
Tailing	0.1	2.0	0.0
-125 +63 µm	15.1	6.2	6.4
-63 µm	18.2	5.0	6.3
Total	100.0	14.5	100.0

APPENDIX 10 Pilot-scale mineral processing of garnet
Sample GAR 3 Mineral spiral processing

Product	Yield	Garnet	
		Grade	Recovery
	wt %	wt %	wt %
First Trial	100.0	26.2	100.0
Concentrate	3.9	69.4	10.3
+300 µm	1.5	98.0	5.8
-300 +150 µm	1.3	80.0	3.9
-150 +75 µm	0.8	20.0	0.6
-75 µm	0.3	1.0	0.0
Middling	44.5	51.0	86.6
+300 µm	29.3	70.0	78.1
-300 +150 µm	10.2	20.0	7.8
-150 +75 µm	3.6	5.0	0.7
-75 µm	1.4	1.0	0.1
Tailing	51.6	1.6	3.1
+300 µm	35.7	2.0	2.7
-300 +150 µm	8.9	1.0	0.3
-150 +75 µm	3.7	0.0	0.0
-75 µm	3.3	0.0	0.0
Second Trial	100.0	26.1	100.0
Concentrate	11.5	73.1	32.2
+300 µm	4.3	99.0	16.2
-300 +150 µm	3.6	80.0	11.2
-150 +75 µm	2.5	50.0	4.8
-75 µm	1.1	1.0	0.0
Middling	34.7	49.9	66.3
+300 µm	20.0	70.0	53.5
-300 +150 µm	9.8	30.0	11.3
-150 +75 µm	3.8	10.0	1.4
-75 µm	1.2	1.0	0.0
Tailing	53.8	0.7	1.5
+300 µm	35.3	1.0	1.3
-300 +150 µm	9.4	0.5	0.2
-150 +75 µm	4.9	0.0	0.0
-75 µm	4.2	0.0	0.0
Third Trial	100.0	25.1	100.0
Concentrate	6.7	72.6	19.3
+300 µm	2.3	99.0	9.1
-300 +150 µm	2.1	90.0	7.7
-150 +75 µm	1.6	40.0	2.5
-75 µm	0.6	1.0	0.0
Middling	28.5	61.8	70.3
+300 µm	17.9	85.0	60.8
-300 +150 µm	7.0	30.0	8.3
-150 +75 µm	2.6	10.0	1.1
-75 µm	0.9	1.0	0.0
Tailing	64.9	4.0	10.4
+300 µm	48.0	5.0	9.6
-300 +150 µm	10.1	2.0	0.8
-150 +75 µm	4.1	0.0	0.0
-75 µm	2.6	0.0	0.0

APPENDIX 10 Pilot-scale mineral processing of garnet (continued)
Sample GAR 16 Spiral processing

Product	Yield	Garnet	
		Grade	Recovery
	wt %	wt %	wt %
First Trial	100.0	21.4	100.0
Concentrate	3.9	72.9	13.2
+300 µm	2.0	98.0	9.3
-300 +150 µm	0.9	80.0	3.4
-150 +75 µm	0.5	20.0	0.5
-75 µm	0.4	1.0	0.0
Middling	44.5	41.3	85.8
+300 µm	32.7	50.0	76.3
-300 +150 µm	6.3	30.0	8.9
-150 +75 µm	3.1	5.0	0.7
-75 µm	2.4	0.0	0.0
Tailing	51.6	0.4	0.9
+300 µm	36.3	0.5	0.8
-300 +150 µm	2.8	0.5	0.1
-150 +75 µm	4.4	0.0	0.0
-75 µm	8.2	0.0	0.0
Second Trial	100.0	22.0	100.0
Concentrate	11.5	85.0	44.5
+300 µm	8.1	99.0	36.3
-300 +150 µm	2.0	80.0	7.3
-150 +75 µm	0.9	20.0	0.8
-75 µm	0.5	1.0	0.0
Middling	34.7	34.6	54.6
+300 µm	21.7	50.0	49.3
-300 +150 µm	6.3	15.0	4.3
-150 +75 µm	3.9	5.0	0.9
-75 µm	2.9	1.0	0.1
Tailing	53.8	0.4	0.9
+300 µm	32.2	0.5	0.7
-300 +150 µm	9.3	0.5	0.2
-150 +75 µm	3.9	0.0	0.0
-75 µm	8.4	0.0	0.0
Third Trial	100.0	20.7	100.0
Concentrate	6.7	75.8	24.4
+300 µm	3.6	98.0	17.2
-300 +150 µm	1.6	80.0	6.3
-150 +75 µm	0.9	20.0	0.9
-75 µm	0.5	1.0	0.0
Middling	28.5	48.2	66.2
+300 µm	16.6	70.0	56.1
-300 +150 µm	6.4	30.0	9.2
-150 +75 µm	3.2	5.0	0.8
-75 µm	2.3	1.0	0.1
Tailing	64.9	3.0	9.4
+300 µm	35.2	5.0	8.5
-300 +150 µm	6.1	1.0	0.3
-150 +75 µm	6.8	0.5	0.2
-75 µm	16.8	0.5	0.4

APPENDIX 11 Specific gravity of garnet produced by laboratory and pilot-scale mineral processing and commercial products

Product	S.G. (g/cm^3)
GAR 1	
+250 -125 μm concentrate	5.4
GAR 3 Laboratory processing	
-2 +1 mm magnetic concentrate	3.9
-2 +1 mm non-magnetic concentrate	3.7
-1 mm +500 μm concentrate	3.8
-1 mm +500 μm middling concentrate	3.8
-500 +250 μm concentrate	3.9
-500 +250 μm middling concentrate	3.7
-250 +125 μm concentrate	3.9
-250 +125 μm middling concentrate	3.7
-125 +63 μm concentrate	4.0
GAR 3 Pilot-scale processing	
Trial 1	4.0
Trial 2	4.0
Trial 3	4.0
GAR 5	
-500 +250 μm	4.3
GAR 7	
-1 mm +500 μm concentrate	3.7
-500 +250 μm concentrate	3.6
-250 +125 μm concentrate	3.6
-125 +63 μm concentrate	3.7
GAR 8	
-250 +125 μm concentrate	3.3
-500 +250 μm concentrate	3.4
GAR 11	
-500 +250 μm concentrate	3.7
-500 +250 μm middling concentrate	3.4
-250 +125 μm concentrate	3.3
GAR 13	
-2.6 +2 mm concentrate	3.5
-2 +1 mm magnetic concentrate	3.7
-2 +1 mm non-magnetic concentrate	3.5
-1 mm +500 μm concentrate	3.6
-1 mm +500 μm middling concentrate	3.5
-500 +250 μm concentrate	3.5
-500 +250 μm middling concentrate	3.4
-250 +125 μm concentrate	3.6
GAR 15	
-500 +250 μm concentrate	3.7
-250 +125 μm concentrate	3.5
GAR 16 Laboratory processing	
-1 mm +500 μm concentrate	3.8
-1 mm +500 μm middling concentrate	3.7
-500 +250 μm concentrate	3.8
-500 +250 μm middling concentrate	3.6
-250 +125 μm concentrate	3.9
-250 +125 μm middling concentrate	3.3
GAR 16 Pilot-scale processing	
Trial 1	4.0
Trial 2	4.0
Trial 3	4.0

Commercial Garnet

Ideally a specific gravity of 4 g/cm^3 is required for most applications.

S.G. = specific gravity. Samples GAR 1 and 5 contain other high density minerals which accounts for their high S.G. values.