

Technical Report WF/89/13
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**Marine deposits of chromite and olivine,
Inner Hebrides of Scotland**

M J Gallagher, I R Basham and others



Technical Report WF/89/13

Mineral Resources Series

**Marine deposits of chromite and
olivine, Inner Hebrides of Scotland**

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A banded carbonate/sphalerite/marcasite/galena vein from the Gwynfynydd Gold Mine, near Dolgellau in North Wales

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Mineral Reconnaissance Programme Report 106

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DATA PACKAGE

This report is a summary of the sampling survey, chemical, and mineralogical analyses, full details of which are contained in a data package available at a current 1989 cost of 1000 pounds sterling plus VAT. This includes:

- A Consultation with available staff of the British Geological Survey who carried out the work.
- B Examination of the seafloor samples and derived mineral concentrates.
- C The listings and maps itemised below.
 - 1. Listing of geographical coordinates and bathymetric depths of all sample stations and of other stations where only bathymetric observations were made. Note that depths were recorded beneath the keel of the survey ship, 3.3 m below water.
 - 2. Listing of acid-soluble carbonate content and X-ray fluorescence analyses of the residues from 154 reconnaissance samples and from 8 earlier regional survey samples (TR 1241-1248), Rhum and Skye.
 - 3. Listing of acid-soluble carbonate content and X-ray fluorescence analyses of the residues from 31 selected samples of Rhum marine sediments.
 - 4. Listing of ICP-MS analyses of 31 selected samples of Rhum marine sediments (30 gram sample fire assay) and 5 fractions (60 gram sample fire assay) of sample TR 1022A.
 - 5. Maps at 1:50 000 scale showing sampling locations and bathymetric depth off southern Rhum and SW Skye. Concentrations of chromite and olivine are outlined.
 - 6. Maps at 1:10 000 scale showing the distribution of chromium and magnesium against bathymetric depth in the submarine deltas off Harris and Dìbidil, southern Rhum, based on bulk samples.
 - 7. Technical Report WG/89/2C.

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CONTENTS

Summary	1
Scope of present investigation	1
Outline geology of the Rhum and Skye volcanic centres	2
The survey off southern Rhum	3
The survey off SW Skye	3
Mineralogy	4
1 Procedures	4
2 Size distribution	7
3 Heavy mineral contents	7
4 Mineralogical analysis of samples TR1058 and TR1210	9
5 Further mineralogical and chemical data for olivine and chrome spinel	11
6 Estimation of olivine and chromite contents from bulk sand analyses for magnesium and chromium	15
7 Preliminary beneficiation trials and assessment	15
8 General comments	15
Conclusions and recommendations	19
Acknowledgements	20
References	20

TABLES

1. Summary of XRF analyses of reconnaissance samples of marine sand.
2. Size distribution in 10 selected samples, expressed as weight percentage of total sand.
3. Total heavy mineral (density $>2.9\text{g.cm}^{-3}$) contents of 5 samples expressed as weight distributions in size fractions.
4. Quantitative mineralogical composition of sample TR1058, expressed as weight percentage of total sand.
5. Quantitative mineralogical composition of sample TR1210, expressed as weight percentage of total sand.

FIGURES

1. Sample locations and bathymetric observations off southern Rhum, showing the approximate positions of the heavy mineral sands off Harris and Dibidil.
2. Sample locations and bathymetric observations off SW Skye.
3. Graph of calcite content (determined by acid dissolution) against calculated olivine content for 31 samples. Samples referred to in Table 2 are indicated.
4. Graph of calculated chromite against calculated olivine - 31 samples.
5. Frequency plot of olivine compositions (electron microprobe analyses of 141 grains from sample TR1058). Magnetic classes are: Sample C3 = moderately to non-magnetic; W = weakly magnetic; N = non-magnetic.
6. Frequency plot of chromite compositions (electron microprobe analyses of 83 grains from sample TR1058). Magnetic classes are:
Sample C1 = highly magnetic;
C2/3 = strongly to moderately magnetic;
W = weakly magnetic.
7. Compositional distribution diagram of 83 measured chromite grains.
Cr-number = $100 \cdot \text{Cr} / (\text{Cr} + \text{Al})$;
Mg-number = $100 \cdot \text{Mg} / (\text{Mg} + \text{Fe})$.

Table 1 Summary of XRF analyses of reconnaissance samples of marine sands

	Rhum (91 samples)				Rhum early survey (8 samples)				Skye (63 samples)			
	\bar{x}	s %	max.	min.	\bar{x}	s %	max.	min.	\bar{x}	s %	max.	min.
Mg	3.5	2.6	14	0	1.3	0.5	2	1	2.0	1.7	9	0
Ca	1.7	0.82	5.3	0.47	0.98	0.41	1.7	0.46	2.3	1.7	7.3	0.44
Ti	0.33	0.16	0.92	0.12	0.36	0.14	0.58	0.13	0.45	0.15	0.83	0.12
V	0.009	0.005	0.029	0.001	0.009	0.004	0.014	0.002	0.012	0.005	0.026	0.003
III A Cr ₂ O ₃	0.12	0.17	1.4	0	0.025	0.011	0.040	0.010	0.047	0.098	0.70	0.010
Fe	4.0	1.8	10.6	0.72	3.3	1.1	5.1	1.3	4.3	1.7	8.5	1.1

SUMMARY

A reconnaissance survey was carried out of near-shore marine deposits considered to have been derived from Tertiary ultrabasic rocks in SW Skye and southern Rhum, rocks known to be enriched in chrome spinel and forsteritic olivine. Dive sampling close to the rocky coastlines supplemented grab sampling at surveyed locations in water depths of 50 m or less. In the bay off Harris, southern Rhum, a heavy mineral sand deposit 3 km² in area occurs within 2 km of the coast in waters 20-25 m in average depth. A 1 km² deposit is present up to 1 km off Dìbidil, in an average water depth of about 20 m. Using a wet density of 2.2 g.cm⁻³ some 9 million tonnes of sand are calculated to be present in the topmost 1 m of the deltas. Shell calcite forming about 20% was removed prior to chemical analysis. The analytical results indicate that the surficial 1 m of sand contains some 70 000 tonnes of chrome spinel averaging 32% Cr₂O₃ at a grade of nearly 1%. Also present are 1.5 - 2 million tonnes of olivine averaging 47% MgO at 25% grade. Accompanying minerals are ilmenite and vanadiferous magnetite and traces of PGE have been detected. The minerals occur in sand-size fractions (125-500 μm from which concentrates of 86% chromite and 78% olivine at recoveries of 60% and 50% respectively have been achieved in the laboratory.

Most seabed samples from Loch Scavaig and the Soay Sound, SW Skye (63) are grey glacial sandy clays averaging only 0.05% Cr₂O₃, 2% Mg after carbonate dissolution. Heavy mineral sands derived from the Cuillins igneous centre may nevertheless underly the glacial deposits. Before glaciation, the 60 million year old ultrabasic rocks of Skye and Rhum were deeply eroded and their detritus supplied to the Sea of the Hebrides. The Harris and Dìbidil deposits, detected in a survey of the Rhum coastline from A'Bhrìdeanach in the extreme west to Loch Scresort in the east (99 samples), formed less than 10 000 years ago.

SCOPE OF PRESENT INVESTIGATION

Geochemical mapping (IGS, 1983), allied to University research (Emeleus, 1987) as well as the early geological mapping, indicate that chrome spinel is widespread in ultrabasic rocks of the Tertiary volcanic centres of southern Rhum and SW Skye. The Regional Geochemical Atlas anomalies of up to 1% Cr in stream sediments from Rhum were briefly evaluated in 1984. Heavy mineral concentrates from the alluvium contain up to 5% Cr and 100 ppb of platinum and palladium. The alluvial enrichment is especially marked in Glen Harris, forming some 10km² of drainage within the 15km² area of the Rhum Tertiary volcanic centre. In Skye, the initial chromium values were lower (maximum 0.17%Cr) but a brief follow-up in 1986 found up to 2% Cr and 30 ppb of platinum and palladium in heavy mineral concentrates from peridotite.

Surficial marine sediment was sampled off Rhum and Skye, 10-16 June 1987, from R V Calanus, a 55 ton Scottish Marine Biological Association vessel, and by the scientific diving team of J A Chesher and N C Campbell. As Calanus' keel depth is 3.3m (the reference point for bathymetric records) it is unable to operate close to rocky shores; the daily diving was therefore invaluable, providing 22 important sampling sites. Direct observation of the extent of heavy mineral sand in water depths down to 25m was obtained by inserting plastic tubing into the sandy seabed and a minimum depth of 1m of heavy mineral sand was established. Shipboard sampling was principally carried out with the Shipek grab device; gravity core sampling with an 0.5 tonne weight was ineffectual in the well graded heavy mineral sands and less satisfactory than the grab device in sandy clays. Only 3 shipboard samples taken in 6 days of sampling were with the corer.

Seafloor samples typically 3+2kg in weight were extracted by the Shipek grab device from 91 sites off southern Rhum and 63 from the waters of SW Skye.

Subsampling of the wet sand was effected on the ship, drying and removal of acid-soluble calcite in the laboratory before pelletising for XRF analysis. A further 8 samples taken in an earlier MGRP survey around Rhum have also been analysed. The samples were analysed for Mg, Ca, Ti, V, Cr₂O₃ and Fe (see Table 1). The bathymetric depth and a qualitative interpretation³ of seafloor lithology were recorded at each shipboard sampling site and at a further 81 unsampled sites using a Slimrad echo sounder. As no account was taken of tidal variation and the measured depths are those beneath the keel of the survey ship then the bathymetry is very approximate. Reproducible positioning was accurately related to the Decca Navigational System utilising a Racal-Decca Colour Video Plotter 3500 recently installed on Calanus whose Skipper, R Hagley, provided systematic records of all locations and depths on magnetic tape as well as listings.

From the analyses of the early subsamples, 31 of the bulk samples were selected, dried subsamples of approximately 0.5 kg taken, acid-soluble calcite removed and the dried residues subsampled for XRF analysis in 1988. 22 elements were determined at BGS, namely Mg, Ca, Ti, Mn, Fe, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Zr, Ag, Sb, Ba, La, Ce, Pb, As and Bi. Additionally, fire assays on 30g samples followed by ICP mass spectrometer analyses for Au, Pt, Pd and Rh were carried out at Acme Analytical Laboratories, Vancouver. All of the analytical data are listed in the Data Package. Mineralogical investigations of a small number of acid-treated and non acid-treated subsamples were also completed in 1988 and are summarised in this report. Electron microprobe data are included in a detailed mineralogy report forming part of the Data Package.

OUTLINE GEOLOGY OF THE RHUM AND SKYE VOLCANIC CENTRES

The igneous rocks of Rhum form part of the Tertiary magmatic province which is exposed in a N-S zone from Skye to northern Ireland. Together with contemporaneous igneous activity in East Greenland and the Faroes it represents a major expression of the evolution of the North Atlantic Ocean. This province comprises a series of basic to acid intrusive central complexes and extensive plateau lava fields along with associated dyke swarms and intrusive sheets. Magmatism probably spans a period of up to 15Ma but the main events were more likely restricted to about 5Ma peaking at about 58Ma ago.

On Skye extrusion of lavas was the earliest of the major igneous events and these can be traced southwards to the west of Rhum as a submarine ridge encompassing the island of Canna. The Cuillin Hills on Skye are formed from a series of arcuate intrusive gabbros, peridotites and allivalites that intrude the lava pile. Both lavas and basic intrusives are cut by the the Red Hills high level granites.

Rhum is situated astride a ridge of PreCambrian (Lewisian and Torridonian) metasedimentary basement which is bounded both east and west by Mesozoic basins which in turn formed the foci for lavas related to the Mull and Skye igneous centres, respectively. The prominent feature of the geology of Rhum, and forming the high central and southern mountains, is a thick (c. 1000 m) sequence of layered peridotites and gabbros. In contrast to Skye, emplacement of the layered basics postdates intrusion of a granite body. Remnants of a later extrusive episode are preserved as several basic to intermediate lava flows.

In the east the layered rocks comprise a series of feldspar peridotites, allivalites and anorthosites with associated eucritic gabbros, whilst to the west the sequence is mostly made up of eucrites and peridotites. Thin chromite rich layers underlie some peridotite layers in the eastern series. The mineralogy of the layered series is thus relatively simple, comprising olivine, diopside, plagioclase and spinel, with minor hypersthene.

Mineral compositions of olivine, spinel, and pyroxene from one sand sample from Harris Bay (see below) agree closely with published analyses of the same phases from the layered rocks (Dunham and Wadsworth, 1978) and confirm that these supplied virtually all the heavy mineral component of the sand. Olivine and pyroxene also occur in the Rhum lavas, which clearly had a greater areal extent than now apparent, but have more Fe-rich compositions (Emeleus, 1985) that do not appear to be represented in the data derived from the sand sample. The contribution from this source is therefore likely to be very small compared to that from the layered sequence.

THE SURVEY OFF SOUTHERN RHUM

Some 28 km of coastline were investigated between the westernmost and easternmost extremities of the island. Several rivers, notably the Abhain Rangail from Glen Harris and the Dibidil River from Glen Dibidil, as well as numerous streams, drain to this coastline from the Tertiary volcanic rocks of southern Rhum (see 1:50 000 OS Sheet 39, Rhum and Eigg and 1:20 000 Solid Geology Map of Rhum: Emeleus, 1980).

Material suitable for analysis was obtained at 91 of 142 stations, most of the bare rock sites occurring SE and NW of Harris. The seabed survey stations lie predominantly within 3 km of shore in water depths of less than approximately 50 m. However, off Harris and to a lesser extent Dibidil some sites were sampled at depths of approximately 60-70 m. Water depths at inshore diving stations were estimated.

Analysis of small shipboard subsamples after carbonate dissolution yielded mean values of 3.5% Mg and 0.12% Cr₂O₃ (Table 1). The submarine deltas off Harris and Dibidil are well-defined by the 0.12% Cr₂O₃ value (Fig. 1) and the heavy mineral sands are characteristically greenish-coloured owing to the abundance of forsterite. Lesser amounts of chromium and magnesium regarded as somewhat anomalous were detected in samples from elsewhere around the southern coast of Rhum and also in samples taken in deeper waters off Rhum as part of an earlier survey by colleagues in the Marine Geology Research Programme (see Table 1).

In the bay off Harris, a heavy mineral sand deposit of some 3 km² is defined within 2 km of the coast by 19 sample stations in waters 20-25 m average depth. A smaller deposit of 1 km² is present up to 1 km off Dibidil as defined by 8 sampling sites (bare rock formed a ninth site) in an average water depth of about 20 m.

It can be calculated that some 9 million tonnes of sand form the topmost 1 m of the Harris and Dibidil submarine deltas, utilising a wet density of 2.2 g.cm⁻³. Shell calcite is a significant component of the surficial sand, averaging about 20% by weight, but is likely to decrease with depth. The analytical results, on a calcite-free basis, indicate the presence of some 70 000 tonnes of chrome spinel averaging 32% Cr₂O₃ at a grade of nearly 1% and 1.5-2 million tonnes of forsterite-rich olivine (47% MgO) at 25% grade, in the topmost metre of sand. The mineralogy of the sands is summarised in a later section and presented in detail in the Data Package together with multi-element analyses of samples much larger than those taken at the reconnaissance stage and reported on here. All 31 of the bulk samples discussed in the Data Package derive from or immediately adjacent to the Harris and Dibidil deltas and the estimations of total heavy mineral and full quantitative mineral analyses given in the Data Package relate to samples from the Harris delta.

THE SURVEY OFF SW SKYE

Compared to southern Rhum, Loch Scavaig and Soay Sound in SW Skye are better

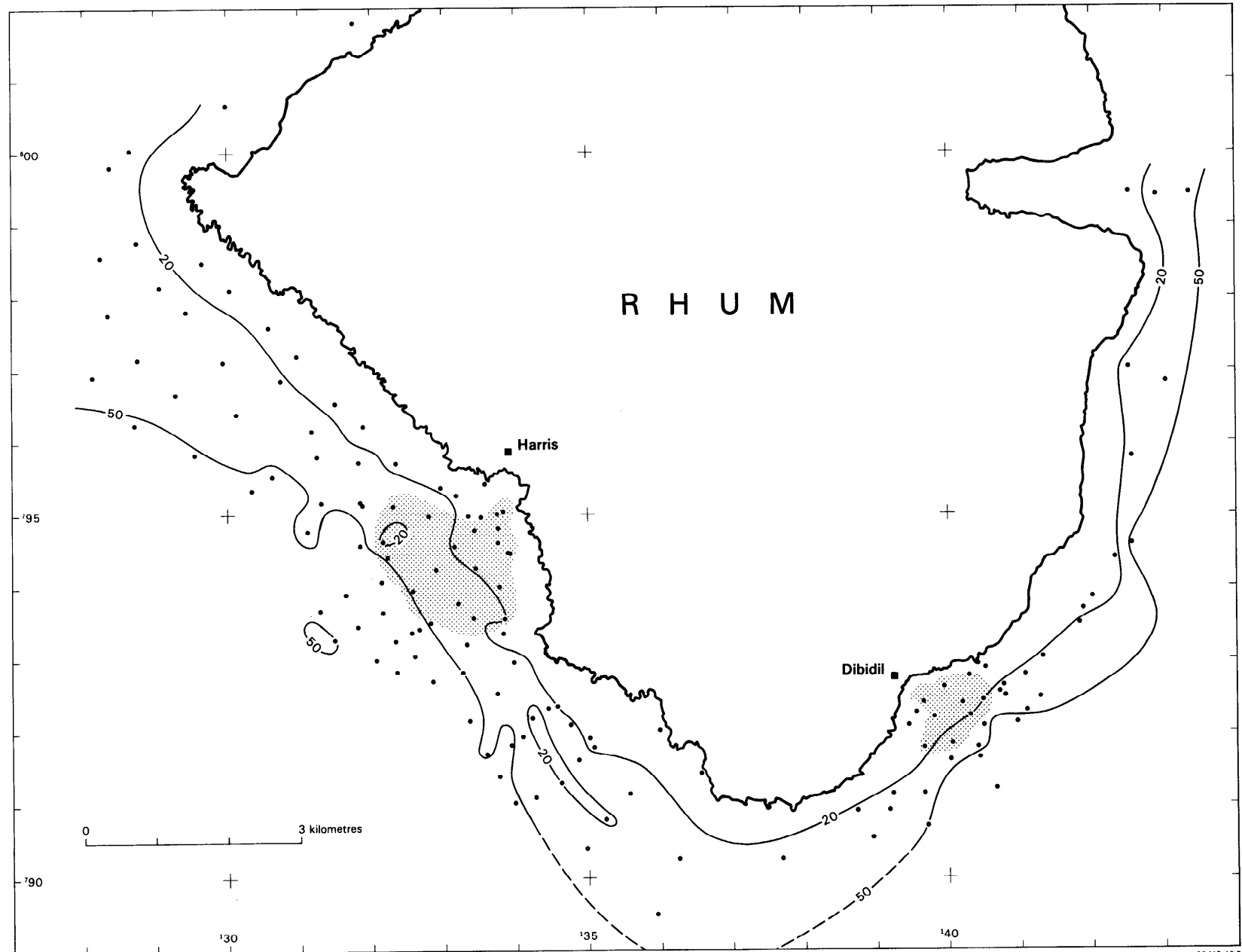


Figure 1 Sample locations and bathymetric observations off southern Rhum, showing the approximate positions of the heavy mineral sands off Harris and Dibidil

protected in severe weather conditions. The Scavaig River at the mouth of Loch Coruisk and the Abhainn Camas Fhionnairidh drain to the head of Loch Scavaig and numerous lesser streams to the Loch and to Soay Sound, transporting detritus from the Tertiary volcanic rocks of SW Skye (see 1:50:000 OS Sheet 32 and 1:63,360 Geological Sheet 70 and 1:50 000 Geological Sheet 71W. Analysable material was recovered at 63 of 93 stations, lying up to 4 km from the nearest shore but predominantly within 1.5 km. Average water depth is approximately 30 m, reaching 60 m at the centre of Loch Scavaig (Fig. 2). Here, grey glacial clays are common whereas nearer to coastlines shelly sands predominate, occasionally containing the pure CaCO_3 coralline alga lithothamnian.

Statistically, the SW Skye sample population is significantly lower in Mg and Cr_2O_3 than that of southern Rhum. On the other hand, Ca, Ti, V and Fe are all at somewhat higher levels in the Skye samples. These metal values were derived from residues after acid-dissolution of CaCO_3 forming on average nearly 50%, compared with about 20% for the Rhum samples. The high CaCO_3 content of the grey clays as well as the shell sands in the surficial sediments of SW Skye suggests admixture by glacial or periglacial action. Whether or not heavy mineral sands lie beneath the calcareous sediments requires a much more thorough investigation. No additional chemical or mineralogical work has been carried out on the Skye samples but clay-free residues of many samples are available as part of the Data Package.

MINERALOGY

An appraisal of representative samples of the sand permits determination of the content of commercially important heavy minerals, principally chromite and olivine, and of the chemical and physical parameters relevant to potential uses and beneficiation procedures.

31 samples were selected, on the basis of preliminary analyses for chromium and magnesium, for more detailed chemical analysis after removal of shell calcite by acid dissolution. Of these 31, size analyses and qualitative mineralogical examinations were carried out on 10 and more detailed estimations of the total heavy mineral contents on 5. Full quantitative mineral analyses were made on 2 samples, from which separated mineral concentrates were analysed by electron microprobe to establish chemical compositions. Partition of magnesium and chromium derived from the analyses was used to normalise calculations of total olivine and chromite contents in all 31 samples.

1. Procedures

Separation: Riffle split representative subsamples of approximately 500g were thoroughly washed with tap water to remove soluble salts, dried and sized on 1000, 500, 250, 125 and 63 μm screens.

Heavy mineral fractions were separated from quartz, feldspar and calcite components of the sands by gravity settling in bromoform or aqueous solution of Sodium polytungstate at density 2.0g.cm^{-3} . Magnetic fractionation was used to assist mineral identification and modal estimation, to determine magnetic susceptibility ranges of individual minerals and also in the production of mineral concentrates. After removal of magnetite with a permanent "U-shaped" magnet, further separations were made using an "Eclipse" variable intensity magnet.

Preliminary assessment of amenability to concentration by wet density methods was made by trials on a laboratory scale "Mozley Sand Concentrator". Magnetic separation of the table concentrates was carried out on a "Boxmag-Rapid" high intensity belt-type separator.

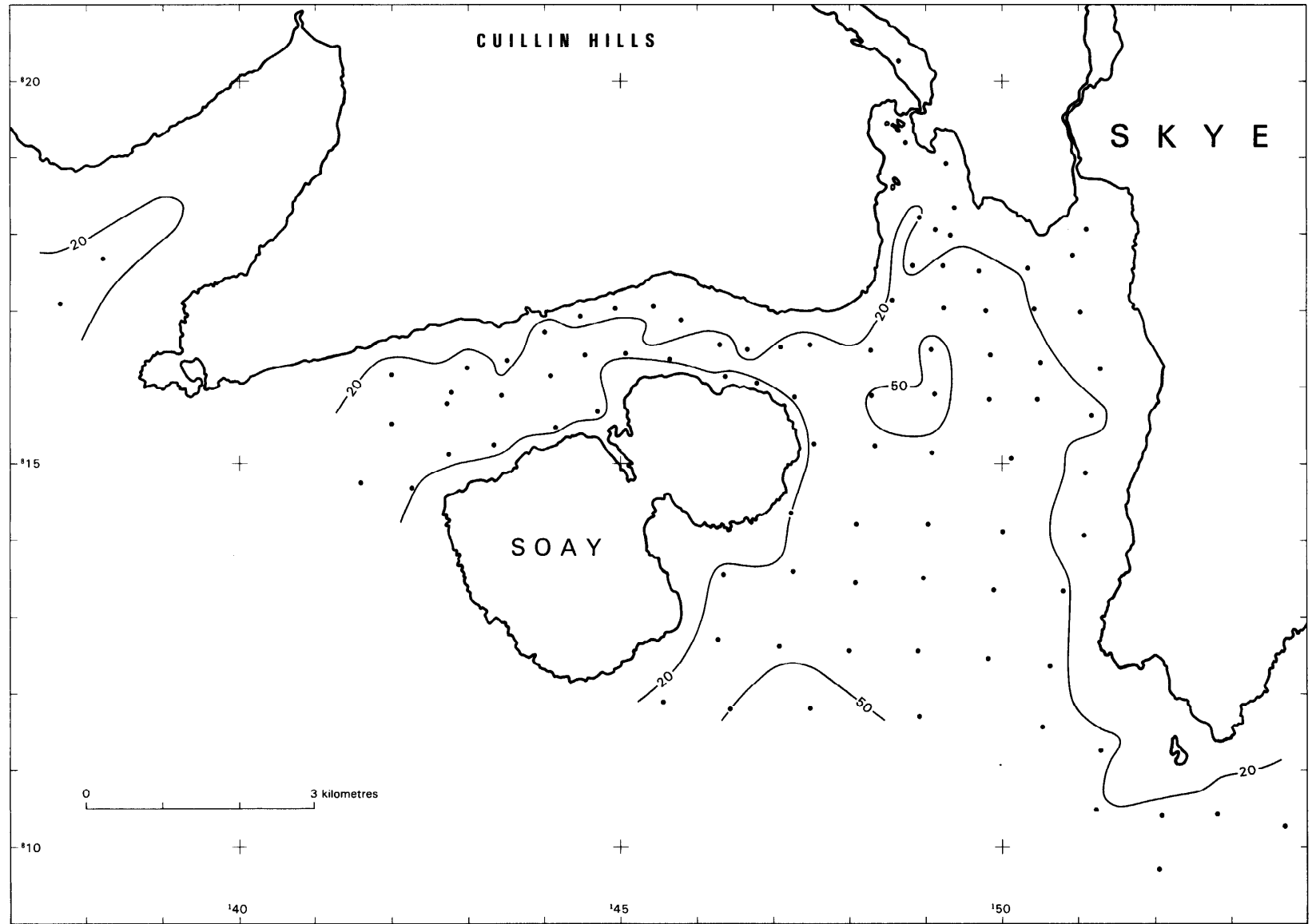


Figure 2 Sample locations and bathymetric observations off SW Skye

Mineral identification and analysis: Separated fractions were examined under a stereomicroscope and identifications made by conventional petrographic techniques. Overall compositions were obtained by grain counting five weighed magnetic separates in each size fraction and compositing derived modes with the gravimetric percentages. In the absence of appreciable amounts of minerals with platy or acicular prismatic habit, no shape factors were applied in the calculation. Likewise, in view of the relatively narrow density range shown among the major components, density corrections were not considered important.

Bulk analyses were obtained for mineral separates using X-ray fluorescence spectrometry (BGS Geochemistry and Hydrogeology Directorate Laboratories). Individual grain analyses on concentrates were made using a "Camebax" electron microprobe at the Grant Institute of Geology, University of Edinburgh.

2. Size distributions

The results of size analyses of 10 samples, chosen on the basis of magnesium, chromium and acid-soluble calcium carbonate contents as representative of all 31 samples, are given in Table 2. With the exception of TR1024, which contains around 10% more shelly material than average in the coarsest fraction, the samples are well-sorted medium to fine sands. Over 80% by weight (90% in 6 samples) reports in the 500 to 125 μ m size range, which is ideal for treatment by density or magnetic beneficiation methods.

3. Heavy mineral contents

Distributions of heavy minerals (density $>2.9\text{g.cm}^{-3}$) in 5 of the sized samples are shown in Table 2. The total heavy mineral contents are 24.5, 36.1, 51.6, 58.8 and 87.3%. Recalculated on a calcite-free basis from the data given in Table 2, these values are equivalent to 35.6, 45.7, 59.6, 63.2 and 93.9% of the detrital mineral sand. A graphical plot of measured calcite content against calculated olivine content (see section 6 below and Figure 3) for all 31 samples indicates that these samples can be considered as typical of the whole population, with the exception of TR1058 in which the concentration of heavy minerals is enhanced.

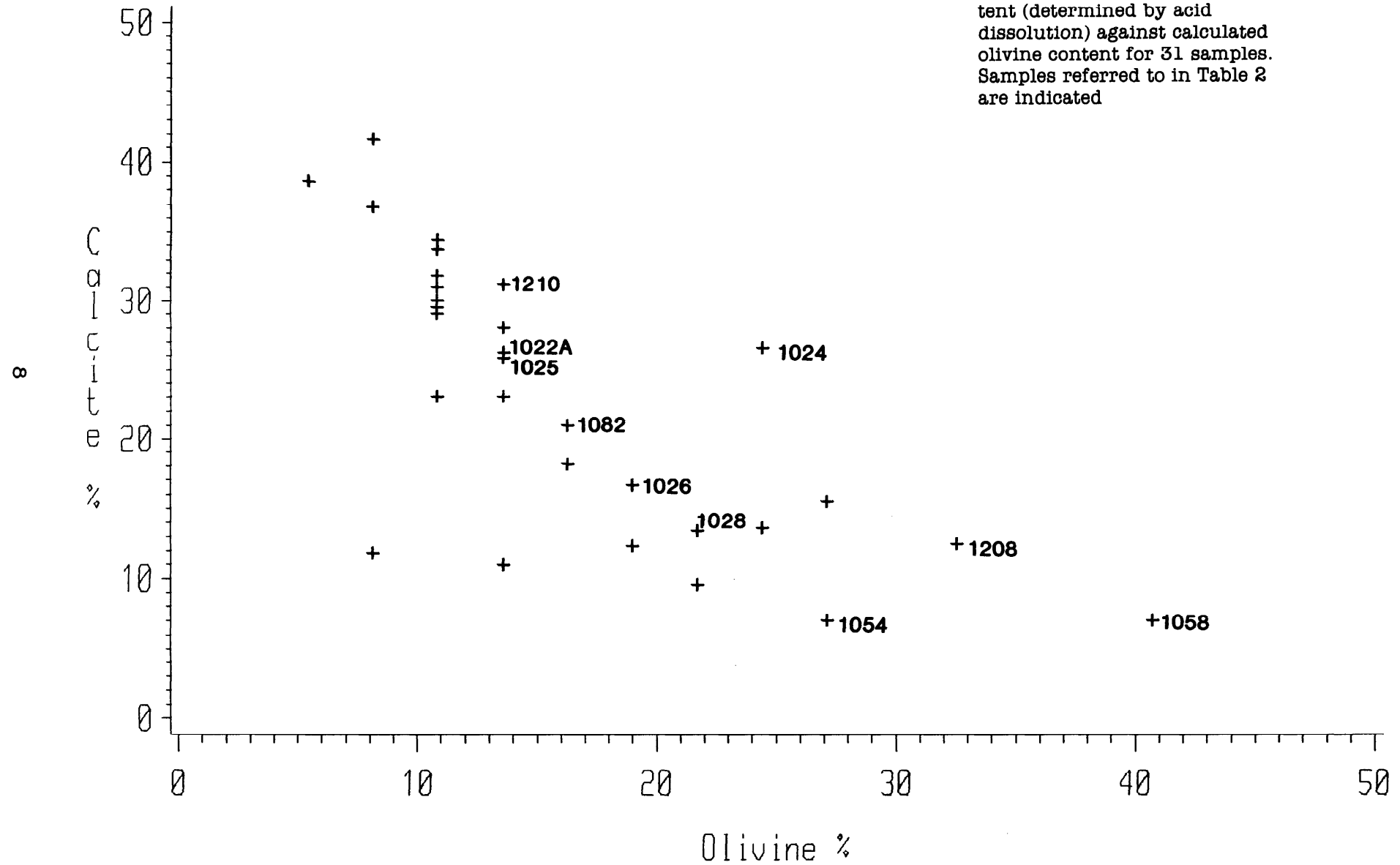
In general, heavy mineral content increases with decreasing grain size, largely reflecting the dominance of shelly material in the coarser sizes. Of the total heavies, the highest proportion generally reports in the 500-250 μ m size range. As expected from probable local variation in the depositional environment, some differences do occur, notably in TR1028 where 22% of the heavy fraction reports in the 125-63 μ m fraction. Variations of this nature may be significant to recovery depending on the processing method used and would need to be considered in flowsheet design.

The plot of calcite versus olivine (Figure 3) and of olivine against chromite (Figure 4), show generally linear relationships, indicating the varying dilutional effect of the shelly material to a compositionally fairly uniform heavy mineral suite. Visual inspection of the 5 samples separated supports this conclusion. The principal minerals recognised are those to be expected from consideration of the on-shore source areas for the detritals.

Olivine dominates in most size fractions in the majority of samples, accounting for up to half the heavy mineral content. A wide compositional range of pyroxenes forms the bulk of the remainder, sometimes exceeding the olivine content. Within the series, orthopyroxenes dominate the clinopyroxenes and as a whole the enstatite or diopside varieties are most abundant. Amphiboles of varying compositions are of relatively minor importance in amounts of less than 1% and other heavy minerals including serpentine generally account for less than 5%.

Rhum Offshore sands

Figure 3 Graph of calcite content (determined by acid dissolution) against calculated olivine content for 31 samples. Samples referred to in Table 2 are indicated



Black opaque minerals occur throughout, with magnetite, ilmenite and chromite-type spinels all recognised. Relative proportions appear to vary with the total content, which accounts for 10-15% of the overall heavy mineral fraction.

Further observations on the main minerals noted are given with reference to the two samples examined in detail below.

4. Mineralogical analysis of samples TR1058 and TR 1210

Samples TR1058 and TR1210 were selected for detailed quantitative assessment in order to represent the ranges in total heavy mineral content and in the analytical figures for calcite, chromium and magnesium. Pertinent data from Figures 3 and 4 can be summarised as follows:-

	Chromite	Olivine	Calcite	Ol:Cr	Ca:Ol+Cr
TR1058	3.98%	46.9%	7.0%	11.8	0.14
TR1201	0.66	16.0	31.2	24.2	1.45
Average (of 31 samples)	0.83	18.7	23.0	22.5	1.24

It can be seen that TR1210 is typical of the range as far as contents and ratios of chromium and magnesium (and derived calculated chromite and olivine) are concerned but with a higher degree of carbonate dilution than average. On the other hand, TR1058 shows a higher concentration of the heavy mineral fraction and of chromite relative to olivine within the suite.

Quantitative mineral compositions given in Tables 4 and 5 provide further details. TR1058 contains 87.3% total heavy minerals of which 50% is olivine and 30.6% (35% of the heavies) pyroxene with a dominance of bronzite/enstatite and diopside. Magnetite and ilmenite in a ratio of about 1:3 make up 5% and chrome spinel 6%. The remaining heavy minerals comprise mainly amphiboles, altered iron oxides and serpentine with only 5.7% of the total sand consisting of quartz and feldspar. TR1210 shows a much lower concentration of heavy minerals with 44.3% and 31.2% (75.5% total) comprising quartz/feldspar and calcite respectively. Of the 24.5% of total heavy mineral, 26% is olivine, 51% pyroxenes, 9% magnetite/ilmenite and 3% chrome spinel.

The size distributions of total heavy minerals are broadly comparable (Table 3-c) with TR1210 showing a slightly lower degree of sorting into the 500-125 μm interval. In keeping with the lower concentration of heavy minerals in this sample, higher proportions of olivine and chrome spinel report in the finer fractions than in TR1058. Nevertheless, both samples contain over 98% of the olivine and 85% of the chrome spinel in the 500-125 μm fractions.

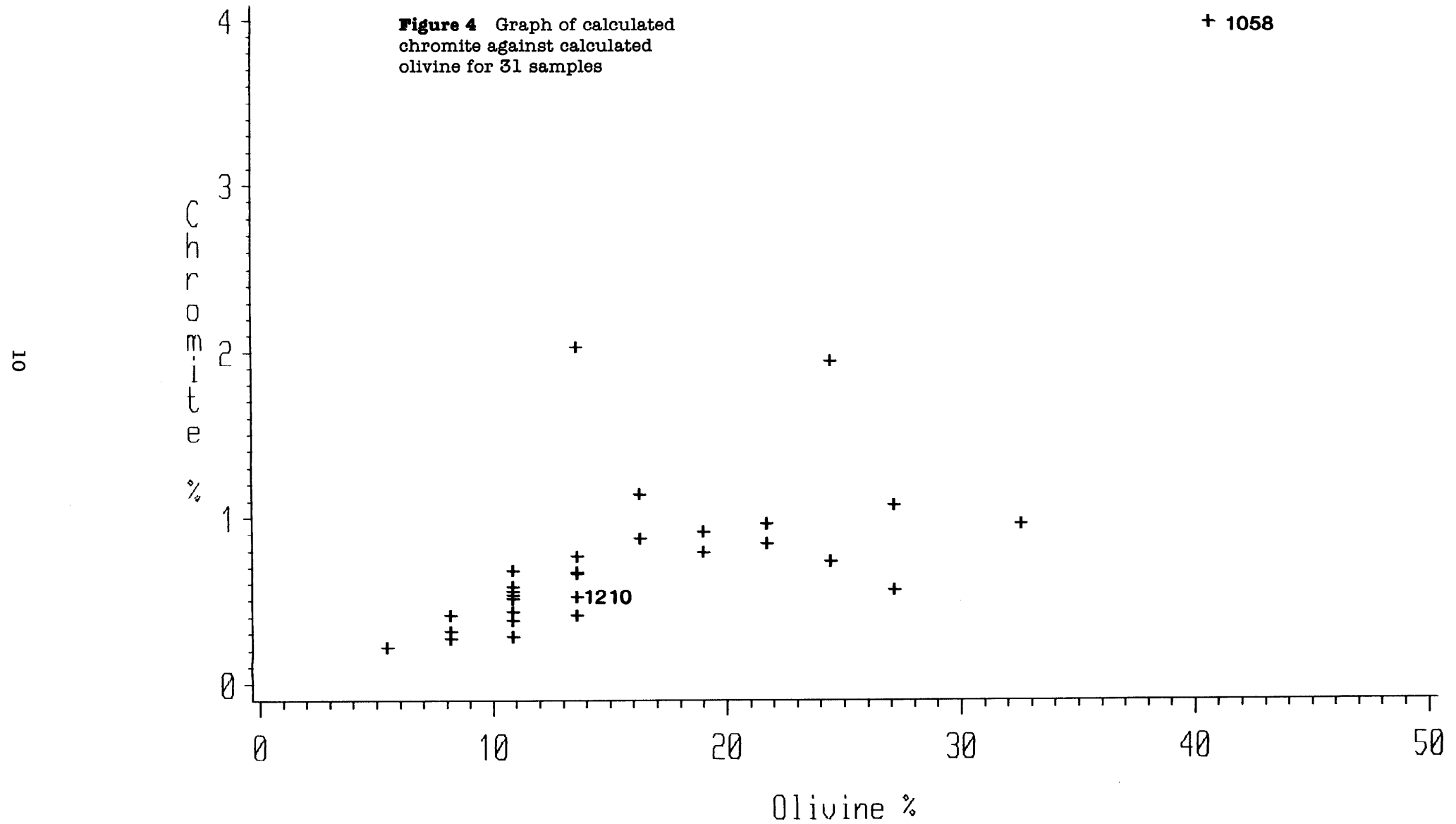
All of the common heavy minerals occur as discrete, unaltered grains, free from secondary coatings on grain surfaces. Little evidence is seen of the effects of weathering during liberation from source rocks or of attrition during transport and deposition. Principal characteristics of the more important individual minerals are as follows:-

Magnetite: black, lustrous well-formed to sub-rounded octahedra; occasional weak alteration coating of reddish brown limonite; highly magnetic.

Ilmenite: purplish black, highly lustrous subhedral grains; strongly magnetic.

Chrome spinel: sub-rounded lustrous to metallic black octahedra; at times difficult to distinguish from magnetite but crushed grains show brown to greenish brown translucency; magnetic susceptibility varies from strongly to weakly magnetic reflecting compositional variation (see below)

Rhum Offshore sands



Olivine: generally pale yellowish green, equant polished grains, sometimes showing crystal faces; magnetic susceptibility varies from strongly to non-magnetic, partly related to compositional variation but mainly dependent on the variable presence of inclusions of magnetite or other magnetic opaques in predominantly forsteritic members (see below).

Orthopyroxene: prismatic to irregular cleavage fragments, mainly showing typical "schiller" inclusions in predominant pale coloured bronzite varieties; more strongly coloured hypersthene types are subordinate.

Clinopyroxene: prismatic to irregular cleavage fragments of pale coloured diopside types predominate with lesser amounts of darker augite varieties; both members show variable inclusions. Both groups show a complete range of magnetic susceptibility from strongly magnetic types (darker coloured or with black opaque inclusions) to weakly or non-magnetic (paler varieties with few inclusions).

Amphiboles: hornblende or actinolite-tremolite types occur in minor amounts as unaltered, prismatic to acicular cleavage fragments, over a range of magnetic susceptibilities.

In summary, the two samples studied in detail show the typical mineralogy observed qualitatively for all of the delta sands examined. It seems reasonable to deduce that little variation in the actual detrital heavy minerals present, or in their approximate relative proportions, might be expected. Variations which do occur from place to place probably reflect mainly local depositional conditions, but the dominant of these is the content of calcite as shell debris.

5. Further mineralogical and chemical data for olivine and chrome spinel

Physical properties: The principal parameters of importance in beneficiation flow sheet design for liberated mineral sands are density, grain size and magnetic susceptibility. Weight distributions of the olivine and chrome spinel from TR1058 according to the latter two properties were determined as follows:-

OLIVINE (43.6% of total sand)

Size (m)	Magnetic Susceptibility			Total
	Strong	Moderate/Weak	Non	
500-250	10	45	29	84
250-125	4	9	2	15
-125		1		1
	14	55	31	100

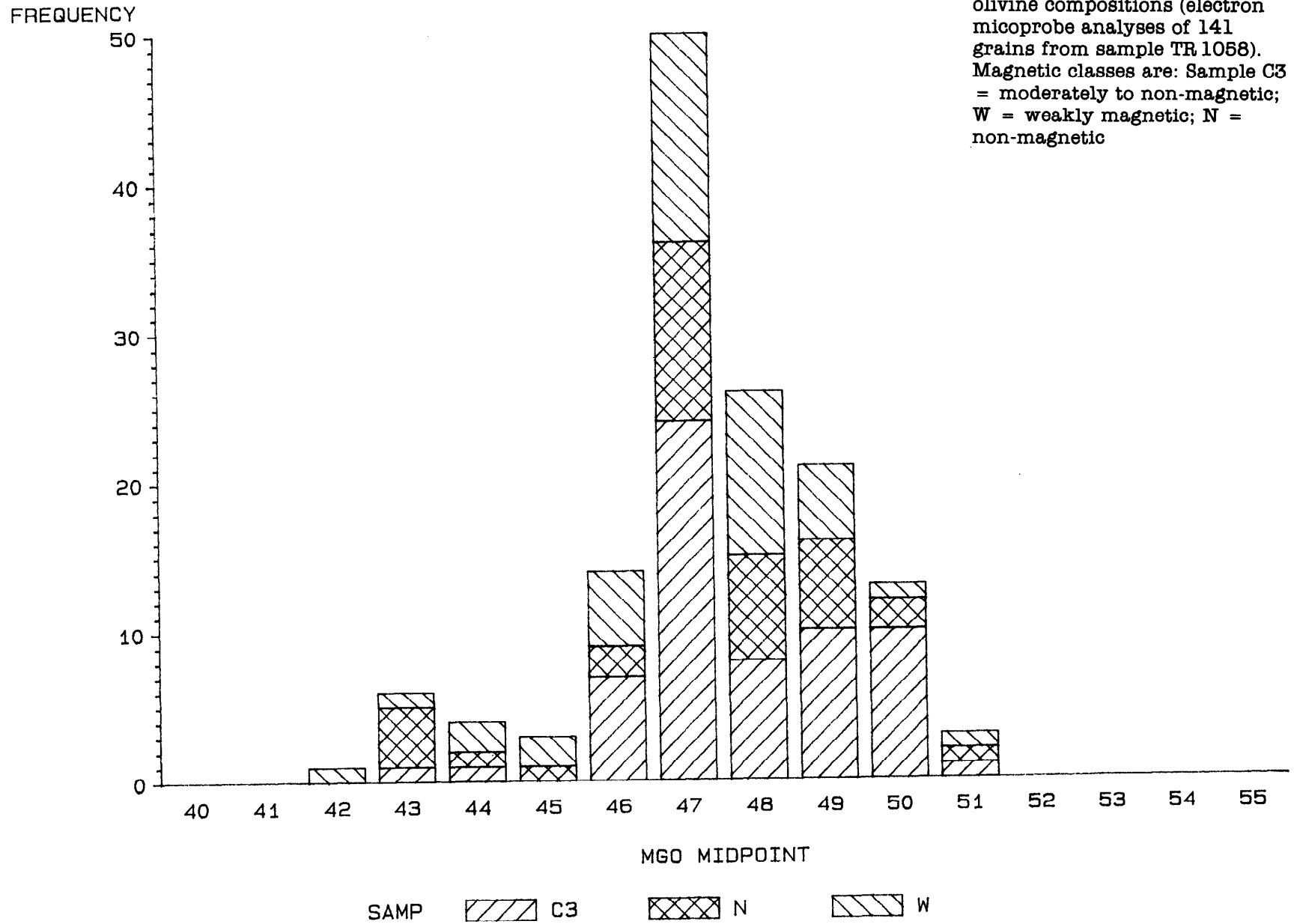
CHROME SPINEL (5.0% of total sand)

Size (m)	Magnet Susceptibility			Total
	Strong	Moderate/Weak	Non	
500-250	23	13	4	40
250-125	41	14	3	58
-125	2			2
	66	27	7	100

As to be expected from consideration of the onshore provenance of the sands, a range in compositional varieties of both olivine and chrome spinel is indicated by the spread over wide magnetic ranges. However, distinct differences in the distributions for the two minerals could be of importance in beneficiation. The olivine distribution is strongly biased towards the moderately to non-magnetic end of the magnetic range (86%), in keeping with a

Rhum Offshore Sands – Olivine

Figure 5 Frequency plot of olivine compositions (electron microprobe analyses of 141 grains from sample TR 1058). Magnetic classes are: Sample C3 = moderately to non-magnetic; W = weakly magnetic; N = non-magnetic



dominantly forsteritic composition. As noted previously, olivine occurring in the more strongly magnetic fraction appears to owe the increased susceptibility largely to magnetic mineral inclusions rather than a highly fayalitic composition. In contrast, the spinel shows dominance of strongly magnetic variants with 66% reporting in the range consistent with a chromite composition. The compositional range of both minerals was further studied by electron microprobe analyse carried out on polished grain mounts of different magnetic fractions.

Chemical compositions: Chemical analyses by electron microprobe of 141 olivine grains and 83 chrome spinels are given in the Data Package. The olivine analyses were made on three concentrates covering moderately to non-magnetic ranges. The strongly magnetic varieties (c.14% of the range) were excluded in view of the common presence of inclusions which would have caused interference in the automated analytical procedure used. The chrome spinel analyses cover the full magnetic range in four separate concentrates. Data can be summarised as follows:-

Olivine

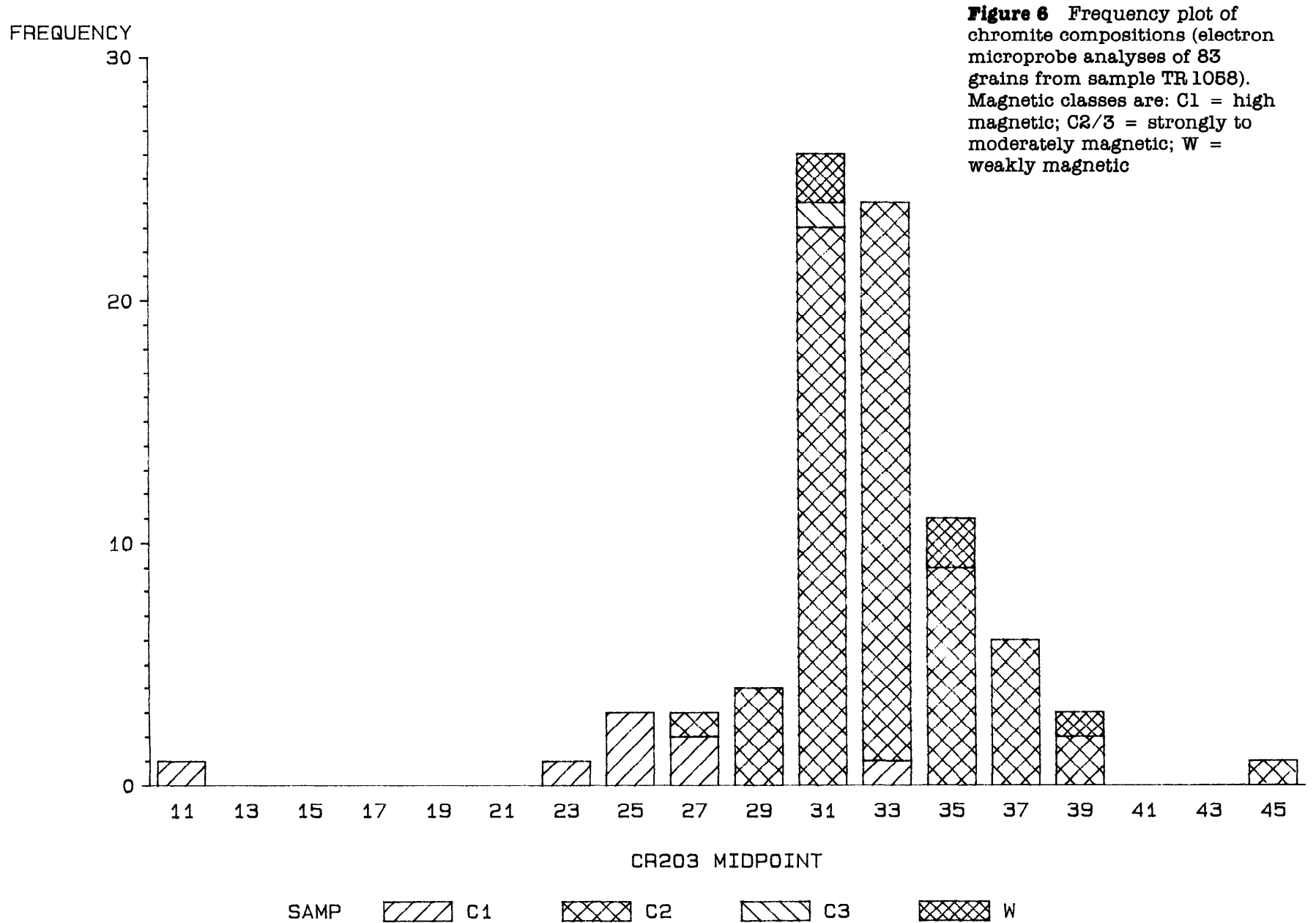
Magnetic fraction No. of analyses	Weak 43	Non 36	Moderate/non 62	All 141
			%	
SiO ₂	39.95	40.25	40.36	40.20
TiO ₂	0.26	0.03	0.04	0.03
Al ₂ O ₃	0.02	0.03	0.04	0.03
FeO ₃	12.83	12.94	11.62	12.33
MnO	0.21	0.20	0.19	0.20
MgO	47.08	47.13	47.66	47.35
CaO	0.07	0.08	0.10	0.08
% Forsterite	86.72	86.62	87.94	87.23

Chrome Spinel

Magnetic fraction No. of analyses	High 8	Strong/moderate 70	Weak 5	All 83
			%	
SiO ₂	0.04	0.02	0.04	0.03
TiO ₂	3.57	2.63	2.27	2.68
Al ₂ O ₃	8.31	19.80	21.33	18.87
Cr ₂ O ₃	24.83	32.98	34.19	32.23
Fe ₂ O ₃	28.35	12.45	10.71	13.86
FeO ₃	28.10	20.02	19.06	20.69
MnO	0.38	0.32	0.27	0.32
MgO	4.70	10.95	11.66	10.42
CaO	0.01	0.01	0.01	0.01

The above data, which are also summarised in frequency plots in Figures 5 and 6, show that the compositional range of the olivine is quite limited, averaging around 87% forsterite, with MgO ranging from 42% to 51%. The spinel grains show wider variation with Cr₂O₃ ranging from around 23% to 39% and averaging 32%. (Single analyses outwith this range were made of 11% and 44% Cr₂O₃). Clear correlations exist between magnetic susceptibility and major elements, in keeping with the common substitutions in the chromite-magnesiocromite series and gradational members with aluminous equivalents (spinel and hercynite). Mean analyses for the strong/moderate and weak magnetic fractions fall within the accepted range for chromites (Deer, Howie and Zussman, 1962). The mean analysis for the whole population has a slightly lowered Cr₂O₃ content, reflecting the inclusion of more ferroan highly magnetic varieties (picotites-hercynites). Figure 7 further demonstrates the compositional range with reference to chromium, aluminium, magnesium and iron and emphasises the relationship between magnetic susceptibility and chemical composition.

Rhum Offshore Sands – Chromite



6. Estimation of olivine and chromite contents from bulk sand analyses for magnesium and chromium

In order to partition chromium and magnesium among the principal host minerals in the sands, further analyses were made of magnetite, ilmenite, diopside and hypersthene in the concentrates from TR1058. Results and details of the calculations used for partitioning and normalising are given in the Data Package. On the basis of these the chromite content of the 31 sands (on a calcite-free basis) was calculated to range from 0.22% to 3.98% while olivine varied from 8% to 41% (on an MgO basis). Figures 3 and 4 are graphical representations of the figures obtained and relationships among calculated olivine and chromite contents and measured calcite content.

7. Preliminary beneficiation trials and assessment

Trials were made to produce olivine and chromite concentrates from bulk samples of TR1058 and TR1210 using laboratory-scale procedures. Preliminary screening into two size fractions (+250 μm and -250 μm) was followed by wet tabling on a "Mozley Sand Concentrator". Dried concentrates and middling products were treated on a "Boxmag-Rapid" electromagnetic belt-type separator and further upgrading of concentrates achieved by differential settling in heavy liquids. Results are described below in qualitative terms as no systematic attempt has been made at this stage to quantify operational parameters or to define a commercial-type flowsheet. In practice, it is likely that the high bulk-flow cost treatment that would be needed to exploit the resource would dictate a wet gravity scheme with use of tables or Humphrey's spirals, for example, on board the operating dredge.

CHROMITE : Results were encouraging and indicated that the density, grain size and grain shape differences between the magnetite/ilmenite/chromite group and the mafic minerals are sufficient to allow concentration by wet density methods, the calcite and light mineral fractions being readily separated by tabling. The opaque group was further fractionated by magnetic means although overlap occurs, mainly between ilmenite and the more magnetic, iron-rich chromites. Mafic minerals with increased density and magnetic susceptibilities due to inclusions were also found to contaminate the concentrate. However, a final concentrate containing 86% chromite, 13% ilmenite and 1% pyroxene at a recovery for chromite of around 60% was readily obtained. The average composition of the chromite in this concentrate, calculated from electron microprobe data, was 33.0% Cr_2O_3 .

OLIVINE : Although the density and magnetic ranges for olivine and the pyroxene group as a whole are closely similar, much of the pyroxene in these sands is moderately to strongly magnetic. As the olivine is predominantly (86%) moderately to non-magnetic, a high degree of concentration is achievable by magnetic means. In the 250-125 μm size fraction, weak to non-magnetic separates contain 65-75% olivine, representing a recovery of over 50%. Further upgrading by differential settling techniques produced a concentrate comprising 78% olivine and 22% pyroxene. Electron microprobe analysis showed the olivine to contain 47.7% MgO. Separation of the more magnetic olivine from pyroxene was difficult with the methods used, although other techniques might be better able to exploit grain shape differences. Losses are estimated as 15-20%. However, in uses such as foundry sand tolerances may permit only limited upgrading.

8. General comments

Chromite: In ferro-chrome production, the tendency is towards acceptance of increasingly higher contents of iron (Power, 1985). The analytical data so far obtained for these samples indicate a rather higher average content than in chromites presently worked (e.g. South African : 40% Cr_2O_3 , 25% FeO) and further analyses need to be made of other samples to establish variations which may related to any favourable onshore provenance.

Rhum offshore sands – Cr spinels

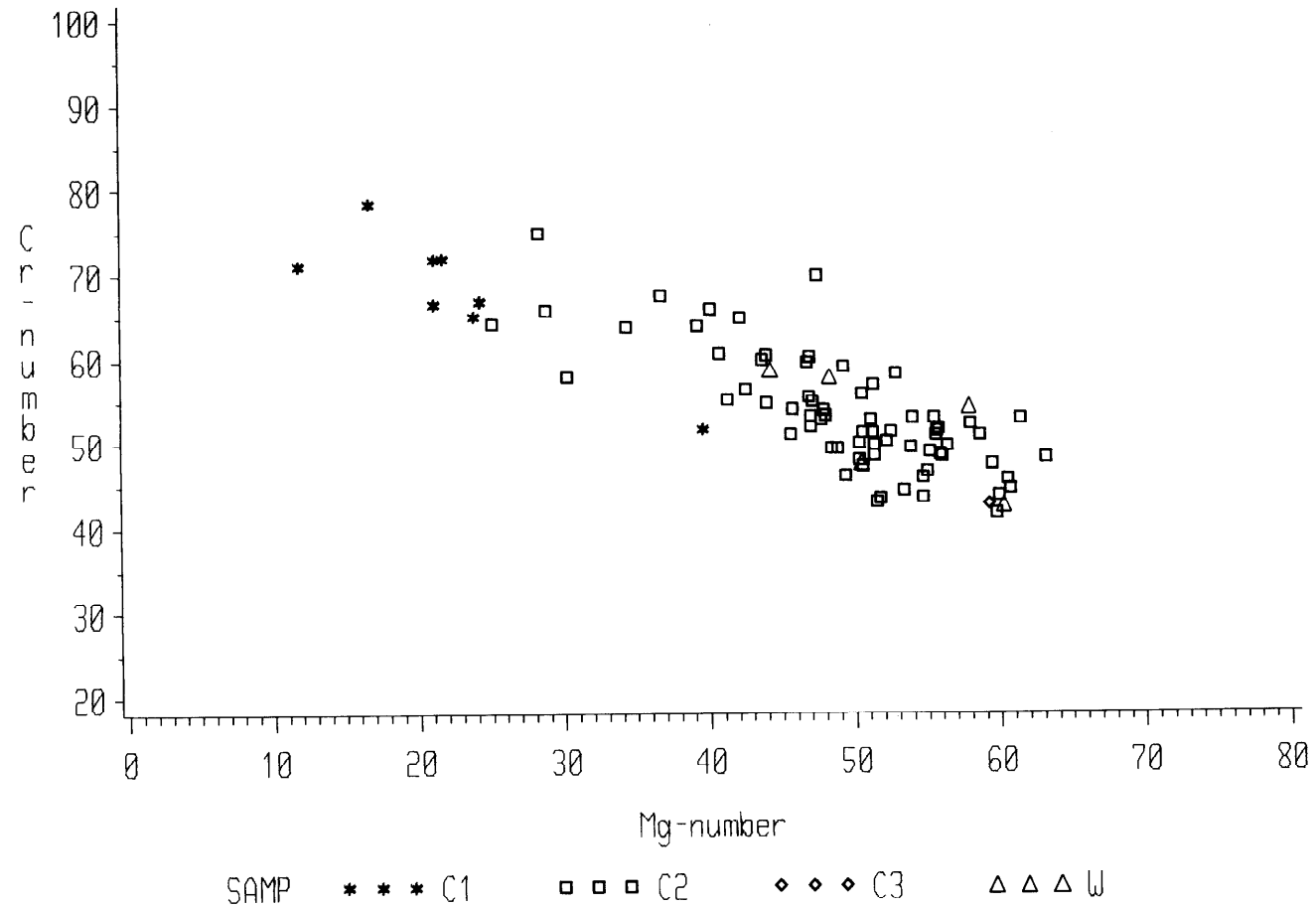


Figure 7 Compositional distribution diagram of 83 measured chromite grains.
 $\text{Cr-number} = 100 \cdot \text{Cr} / (\text{Cr} + \text{Al})$; $\text{Mg-number} = 100 \cdot \text{Mg} / (\text{Mg} + \text{Fe})$

Olivine: Results for olivine are very encouraging. Comprising up to 44% of the total sand after shell calcite removal, the size range (99% in 500-125 μm) compares favourably with current products, for example Norwegian foundry sand : 96% 500-125 μm ; (Griffiths, 1984). The chemical composition (48%MgO, 40%SiO₂) also compares well with the current desired range for refractory use (45-50%MgO, 40-43%SiO₂). Potential expanding applications are in blast furnace use, for which pelletising to provide the required coarser lump is now being carried out in the USA, and as a sand blasting abrasive. Legislation against abrasives containing free silica is now effective in most of Europe and can be anticipated in the near future in the UK. Olivine sands are already in use for building cleaning (Griffiths, 1989).

Other minerals:

Ilmenite is present as 2-3% of the total sand and is readily separated by density and magnetic methods. As the current principal non-metallic import to the UK, recovery as a by-product would be attractive.

Magnetite is also present in small but readily recoverable amounts. The principal interest would be in its vanadium content. Preliminary analytical data suggest that this could be significant but further study is needed to establish actual levels in comparison with current ore-grade figures of, for example, c.0.8%V for magnetite from the Bushveldt, South Africa.

**Table 2 Size distributions in selected samples
(expressed as weight % of total sand)**

Size Fraction (in μm)	1022A	1024	1025	1026	1028	1054	1058	1082	1208	1210
+100	0.9	10.5	0.5	0.1	0.1	0.2	1.7	0.1	1.0	3.2
1000-500	5.9	8.5	3.8	2.0	0.7	0.3	1.5	0.1	12.0	12.3
500-250	63.4	38.6	54.5	38.6	22.3	63.0	70.0	53.8	83.0	64.9
250-125	27.8	39.0	37.8	52.3	64.8	35.3	25.3	42.3	3.8	18.8
125-63	1.9	3.2	3.4	7.0	12.1	1.2	1.4	2.6	0.1	0.8
-63	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Note: Further data referred to in the text are as follows:-

Total										
500-125 μm	91.2	77.6	92.3	90.9	87.1	98.3	95.3	96.1	86.8	83.7
Shell calcite %	26.2	26.5	25.8	16.6	13.4	7.0	7.0	21.0	12.4	31.2
MgO %	5	9	5	7	8	15	15	6	12	5
Cr ₂ O ₃ %	0.25	0.26	0.27	0.33	0.34	1.42	1.42	0.31	0.34	0.28
(MgO ³ and Cr ₂ O ₃ wt.% on calcite-free basis)										

**Table 3 Total heavy mineral fraction (density >2.9g.cm⁻³)
distributions in five selected samples**

		WEIGHT PERCENTAGE HEAVY MINERALS					
		SIZE FRACTION (in μm)					
		+1000	1000-500	500-250	250-125	125-63	Total
a) As wt.% of size fraction							
	TR1208	ns	ns	38.2	48.7	94.7	
	TR1054	ns	20.8	52.2	70.6	76.8	
	TR1058	3.4	26.9	92.9	81.1	91.7	
	TR1082	ns	21.2	30.2	40.8	94.2	
	TR1210	4.0	6.0	25.2	35.0	87.0	
B) As wt.% of total sand							
	TR1028	ns	ns	8.5	31.6	11.5	51.6
	TR1054	ns	0.1	32.9	24.9	0.9	58.8
	TR1058	0.1	0.4	65.0	20.5	1.3	87.3
	TR1082	ns	0.2	16.2	17.3	2.4	36.1
	TR1210	0.1	0.7	16.4	6.6	0.7	24.5
c) As wt % of total heavy minerals							
	TR1028	ns	ns	16.5	61.2	22.3	100.0
	TR1054	ns	0.2	56.0	42.3	1.5	100.0
	TR1058	<0.1	0.5	74.5	23.5	1.5	100.0
	TR1082	ns	0.6	44.9	47.9	6.6	100.0
	TR1210	0.5	3.0	66.7	26.9	2.8	99.9

ns = not separated as fraction too small.

None of the -63 μm fractions were separated as all were <0.1% of total sand.

**Table 4 Mineralogical composition of sample TR1058
(expressed as weight percentage of total sand)**

	SIZE FRACTION (in μm)			Total
	500-250	250-125	125-63	
Magnetite and ilmenite	1.3	3.1	0.1	4.5
Chrome spinel	2.0	2.9	0.1	5.0
Olivine	36.7	6.6	0.3	43.6
Orthopyroxene (1)	10.7	4.7	0.4	15.8
Orthopyroxene (2)	1.1	0.7	0.1	1.9
Clinopyroxene (1)	9.3	1.0	0.2	10.5
Clinopyroxene (2)	1.1	1.2	0.1	2.4
Amphibole	0.2	0.2	<0.1	0.4
Other heavy minerals	2.6	0.1	<0.1	2.7
Heavy minerals >500 μm				0.5
Quartz and feldspar				(5.7)
Shell calcite				(7.0)
Total heavy minerals	65.0	20.5	1.3	87.3

- Notes :
- Pyroxenes were sub-divided approximately into four groups on the basis of morphology, colour and inclusions viz:-
Orthopyroxene (1) - enstatite-ferrosilite series, mainly bronzite
Orthopyroxene (2) - strongly coloured, hypersthene variety
Clinopyroxene (1) - diopside type
Clinopyroxene (2) - strongly coloured augites
 - Other heavy minerals : mainly hematite and serpentines
 - Heavy minerals >500 μm size not differentiated
 - Weight percentage figures based on grain counts of separated magnetic sub-fractions but not corrected for density

**Table 5 Mineralogical composition of sample TR1210
(expressed as weight percentage of total sand)**

	SIZE FRACTION (in μm)			Total
	500-250	250-125	125-63	
Magnetite and ilmenite	1.5	0.6	0.1	2.2
Chrome spinel	0.1	0.5	0.1	0.7
Olivine	5.2	1.2	0.1	6.5
Orthopyroxene (1)	3.5	2.2	0.2	5.9
Orthopyroxene (2)	0.9	0.3	<0.1	1.2
Clinopyroxene (1)	2.8	1.0	0.1	3.9
Clinopyroxene (2)	1.1	0.4	<0.1	1.5
Amphibole	0.2	0.1	<0.1	0.3
Other heavy minerals	1.1	0.3	<0.1	1.4
Heavy minerals >500 μm				0.8
Quartz and feldspar				(44.3)
Shell calcite				(31.2)
Total heavy minerals	16.4	6.6	0.7	24.5

Notes : 1-4 As for Table 3
5 0.8% heavy minerals in >500 μm size includes
0.2% olivine giving 6.7% total olivine

CONCLUSIONS AND RECOMMENDATIONS

The Harris and Dibidil deltas off southern Rhum represent very large resources of freely available mineral - forsterite, chrome spinel, calcite, ilmenite, vanadiferous magnetite and possibly associated platinum group elements. Virtually all of the olivine and chromite occur in the favourable sand-size fractions (125-500 μm). The magnetic susceptibility of the chromite is very variable, that of the olivine quite variable, indicating significant ranges in composition as anticipated from consideration of the onshore provenance of the sands. The Cr_2O_3 content of 83 chrome-spinel grains ranges from 10.7% to 44.4%, averaging 32.23%. Analyses of 141 olivine grains illustrate a range in MgO content from 42.4% to 50.7%, averaging 47.3%.

Beneficiation trials using laboratory-scale procedures, namely screening, wet tabling, electromagnetic separation and dense media separation, yielded concentrates of 86% chromite and 78% olivine with recoveries of 60% and 50% respectively. While separation of the more magnetic olivine from associated pyroxenes is difficult it may not be necessary in uses such as foundry sand.

The size-range and chemical composition of the olivine compare well with current products such as Norwegian foundry sand and its use as a sand blasting abrasive is expanding. In ferro-chrome production, the tendency is towards accepting increasingly higher contents of iron in chromite. However, it is noted that the average iron content of the Rhum chromites (about 31% FeO) is rather higher than in chromites presently worked, eg South African with 25% FeO. Both ilmenite, currently the principal non-metallic import into the UK, and the vanadiferous magnetite occurring in the Rhum sands are readily recoverable as by-products, as well as the shell calcite.

The full economic significance of the Inner Hebridean marine deposits cannot be estimated without information on thickness and grade variation in depth. Geophysical surveys are required to provide estimates of sand thickness, followed by profile sampling to determine grade and especially any relative

concentration of heavy minerals and PGE's with depth. Sampling and geophysical surveys of the entire southern coastline of Rhum into water deeper than that tested in this reconnaissance are needed for a full evaluation of the marine sands. Surveys over the marine deposits off SW Skye, with deep sampling, should also be attempted.

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