DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/3

Computer-Controlled Scanning Electron Microscopy (CCSEM)

Method, advantages and limitations of the fully automated analyses of grain chemistry, size and morphology

Nynke Keulen & Roger K. McLimans

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

GEUS

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G E U S

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Introduction

Computer controlled scanning electron microscopy (CCSEM) combines the advantages of energy dispersive X-ray spectrometry (EDX) with those of digital image analysis of back scattered electron (BSE) micrographs. CCSEM analyses of a wide range of geological and other materials have been developed at the Geological Survey of Denmark and Greenland (GEUS) as a fast and reliable method to determine the chemistry of individual grains and bulk samples. The chemical analyses are combined with measurements of the two-dimensional size and morphology of every single grain.

Range of application for the technique

The CCSEM technique was initiated at the beginning of the 1980s for the characterisation of coal minerals (Lee & Kelly 1980; Huggins *et al.* 1980) and the study of synthetic crystals for super-conductors and catalysts (Lin & Barnes 1984). Soon it was developed to a broader range of application in the study of dust particles and fibres in lung tissue of mine workers (Friedrichs 1987); in the analyses of aerosols for air quality control and source emission characterisation (e.g. Heasman & Watt 1989); and the degree of sintering and consolidation of coal ash deposits (e.g. Huffman *et al.* 1994). CCSEM has been used in the earth sciences for the determination of the sediment budget of a lake (Yin & Johnson 1984), for the characterisation of soil and dust (Pirrie *et al.* 2004), for provenance analysis of ilmenite-bearing beach sands (Knudsen *et al.* 2005; Bernstein *et al.* 2008), and provenance studies on sandstones in oil-bearing basins (Frei *et al.* 2005). Other areas where CCSEM has been applied include characterisation of small inclusions, e.g. impurities in metal alloys or steel (Schwoeble *et al.* 1988), analyses of gun-shot residues (e.g.

Steffen *et al.* 2007), and analyses of bladder stones obtained from a skeleton found in a Mesolithic cave-tomb (D'Alessio et al. 2005). In this report, further geological benefits of the method are demonstrated with examples from (ilmenite-bearing) heavy mineral sands and from diamond prospecting.

Analytical technique

Sample preparation

Samples can be (1) a representative part of a bulk sample, (2) carefully selected grains held on double-sided sticky tape, or (3) a heavy mineral separation of a bulk sample. Grains, beads, and powders of both geological and non-geological origins can be analysed. For most studies, approximately 1 g of sample material is mounted in epoxy resin, using a technique that ensures that almost every grain is completely embedded in the epoxy, without touching any neighbouring grains (e.g. McLimans et al., 1999). The epoxy mounts are cut to show a representative part of the mount, subsequently polished, and coated with carbon to enhance their conductivity. However, it is also possible to use thin sections of sample material prepared in a similar way.

CCSEM analyses

CCSEM analyses use a Philips XL40 SEM equipped with two EDX detectors: a Thermo Nanotrace 30 mm^2 window and a Pioneer Voyager 2.7 10 mm^2 window Si(Li) detector. The tungsten filament of the SEM is operated with an acceleration voltage of 17 kV, a filament current of typically 50–70 µA, and the sample is placed at a distance of 10 mm from the detector. The Noran System SIX software package automatically collects X-ray spectra, grain size and morphology of all particles and recalculates the data following the Proza ($\phi\rho Z$) data correction and the filtering quantification technique. The technique described here is an improvement of the method described by Frei *et al.* (2005) and Bernstein *et al.* (2008).

The samples are studied in the BSE contrast mode of the electron microscope; the individual particles appear as different shades of grey in their black epoxy matrix (Fig. 1). Grey-level intensity thresholding by the image analysis function integrated in the software creates a binary image of the BSE micrograph and allows for the separation and selection of individual grains (Fig. 1B). A grid of image frames covering the whole sample area is defined by feeding the end-coordinates of the sample to the computer and by setting the required magnification (typically 30–100×) for the analyses (Fig. 1A). Grids consisted of 15 to 60 frames with approximately 20–35 grains per frame. A guard region between each frame avoids the double measurement of very large particles in the sample and ensures that only grains that lie completely within the image

frame are included for analysis. A ‘hole-fill’ function enabled more precise measurement of the grain size and shape from the binary

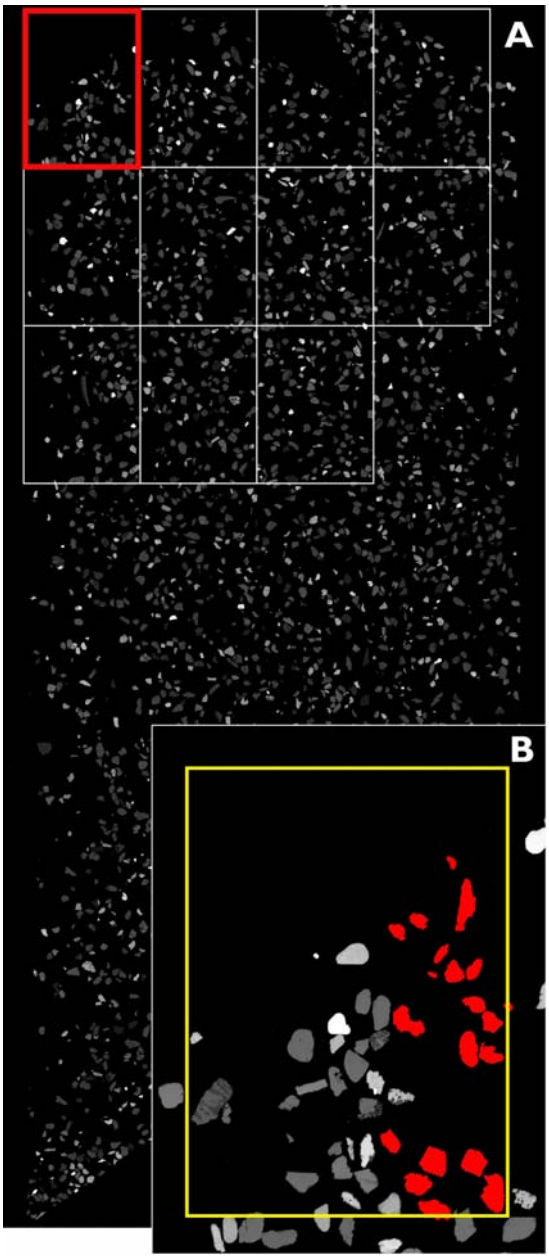

Fig. 1. A: CCSEM sample of beach sediment from Jutland, western Denmark, divided into a number of frames in a grid. Part of the grid is outlined in white. Grains of different chemical compositions (different grey values) are embedded in an epoxy resin. Length of the sample is approximately 1.5 cm. B: Enlargement of one of the frames of the grid (indicated in red in A). The guard region (yellow) prevents double or incomplete measurements of grains (see text). The grey-level threshold function selects the grains one after one from the matrix for analyses of chemical composition, grain size and grain shape. Already analysed grains are shown in red; the image represents a snapshot of the CCSEM-procedure.

image. Since the grains are mounted in epoxy resin in such a fashion that they do not touch each other, no grain separation techniques, as commonly applied in automatic particle analysis software are required. Thus, the original 2D grain shape and grain size were completely available for analyses, without the introduction of artefacts by grain erosion and dilation or median filtering. All standard grain shape factors can be measured. The smallest grains in the sample can be excluded from the analysis to avoid the measurement of particles that are only a few pixels in size, especially if a good grain morphology resolution is required.

The binary images created formed the basis for the measurements of the grain chemistry. The software controlled the microscope to scan within the perimeter of each grain to obtain the chemistry of either the whole grain area or from a single point in the centre of the grain mass. A typical spectrum for one particle contained 1000–2000 counts for the highest peak. Spectra with a very low number of counts can be removed to ensure good measurement statistics. Commonly, 800–1200 grains are measured in approximately two hours.

CCSEM output files and parameters

The Noran software produces a results table that lists grain shape, grain size and grain chemistry for each individual grain. All spectrum files and image frames, with a typical size of 1024 × 774 pixels are stored after analysis in the database. Spectrum files can be reprocessed to include elements retrospectively, without the need to physically reanalyse the sample. The chemical data are further reduced using a software package developed at GEUS in cooperation with DuPont that is connected to a mineral library database for automatic mineral classification and data storage. Data can be exported from the database in Excel format and SEM BSE images of analysed grains can be viewed and saved.

Samples are currently analysed for the following elements:
Na, Mg, Al, Si, P, S, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Y, Zr, Nb, Sn (since May 2008), and Ce. All elements heavier than Ne can be added to the analyses. However, some elements show a peak-overlap in the EDX spectrum, and can therefore be problematic (see later discussion). Oxygen (and other light elements between B and F in the periodic system) is hard to measure precisely. To avoid problems, it is common practise for EDX analyses to assume that all elements are bound to oxygen and to express elements as oxide phases, e.g. Na2O, MgO, Al2O3. For the recalculation, it is assumed that enough oxygen was present in the sample. This can occasionally cause problems in hydrated samples.

The following minerals are currently identified in the database:

Ilmenite, leucoxene, rutile, Ti-magnetite, magnetite, chromite, spinel, garnet, sillimanite-kyanite, staurolite, mica, mafic silicates, feldspar, quartz, other silicates, corundum, pyrite, monazite, xenotime, phosphates, carbonates, and other minerals (unclassified). A list of the mineral classification boundary criteria is added as an Appendix (App. 1). Note however, that the mineral classification scheme is based on element percentages normalising to 100% without including oxygen, assuming oxygen is abundant and thus that the threshold values separating elements from others need recalculation to obtain true element or oxide wt%.

Currently the boundaries in the CCSEM classification scheme for Ti-minerals lie at: Magnetite < 21 wt% TiO2 < Ti-Magnetite < 46 wt% TiO2 < Ilmenite < 70 wt% TiO2 < Leucoxene < 90 wt% TiO2 < Rutile.

Care should be taken when interpretating the CCSEM results on heavy minerals. The mineral classification is purely based on chemical composition of the measured grains. There are no further petrological investigations involved in the classification. The distinction between ilmenite, leucoxene and rutile occurs on TiO2 wt% only. This can have major implications for the provenance and metamorphic history of the samples, as grains interpreted as leucoxene based on their TiO2 grade can in fact be ilmenite or rutile grains. Additionally, grains might have (micro-) inclusions, which composition will be included in the chemistry of the host grain. Grains can incidentally be non-liberated, which leads to a mixed chemistry of the two compositions. For a full interpretation of the data, additional petrography is needed.

For each of the grains the following grain shape parameters are measured: minimum/maximum/mean particle projection (= minimum/maximum/mean calliper dimension) on the particle convex perimeter; orientation of the angle between positive X-axis and maximum particle projection; length (the derived length of particle or fibre, after it is straightened into a rectangle of equal area and perimeter); width (particle projection perpendicular to the maximum projection), aspect ratio, circularity. Additionally the convex envelope's perimeter, area, length, circularity can be measured. These grain shapes are illustrated in Figure 2.

Data can be exported as a PDF report. Currently two versions for the PDF-report exist: one concentrating on Ti-minerals (Appendix 3) and one concentrating on garnets (Appendix 4). These Appendices show examples of the plots showing TiO2-grade distribution in Ti-minerals, garnet composition and an interactive grain size distribution plot. The plots are also available directly via the web-interface of the database.

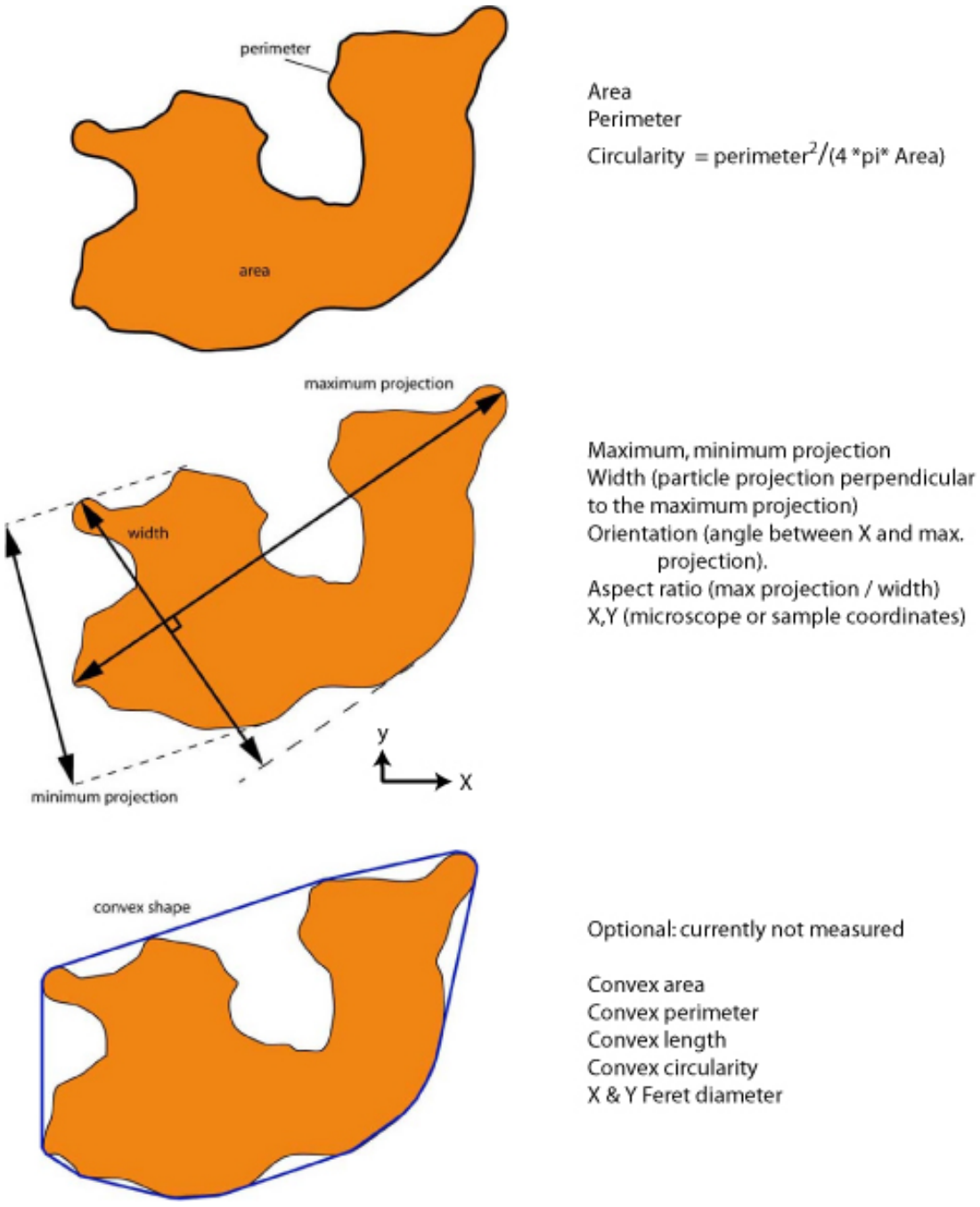

Fig. 2.: Overview of most grain morphology parameters that can be measured by the CCSEM software. The convex shape is the shape of the convex envelope around a grain, indicated with a blue line. Of this shape, area, perimeter, etc. can be determined. The Feret diameter is the projection of the grain to the X or Y axis.

Examples of geological application of CCSEM

Provenance of beach and river sand

CCSEM is used to investigate the provenance of high grade ilmenite in river and beach sands from India (Bernstein et al. 2008). For this study the single grain chemistry of ilmenite and garnet grains was used to couple the sediments to their areas of origin. In Denmark, the distribution of heavy minerals in Miocene sand deposits is determined from the mineral composition of the heavy mineral fraction of sand samples (Fig. 3).

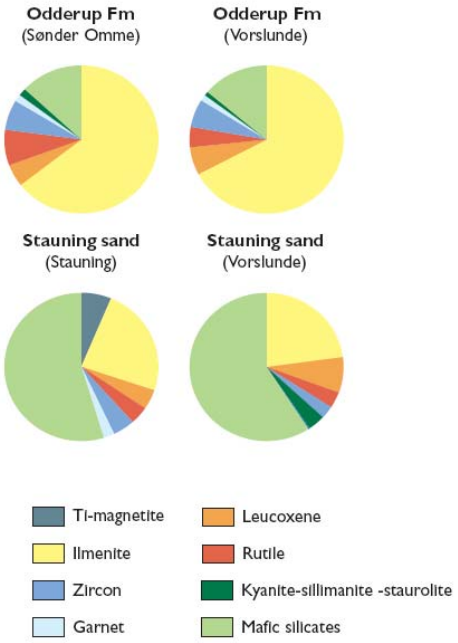

Fig. B: Modal abundances in the heavy mineral fraction of Odderup Formation sand and Stauning sand determined by CCSEM. For location, see Fig. A.

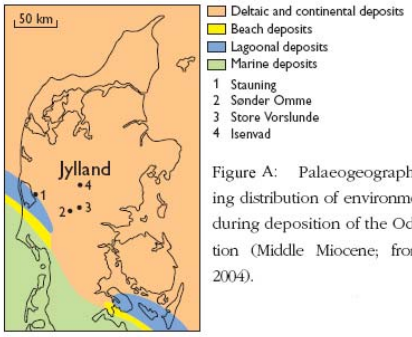

Figure A: Palaeogeographic map showing distribution of environments in Jylland during deposition of the Odderup Formation (Middle Miocene; from Rasmussen 2004).

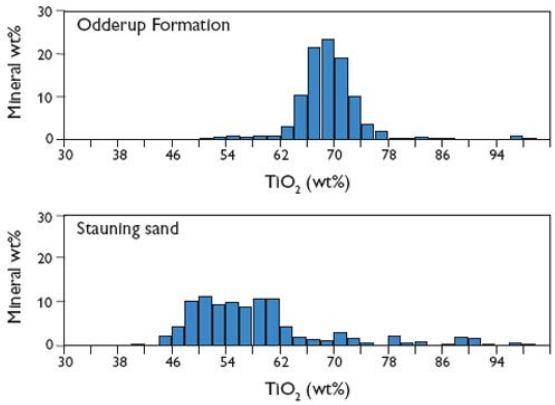

Fig. C. Distribution of TiO_2-content of the Ti-mineral fraction in the Odderup Formation and the Stauning sand at Vorslunde, determined by CCSEM. The higher TiO_2-content in the quartz sand reflects its higher maturity. For location, see Fig. A.

Fig. 3.: Example of the applications of CCSEM to four Miocene sand deposits from Jylland, Denmark. The Odderup Formation and the Stauning sand show a different heavy mineral suite and a different TiO2-content in the Ti-minerals. See Knudsen et al., 2005, for the full report.

The geochemical database currently lists 25 reports (listed in Appendix 2), mainly on the geological application of CCSEM to heavy mineral sands from Ghana, Hainan China, southern India, Sri Lanka, Denmark, Vietnam, and Madagascar. Additionally, reports on the alteration of

ilmenite, especially in relation to phosphorus, are available from the same source. https://jupiter.geus.dk/Titan/Login.

Quality control of ilmenite

The CCSEM technique has been applied to study the amount and nature of minor and trace elements in ilmenite grains. Such studies are relevant to ilmenite quality, especially with respect to specific problems in pigment manufacture due to trace element compositions in the ore feeds, but also bear on provenance investigations. Elements analysed include: Ca, P, Mn, Cr, Mg, Sn, Si, Al, and Nb. Studies related to the P and Sn trace element composition of ore can be found in the geochemical database (see Appendix 2).

Possibility to perform an element search and to track measured grains.

The output file of the CCSEM software lists BSE image number and pixel coordinates of each grain. In this way each grain can be traced back after the analyses. This is a useful tool for combining bulk CCSEM measurements (sum of individual measurements) on hundreds or thousands of grains with microprobe work on single grains selected from the whole series.

Cost and efficiency

CCSEM provides a rapid and cost effective way of measuring samples. With CCSEM, analyses can be performed on large numbers of single grains in a short amount of time and without intensive labour by an operator. CCSEM is also able to provide data on the size and shape of each of the particles. The types of data obtained by CCSEM are compared to XRF and EMP methods, along with relative cost, in the table below:

method	**XRF**	**EMP**	**CCSEM**
Multi grain analysis	no	no	yes
Single grain analysis	no	yes	yes
Bulk analysis	yes	no	yes
Grain size and shape	no	limited	yes
error	low	low	medium
cost	low	high	low-medium

Validity of the CCSEM measurements

Accuracy of the CCSEM in comparison to the electron microprobe

To test the accuracy of the CCSEM, indicator minerals from the 'Garnet Lake' kimberlite body in West Greenland were used. A series of hand-picked pyrope (garnet) grains were mounted in epoxy resin. The sample was analysed using CCSEM, with extended counting times (5000 counts in the highest peak) to ensure good statistics. The relative error in the reproducibility of the measurements is *ca.* 1–2% for major elements (here defined as present with >20 wt %) and *ca.* 4–8% for minor elements (here defined as present with >2 wt %). The accuracy of CCSEM was tested by comparing the results with compositional data obtained from electron microprobe analyses for the same minerals, as reported in Hutchison (2005). A good reproduction of the EMP measurements was achieved by CCSEM (Fig. 4); the statistical correlation between the two methods for these elements is 70%. The three outliers reflect those three garnet grains that show a compositional gradient from core to rim. The EMP point analyses were carried out on the cores of the grains, whereas the CCSEM analyses average the whole surface of the grains, therefore providing slightly different results that are closer to the bulk composition of the grains.

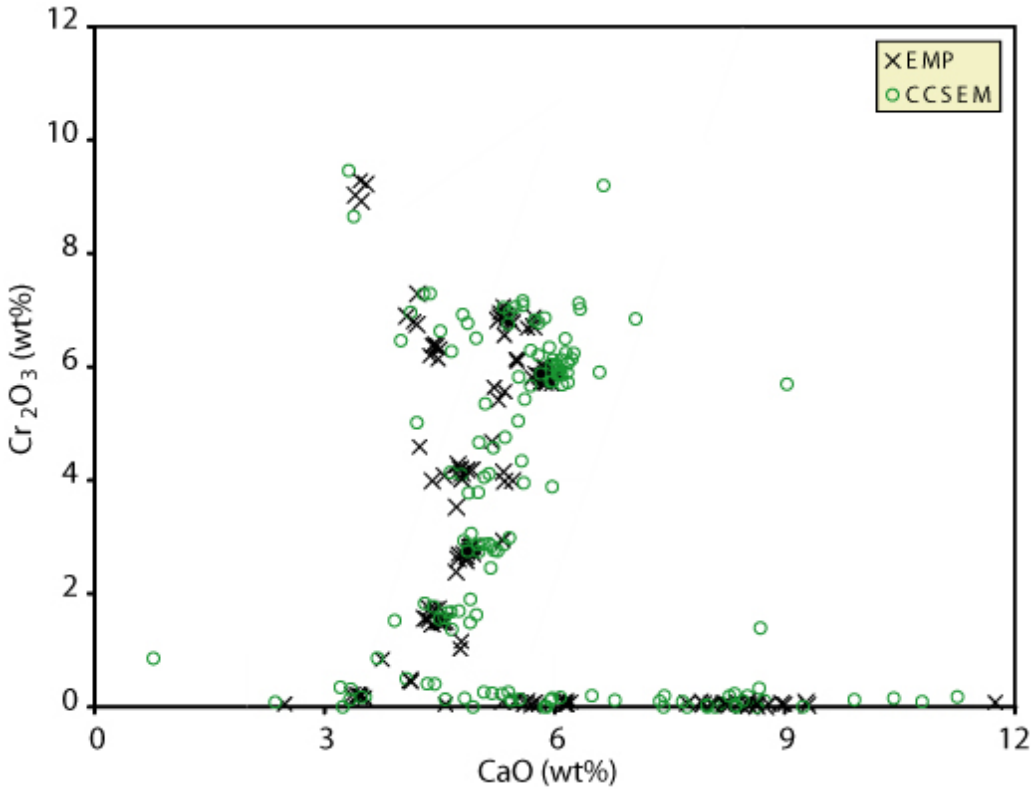

Fig. 4.: Comparison of electron microprobe (EMP) and CCSEM measurements for chromium oxide and calcium oxide in Mg-rich garnets from diamond bearing rocks. Note the good correlation between the results obtained with CCSEM and the EMP data.

Precision of the CCSEM analyses

Figure 5 shows the precision of the CCSEM method for a major element (TiO2; 93.71 wt %), a minor element (Fe2O3; 2.19 wt %) and a trace element (SO2; 0.21 wt %), measured repeatedly from the same grain. Five sets of measurements at nine different maximum peak count settings (equivalent to nine different time periods) were undertaken to evaluate the reproducibility of the data. For standard (i.e. approximately 60 seconds measuring time) single spot or single grain analyses the relatively errors are high compared to other analytical methods: 2–3% for major elements (>20 wt %), 5–10% for minor elements (>2 wt %) and 50–100% for elements present in smaller quantities. However, these figures can easily be improved by increasing the counting time slightly (Fig. 5). This shows that the analysis time can be usefully tailored to the sample set depending on the required precision of the measurements and the amount of available time or money.

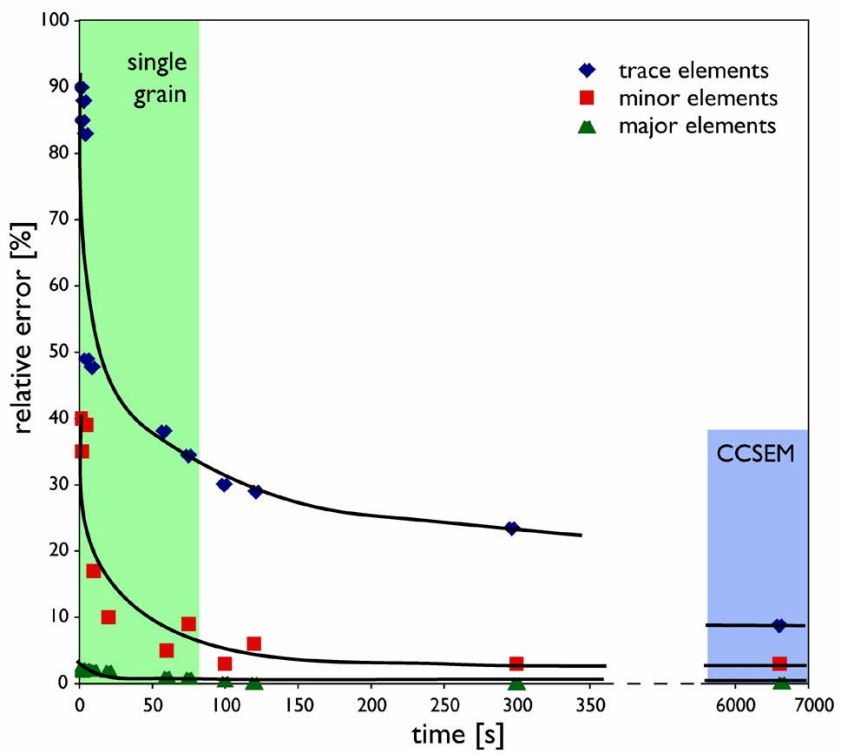

Fig. 5.: Precision of single grain (green background) and bulk sample CCSEM (blue background) analyses as a function of measurement times. Note that two detectors were used for the analyses. The precision increases with longer counting time, thus bulk sample (average of all grains) values have a much lower analytical error than single grain analyses.

Limitations to the CCSEM measurements

Analyses of trace elements

The electron microscope EDX system was not developed for the measurements of trace elements in samples. Trace elements are here defined as present with less than the error in the precision and the accuracy are large for single grain analyses: according to the manufacturer approximately 50-100% for a quantity of 0.1 wt%. By performing bulk CCSEM analysis however, this error may be largely decreased.

For typical CCSEM analyses hundreds to a few thousand measurements are made during short measuring intervals. Since two detectors are used for the measurements this yields an acceptable precision for major and minor elements. For trace elements two lines of reasoning can be followed: 1) the bulk sample value (average chemistry of the hundreds to few thousand measurements on different grains) gives the same precision as one measurement of the same duration as the sum of the hundreds of short measurements on a single grain. Random variations in the measurements will be averaged out in the bulk value, thus the bulk value has a low error (< 15%). 2) Statistics show that hundreds of independent measurements added up have an error in the same order of magnitude as the individual errors. Therefore, the bulk value of the CCSEM measurements shows a value with an error in the same order of magnitude as the individual measurements (50-100% for trace elements). The difference between the two lines of thought lie in how different the individual grains are with respect to each other and how likely the machine settings are to change between two grains.

To test this, a set of five samples supplied by DuPont consisting mainly of four natural and one synthetic rutile sample ore was run through the CCSEM procedure several times to check the precision of the phosphorus measurements (see Figure 6 and Weibel et al., 2008) for details. Phosphorus is a trace element in these samples. The results of these measurements gave an error in the precision of 4-18% for a phosphorus content of 0.025-0.07. This fits well with the error found for trace elements in bulk CCSEM measurements of <15 wt% (Figure 5).

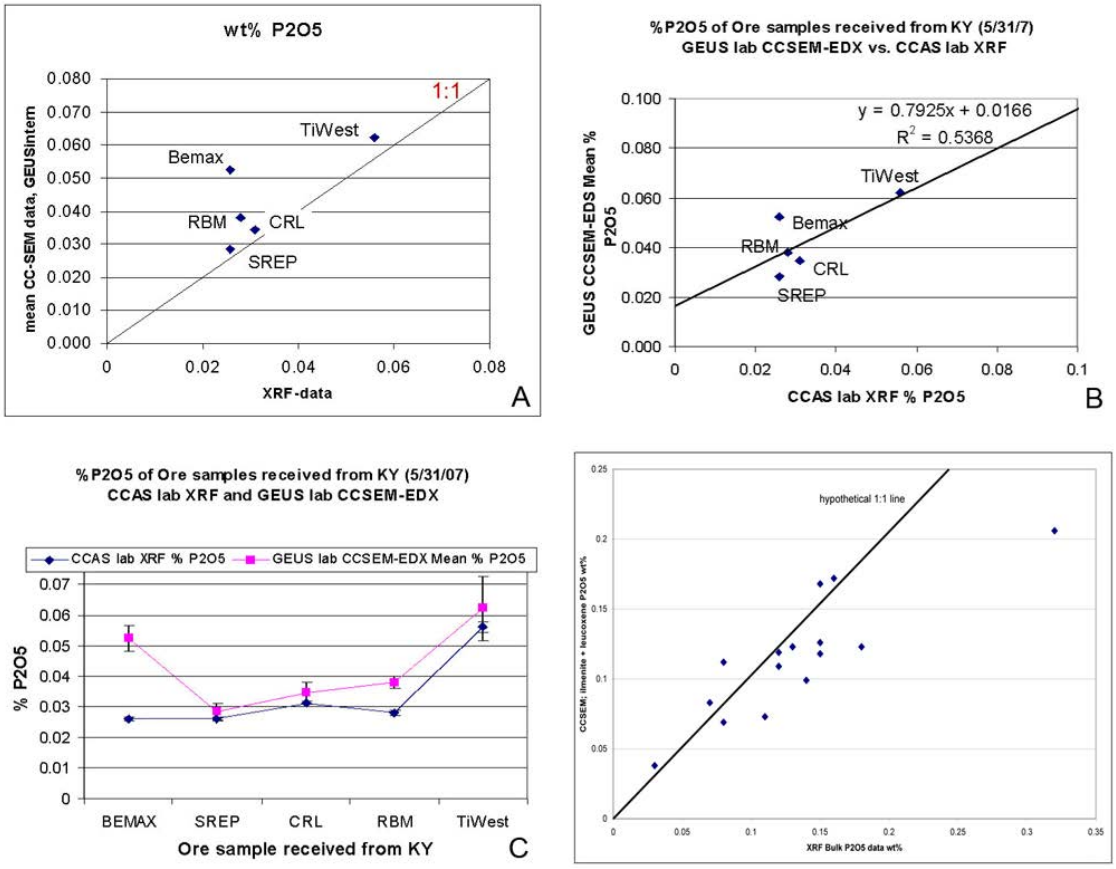

Fig. 6: Comparison of bulk CCSEM data to bulk XRF-data for P2O5 in the sample. A) The ideal 1:1 line for the samples – indicating the same amount of P2O5 observed with XRF and CCSEM. Note that CCSEM always indicates a higher concentration than XRF. B) Best-fit line for the relationship between XRF measurements and CCSEM measurements. C) wt% P2O5 for XRF and CCSEM with their relative errors. D) Extension of the measurement range to higher phosphor contents was done previously (Weibel et al., 2008).

The accuracy of the measurements on these five samples was compared to XRF-measurements on the bulk sample made by the Dupont CCAS laboratory. CCSEM measures the P2O5 contents of the samples for all non-phosphate minerals. Since these samples did not contain any phosphate minerals, the results between CCSEM and XRF should be comparable. For this test the value listed in the Geochemical database under "P in Ti-minerals" was used. In Figure 6A the results are plotted against the ideal 1:1 line. Considering the low amounts of P2O5 present in the samples (<0.07 wt %), the fit between both methods is very good. However, all CCSEM data fit above the 1:1 line. This might be caused by a systematic error (Fig. 6B) or, since all CCSEM data have higher values than the XRF data (Fig. 6C), a systematic off-set. Analysis of other samples (ilmenite and leuxocene grains), containing up to 0.25 wt% P2O5 showed the same linear trend (see Frei et al., 2004; image taken from Weibel et al., 2008). The value for P in the

CCSEM samples is the average value for P in individual ilmenite and leucoxene grains. These results show that the accuracy of the CCSEM for bulk analyses of phosphor is good, but a systematic off-set compared to XRF is observed. CCSEM yields a lower value for "P in Ti-minerals" and a higher value when using P in individual leucoxene and ilmenite grains.

These tests show, at least for the case of phosphorus, that the bulk CCSEM error value lies near the error value for one measurement of the same duration. The empirically derived precision in the measurements is better than would be expected on the basis of statistical calculations based on the sum of hundreds of measurements with a high error value.

Peak overlap within the EDX-spectrum

One of the reasons for a systematic off-set in the measurements of phosphor as described above might be the overlap of the phosphor peak in the EDX-spectrum with peaks of other elements, especially Zr. The KY rutile samples had a few zircon grains. Small fractions of Zr might have been classified as P, which might be a source of "extra" phosphor.

This problem occurs not only for Zr and P, but for many combinations of other minerals as well. Of major concern are S, Mo and Pb; and Zn and Na, but also smaller peaks of elements adjacent to each other in the periodic system may cause discrepancies in the measurement; e.g. K and Ca; Ti and V; and the light elements Na, Mg, Al, and Si that lie very close to each other in the spectrum. Therefore, the validity of the measurement of each minor and trace element does not only depend on its concentration in the grain, but also on the concentration of other elements in the same grain.

Conclusions

The examples discussed above indicate that CCSEM provides a relatively accurate and precise way to rapidly and cheaply measure single grain and bulk compositions of minerals and of other geological and non-geological materials. Coupled with measurements of the grain size and other grain parameters for the individual particles this technique is a potent tool to solve a wide range of problems. Applied to heavy mineral deposits, is a rapid and cost effective means to evaluate the heavy mineral suite and the quality of contained titanium minerals. Caution should be applied with the data interpretation, since all mineral classifications are solely based on grain chemistry.

Acknowledgements

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References

Bernstein, S., Frei, D., McLimans, R.K., Knudsen, C. & Vasudev, V.N. 2008: Application of CCSEM to heavy mineral deposits: source of high-Ti ilmenite sand deposits of South Kerala beaches, SW India. Journal of Geochemical Exploration **96**, 25–42.

D'Alessio, A., Bramanti, E., Piperno, M. Naccarato, G. Vergamini, P. & Fornaciari, G. 2005: An 8500-year-old bladder stone from Uzzo cave (Trapani): fourier transform-infrared spectroscopy. Archaeomotry **47**, 127–136.

Frei, D., Knudsen, C., McLimans, R.K.: Phosphorus in Ilmenite Ores. June 2004.

Frei, D., Rasmussen, T., Knudsen, C., Larsen, M., Whitham, A. & Morton, A. 2005: Linking the Faroese area and Greenland: new methods and techniques used in an innovative, integrated provenance study. Fróðskaparrit **43**, 96–108.

Friedrichs, K.H. 1987: Electron microscopic analyses of dust from the lungs and the lymph nodes of talc-mine employees. American Industry Hygiene Association Journal **48**, 626–633.

Heasman I. & Watt, J.: Particulate pollution case studies which illustrate uses of individual particle analysis by scanning electron microscopy. Environmental Geochemistry and Health **11**, 157–162.

Huggins, F.E., Kosmack, D.A., Huffman, G.P. & Lee, R.J. 1980: Coal mineralogy by SEM analysis. Scanning Electron Microscopy **1**, 531–540.

Huffman, G.P. et al. 1994: Investigation of ash by microscopic and spectroscopic techniques. In: Williamson, J. & Wigley, F. (eds): Proceedings of the Engineering Foundation Conference (June 20–25, 1993, Solihull, Birmingham, UK), The impact of ash deposition on coal fired plants, 409–423. London: Taylor & Francis.

Hutchison, M.T. 2005: Diamondiferous kimberlites from the Garnet Lake area, West Greenland: exploration, methologies and petrochemistry. In: Secher, K & Nielsen, M.N. (eds.): Workshop on Greenland's diamond potential. Geological Survey of Denmark and Greenland Geological Report **2005/68**, 33–42.

Knudsen, C., Frei, D. , Rasmussen, T., Rasmussen, E. S. & McLimans, R. 2005: New methods in provenance studies based on heavy minerals: an example from Miocene sands in Jylland, Denmark. Geological Survey of Denmark and Greenland Bulletin **7**, 29–32.

McLimans, R. K., Rogers, W. T., Korneliussen, A., Garson, M, & Arenberg, E., 1999, Norwegian eclogite; an ore of titanium; Miner. Deposits: Processes, Proc. Fifth Bien. SGA Mtg, IAGOD symp – 1999; V2, 1125-1127; Stanley, C.J., ed.; A. A. Balkema, pub., Rotterdam, Netherlands

Lee, R.J. & Kelly, J.F. 1980: Overview of SEM-based automated image analysis. Scanning Electron Microscopy **1**, 303 only.

Lin, M.C. & Barnes, R.G. 1984: Møssbauer spectroscopy and scanning electron microscopy study of iron-graphimet. Journal of Applied Physics **55**, 2294–2296.

Pirrie, D., Butcher, A.R., Power, M.R., Gottlieb, P. & Miller, G.L. 2004: Rapid quantitative mineral and phase analysis using automated scanning electron microscopy (QemSCAN); potential applications in

forensic geoscience. In: Kenneth, P. & Croft, D.J.: Forensic geoscience; principles, techniques and applications.Geological Society, London, Special Publications **232**, 123–136

Steffen, S., Otto, M., Niewoehner, L., Barth, M., Brozek-Mucha, Z., Biegstraaten, J. & Horvath, R. 2007: Chemometric classification of gunshot residues based on energy dispersive X-ray microanalysis and incuctively coupled plasma analysis with mass-spectrometric detection. Spectrochimica Acta **B62**, 1028–1036.

Schwoeble, A.J., Dalley, A.M., Henderson, B.C. & Casuccio, G.S. 1988: Computer-Controlled SEM and microimaging of fine particles. Journal of Metals **40**, 11–14.

Yin, C. & Johnson, D.L. 1984: An individual particle analysis and budget study of Onondaga Lake sediments. Limnology & Oceanography **29**, 193–1201.

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Appendix 1: classification CCSEM June 2008

```
PROCEDURE classify_mineral

IS

Al_divisor NUMBER;

BEGIN

IF ccsem_result_tab('Al').analysisresult = 0 THEN

Al_divisor := 0.00000001;

ELSE

Al_divisor := ccsem_result_tab('Al').analysisresult;

END IF;

IF ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Ti').analysisresult >= 60

AND ccsem_result_tab('Ti').analysisresult < 42.3

AND ccsem_result_tab('Ti').analysisresult > 15

THEN

ccsem_rec.mineralid := 3; -- "Ti magnetite"

ELSIF ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Ti').analysisresult >= 60

AND ccsem_result_tab('Ti').analysisresult >= 42.3

AND ccsem_result_tab('Ti').analysisresult < 66.8

THEN

ccsem_rec.mineralid := 4; -- "ilmenite"

ELSIF ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Ti').analysisresult >= 60

AND ccsem_result_tab('Ti').analysisresult >= 66.8

AND ccsem_result_tab('Ti').analysisresult < 88.5

THEN

ccsem_rec.mineralid := 5; -- "leucoxene"

ELSIF ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Ti').analysisresult >= 65

AND ccsem_result_tab('Ti').analysisresult >= 88.5

THEN

ccsem_rec.mineralid := 6; -- "rutile"

ELSIF ccsem_result_tab('Fe').analysisresult > 60
```

```
AND ccsem_result_tab('Ti').analysisresult <= 15

AND ccsem_result_tab('Cr').analysisresult <= 10

AND ccsem_result_tab('S').analysisresult < 40

THEN

ccsem_rec.mineralid := 7; -- "Magnetite"

ELSIF ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Cr').analysisresult > 60

AND ccsem_result_tab('Cr').analysisresult > 10

THEN

ccsem_rec.mineralid := 8; -- "Chromite"

ELSIF ccsem_result_tab('Si').analysisresult > 18

AND ccsem_result_tab('Zr').analysisresult > 65

THEN

ccsem_rec.mineralid := 9; -- "zircon"

ELSIF ccsem_result_tab('P').analysisresult > 22

AND ccsem_result_tab('Y').analysisresult > 10

AND ccsem_result_tab('Zr').analysisresult < 10

THEN

ccsem_rec.mineralid := 10; -- "Xenotime"

ELSIF ccsem_result_tab('P').analysisresult > 10

AND ccsem_result_tab('Ce').analysisresult > 20

AND ccsem_result_tab('Zr').analysisresult < 15

THEN

ccsem_rec.mineralid := 11; -- "Monazite"


ELSIF ccsem_result_tab('P').analysisresult > 20

THEN

ccsem_rec.mineralid := 33; -- "phosphate"

ELSIF ccsem_result_tab('Ca').analysisresult > 80

AND ccsem_result_tab('Ca').analysisresult +
ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Mg').analysisresult > 90

THEN

ccsem_rec.mineralid := 32; -- carbonate
```

```
ELSIF ccsem_result_tab('Ca').analysisresult +
ccsem_result_tab('Si').analysisresult +
ccsem_result_tab('Ti').analysisresult >= 90

AND ccsem_result_tab('Ca').analysisresult >= 25

AND ccsem_result_tab('Ti').analysisresult >= 25

THEN

ccsem_rec.mineralid := 13; -- "sphene"

ELSIF ccsem_result_tab('S').analysisresult > 40

AND ccsem_result_tab('Fe').analysisresult >= 20

AND ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('S').analysisresult >= 60

THEN

ccsem_rec.mineralid := 14; -- "pyrite"

ELSIF ccsem_result_tab('Si').analysisresult / Al_divisor > 1.44

AND ccsem_result_tab('Si').analysisresult / Al_divisor < 3.12

AND ccsem_result_tab('Si').analysisresult > 27 AND
ccsem_result_tab('Si').analysisresult < 38

AND ccsem_result_tab('Al').analysisresult > 15 AND
ccsem_result_tab('Al').analysisresult < 25.56

AND ccsem_result_tab('Ca').analysisresult < 10

AND ccsem_result_tab('K').analysisresult < 1

AND ccsem_result_tab('Na').analysisresult < 1

AND ccsem_result_tab('Ti').analysisresult < 5

AND ccsem_result_tab('Nb').analysisresult < 2

AND ccsem_result_tab('Y').analysisresult < 2

AND ccsem_result_tab('Zr').analysisresult < 2

AND ccsem_result_tab('S').analysisresult <2

THEN

ccsem_rec.mineralid := 15; -- "garnet"

ELSIF ccsem_result_tab('Al').analysisresult > 54

AND ccsem_result_tab('Si').analysisresult < 40 AND
ccsem_result_tab('Si').analysisresult > 29

AND ccsem_result_tab('Fe').analysisresult < 5

THEN

ccsem_rec.mineralid := 17; -- "sillimanite-kyanite"
```

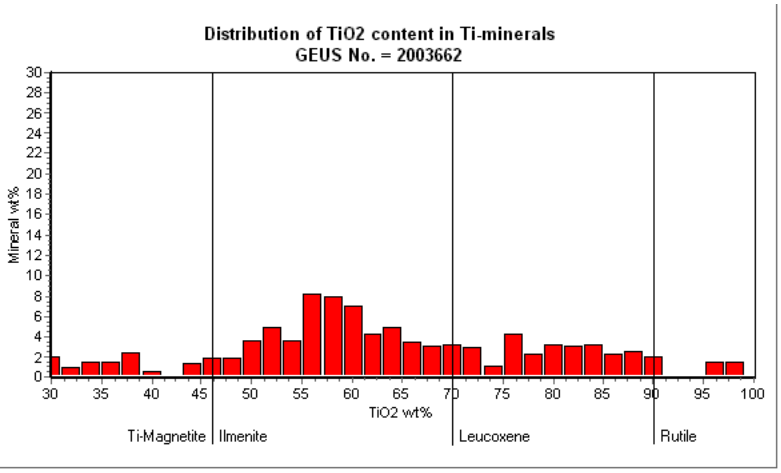
```
ELSIF ccsem_result_tab('Al').analysisresult +
ccsem_result_tab('Si').analysisresult > 70

AND ccsem_result_tab('Fe').analysisresult > 10 AND
ccsem_result_tab('Fe').analysisresult < 30

AND ccsem_result_tab('Al').analysisresult > 40 AND
ccsem_result_tab('Al').analysisresult < 60

THEN

ccsem_rec.mineralid := 18; -- "staurolite"

ELSIF ccsem_result_tab('Si').analysisresult > 85

THEN

ccsem_rec.mineralid := 21; -- "quartz"

ELSIF ccsem_result_tab('Al').analysisresult > 90

THEN

ccsem_rec.mineralid := 22; -- corundum

ELSIF ccsem_result_tab('Al').analysisresult > 70

AND ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Al').analysisresult +
ccsem_result_tab('Mg').analysisresult > 90 THEN

ccsem_rec.mineralid := 23 ; --spinel

ELSIF ccsem_result_tab('K').analysisresult > 8

AND ccsem_result_tab('K').analysisresult < 17

AND ccsem_result_tab('Si').analysisresult > 30

AND ccsem_result_tab('Ca').analysisresult < 2

THEN

ccsem_rec.mineralid := 29; -- mica




ELSIF ccsem_result_tab('Si').analysisresult +
ccsem_result_tab('Al').analysisresult > 36

AND ccsem_result_tab('Si').analysisresult +
ccsem_result_tab('Al').analysisresult < 70

AND ccsem_result_tab('Mg').analysisresult +
ccsem_result_tab('Fe').analysisresult > 10

AND ccsem_result_tab('Si').analysisresult/Al_divisor > 1

AND ccsem_result_tab('Na').analysisresult +
ccsem_result_tab('Mg').analysisresult +
ccsem_result_tab('Si').analysisresult +
ccsem_result_tab('Fe').analysisresult +
```

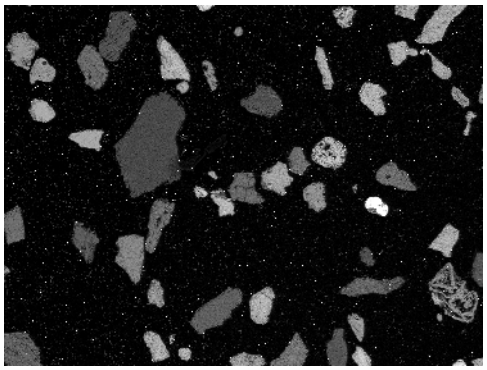
```
ccsem_result_tab('Mn').analysisresult +
ccsem_result_tab('Ca').analysisresult +
ccsem_result_tab('Al').analysisresult> 90

THEN

ccsem_rec.mineralid := 34; -- mafic silicates


ELSIF ccsem_result_tab('Si').analysisresult +
ccsem_result_tab('Al').analysisresult > 70

AND ccsem_result_tab('K').analysisresult +
ccsem_result_tab('Ca').analysisresult +
ccsem_result_tab('Na').analysisresult > 10

THEN

ccsem_rec.mineralid := 25; -- feldspar


ELSIF ccsem_result_tab('Al').analysisresult > 47

AND ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Al').analysisresult +
ccsem_result_tab('Mg').analysisresult > 90 THEN

ccsem_rec.mineralid := 23 ; --spinel (herzynite)


ELSIF ccsem_result_tab('Sn').analysisresult > 85

THEN

ccsem_rec.mineralid := xx ; --cassiterite


ELSIF ccsem_result_tab('Na').analysisresult +
ccsem_result_tab('Mg').analysisresult +
ccsem_result_tab('Al').analysisresult +
ccsem_result_tab('Si').analysisresult +
ccsem_result_tab('Ca').analysisresult +
ccsem_result_tab('Fe').analysisresult +
ccsem_result_tab('Mn').analysisresult > 90

AND ccsem_result_tab('Si').analysisresult > 30

THEN

ccsem_rec.mineralid := 19; -- "silicate"

ELSE

ccsem_rec.mineralid := 20; -- "unclassified"

END IF;

END;
```

Appendix 2: list of reports in the Geochemical database (autumn 2008)

Hansen, H.	Heavy mineral enriched beach sands from King Island, Australia	2002
Stendal, H.	Heavy minerals in Ghana	2002
Stendal, H.	Heavy mineral resource potential of India	2002
Bernstein, S.	Ilmenite heavy sand deposits, South India - provenance and chemistry clues to their origin	2003
Rasmussen, T.	U-Pb age dating of alteration of ilmenite in the Miocene Odderup Formation at Voerslunde, Jutland	2003
Sorensen, J.B.	Heavy mineral exploration in Denmark reconnaissance 1998-2000	2003
Stendal, H.	Heavy mineral sands in Kerala and Tamil Nadu, southern India	2003
Stendal, H.	Heavy mineral sands in Vietnam	2003
Bernstein, S.	Source rocks for SW Indian heavy sand deposits	2004
Bernstein, S.	Heavy sand deposits in southern Madagascar	2004
Stendal, H.	Heavy Mineral Sands in Vietnam 2003	2004
Stendal, H.	Heavy Mineral Sands in Vietnam 2004	2004
Thorning, L.	Database for titanium placer deposits	2004
Stefan Bernstein	CCSEM - mineral categories	2006
Nynke Keulen	Trace amounts of P2O5 in TiO2-minerals measured with CCSEM	2007
Nynke Keulen	Analysis of ilmenite ores from Sri Lanka-CCSEM results	2007
Riisager, P.	Web interface for Titan and Commercial Ore	2007
Uffe Larsen	Presentation, Statistics and upload facilities	2007
Weibel, R.	Element Mapping in Ilmenite Ore	2007
Christian Knudsen	Hainan Island Ilmenilte	2008
Nynke Keulen	Update on the mineral classification with the new CCSEM software - progress report june 2008	2008
Nynke Keulen	Sri Lanka Januari 2008	2008
Nynke Keulen	Sn (tin) in ilmenite and leucoxene ores	2008
Nynke Keulen / Roger McLimans	Fully automated analysis of grain chemistry, size and	2008
Rikke Weibel Hansen	Phosphorus in ilmenite ore. Status report for DuPont, 2008	2008

Titanium Report - Page 1/3
Sample GEUS #: 2003662
Sampler's sample#: 16
Description: Active dune. Fine-grained Buff coloured. Ca 1 km wide dunefield of active dunes ca 15 m high. Rich in hesvy minerals
Potengi
Country: BRAZIL
This document was created on: Wed Feb 04 15:51:43 CET 2009





Average Content

Mineral	Na2O	MgO	Al2O3	SiO2	SO3	K2O	CaO	TiO2	Cr2O3	MnO	Fe2O3	NiO	CuO	ZrO2	Nb2O5	P2O5	Y2O3	Ce2O3	SnO	Particles
ilmenite	0.0	0.5	1.53	3.03	0.17	0.09	0.35	57.26	0.12	1.74	34.29	0.09	0.1	0.19	0.22	0.16	0.02	0.05	0.09	317
leucoxene	0.01	0.28	3.7	6.42	0.24	0.2	0.25	76.97	0.25	0.34	9.77	0.09	0.1	0.31	0.42	0.47	0.07	0.02	0.08	105
rutile	0.0	0.11	1.01	1.76	0.18	0.06	0.12	93.57	0.27	0.08	1.67	0.11	0.09	0.17	0.55	0.12	0.01	0.03	0.09	40
Ti magnetite	0.18	2.56	2.62	5.01	0.23	0.17	0.66	27.66	0.37	0.62	58.44	0.07	0.11	0.61	0.28	0.24	0.08	0.0	0.09	62
magnetite	0.1	2.35	4.6	7.38	0.26	0.27	0.19	8.46	0.44	0.45	74.4	0.1	0.11	0.14	0.11	0.46	0.03	0.01	0.12	75
chromite	1.44	7.61	4.32	0.73	0.05	0.05	0.08	12.22	22.57	0.69	49.74	0.25	0.07	0.0	0.09	0.07	0.0	0.01	0.0	3
spinel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
zircon	0.04	0.06	0.23	31.17	0.07	0.02	0.05	0.23	0.06	0.07	0.87	0.16	0.02	59.96	6.58	0.0	0.01	0.16	0.25	75
sphene	0.0	0.16	1.55	11.93	0.23	0.06	31.59	50.43	0.15	0.06	2.44	0.18	0.02	0.01	0.36	0.18	0.09	0.44	0.12	18
garnet	0.0	3.19	21.13	36.79	0.62	0.07	3.17	0.41	0.08	1.98	30.46	0.05	0.0	0.0	0.65	1.0	0.25	0.12	0.03	15
sillimanite-kyanite	0.13	0.12	55.04	37.86	0.85	0.17	0.06	0.25	0.08	0.08	1.0	0.08	0.05	0.09	0.83	2.4	0.72	0.18	0.03	10
staurolite	0.3	1.82	46.56	34.03	0.84	0.14	0.17	0.71	0.08	0.18	12.47	0.08	0.05	0.02	0.71	1.36	0.31	0.1	0.08	25
mica	1.06	0.27	34.5	44.11	1.23	5.93	0.0	3.29	0.24	0.0	3.71	0.22	0.0	0.0	1.46	2.38	0.0	1.49	0.11	1
mafic silicates	0.41	6.55	13.73	44.07	0.75	0.46	13.72	0.95	0.2	0.47	16.84	0.1	0.07	0.02	0.62	0.44	0.28	0.05	0.26	225
feldspar	2.49	0.0	23.37	55.39	1.16	7.9	4.89	0.37	0.11	0.04	1.56	0.05	0.06	0.07	0.83	0.53	0.6	0.0	0.6	4
silicate-other	1.61	4.43	34.15	43.81	1.12	0.13	1.53	0.88	0.09	0.1	8.8	0.08	0.05	0.03	1.16	1.36	0.48	0.09	0.1	75
quartz	0.05	0.03	0.21	90.05	2.98	0.0	0.0	0.31	0.05	0.06	0.62	0.17	0.06	0.02	2.71	0.51	0.13	0.21	1.84	20
corundum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
monazite	0.0	0.69	2.79	6.33	1.38	0.0	1.9	9.15	0.0	0.0	10.28	0.05	0.09	7.46	0.0	32.55	1.97	25.38	0.0	3
xenotime	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
phosphate	0.0	0.0	39.16	6.84	5.33	0.3	1.58	0.0	0.0	0.0	3.01	0.0	0.0	7.93	0.0	30.51	0.0	4.81	0.53	1
carbonate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pyrite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
unclassified	0.18	1.09	7.32	43.98	2.52	0.61	3.45	13.74	0.19	0.31	9.74	0.26	0.21	7.6	3.8	1.43	2.32	0.47	0.78	126

P2O5 budget of ore in Ti-minerals: 0.084
P2O5 budget of ore in bulk sample: 0.165

Titanium Report - Page 2/3
Sample GEUS #: 2003662
Sampler's sample#: 16
Description: Active dune. Fine-grained Buff coloured. Ca 1 km wide dunefield of active dunes ca 15 m high. Rich in hesvy minerals
Potengi
Country: BRAZIL
This document was created on: Wed Feb 04 15:51:44 CET 2009

Valuable Heavy Minerals								
Category	Ilmenite	Leucoxene	Rutile	Ti magnetite	Garnet	Zircon	Kya/Sill	Staurolite
Weight-percent:	43.2	23.2	6.1	11.6	0.9	9.4	1.3	4.2

Normalised average content of the valuable Ti-bearing minerals				
contents	Ilminite	Leucoxene	Rutile	Ti magnetite
TiO2 wt%	57.8	78.3	94.7	28.1
Fe2O3 wt%	34.6	9.9	1.7	59.3
Mno wt%	1.8	0.3	0.1	0.6
Cr2O3 wt%	0.1	0.3	0.3	0.4
SiO2 wt%	3.1	6.5	1.8	5.1
Al2O3 wt%	1.5	3.8	1.0	2.7
MgO wt%	0.5	0.3	0.1	2.6
CaO wt%	0.4	0.3	0.1	0.7
ZrO2wt%	0.2	0.3	0.2	0.6

TiO2 Content	
Average TiO2 content of all the TiO2 minerals :	61.7
Average TiO2 content of all the TiO2 minerals excl. Rutile:	59.2

Titanium Report - Page 3/3
Sample GEUS #: 2003662
Sampler's sample#: 16
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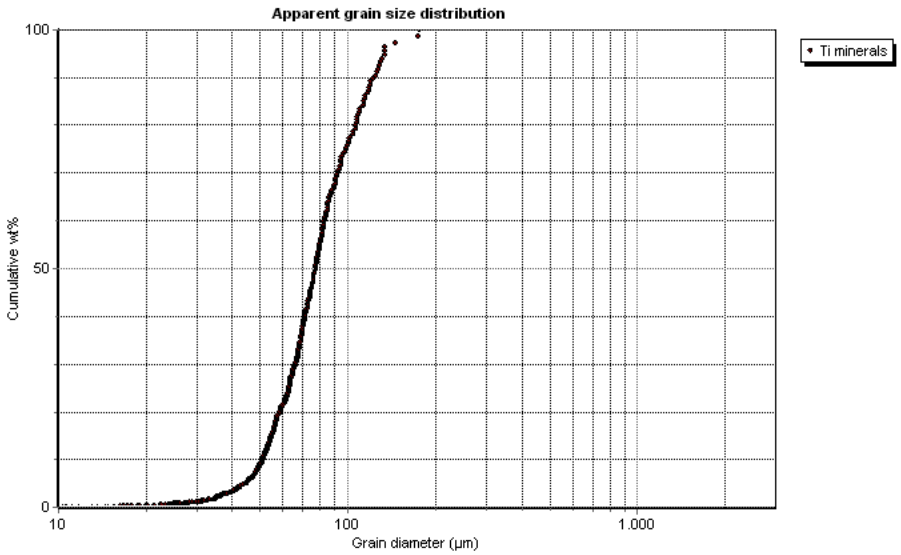
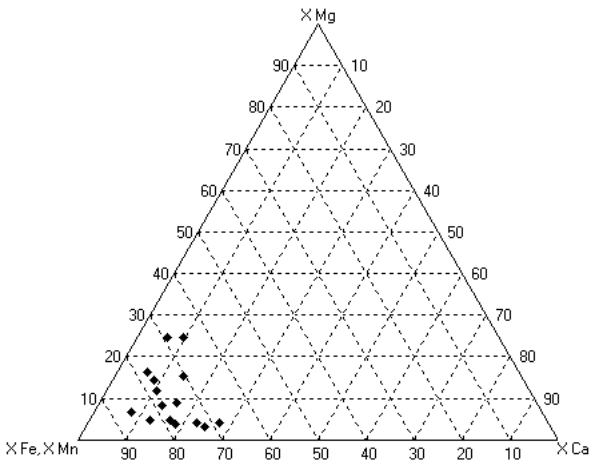
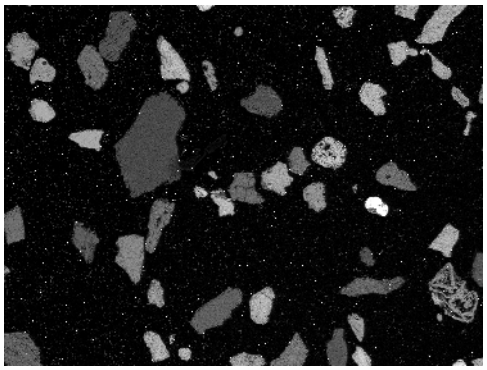


Weight percent and average grain parameters on a mineral basis								
Category	Heavy mineral concentrate wt %	Raw sand wt %	Aspect ratio	Circularity	Perimeter	Length	Area	Total grains
ilmenite	-	-	1.5	1.6	227.1	77.3	2996.5	317
leucoxene	-	-	1.6	1.6	286.8	101.4	4862.9	105
rutile	-	-	1.5	1.5	213.2	70.4	3016.0	40
Ti magnetite	6.1	0.1	1.7	1.7	262.3	95.9	3868.4	62
magnetite	6.1	0.1	1.6	1.6	238.3	83.6	3501.8	75
chromite	6.1	0.1	1.5	1.5	243.9	83.2	3254.0	3
spinel	6.1	0.1	0	0	0	0	0	0
zircon	6.1	0.1	1.2	1.3	198.9	59.2	2657.9	75
sphene	6.1	0.1	1.6	1.6	230.9	82.6	3116.9	18
garnet	6.1	0.1	1.7	1.7	155.8	58.3	1549.3	15
sillimanite-kyanite	6.1	0.1	1.8	1.8	286.0	104.8	4097.6	10
staurolite	6.1	0.1	1.5	1.6	268.0	91.2	4376.2	25
mica	6.1	0.1	2.4	2.4	172.1	72.2	1001.0	1
mafic silicates	6.1	0.1	1.9	1.9	333.5	127.8	5528.1	225
feldspar	6.1	0.1	1.3	1.3	141.7	42.4	1773.4	4
silicate-other	6.1	0.1	1.5	1.6	332.3	114.6	6523.5	75
quartz	6.1	0.1	1.5	1.5	265.1	87.3	5231.3	20
corundum	6.1	0.1	0	0	0	0	0	0
monazite	6.1	0.1	1.8	1.8	242.1	93.8	2612.7	3
xenotime	6.1	0.1	0	0	0	0	0	0
phosphate	6.1	0.1	2.5	1.7	125.9	47.6	731.3	1
carbonate	6.1	0.1	0	0	0	0	0	0
pyrite	6.1	0.1	0	0	0	0	0	0
unclassified	6.1	0.1	1.8	1.8	248.4	96.1	4298.8	126

Garnet Report - Page 1/3
Sample GEUS #: 2003662
Sampler's sample#: 16
Description: Active dune. Fine-grained Buff coloured. Ca 1 km wide dunefield of active dunes ca 15 m high. Rich in hesvy minerals
Potengi
Country: BRAZIL
This document was created on: Wed Feb 04 15:50:51 CET 2009





Weight percent and average grain parameters on a mineral basis								
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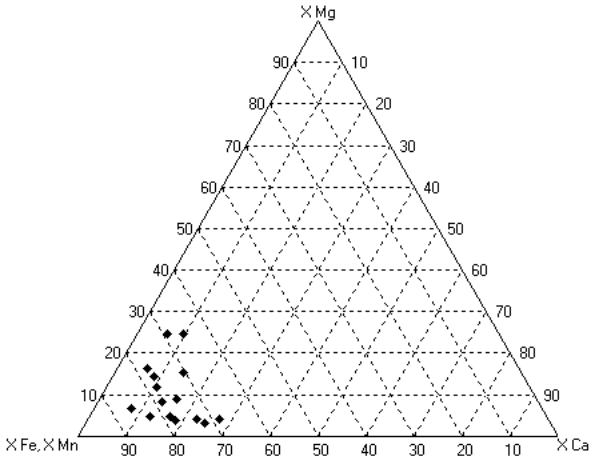
rutile	-	-	1.5	1.5	213.2	70.4	3016.0	40
Ti magnetite	6.1	0.1	1.7	1.7	262.3	95.9	3868.4	62
magnetite	6.1	0.1	1.6	1.6	238.3	83.6	3501.8	75
chromite	6.1	0.1	1.5	1.5	243.9	83.2	3254.0	3
spinel	6.1	0.1	0	0	0	0	0	0
zircon	6.1	0.1	1.2	1.3	198.9	59.2	2657.9	75
sphene	6.1	0.1	1.6	1.6	230.9	82.6	3116.9	18
garnet	6.1	0.1	1.7	1.7	155.8	58.3	1549.3	15
sillimanite-kyanite	6.1	0.1	1.8	1.8	286.0	104.8	4097.6	10
staurolite	6.1	0.1	1.5	1.6	268.0	91.2	4376.2	25
mica	6.1	0.1	2.4	2.4	172.1	72.2	1001.0	1
mafic silicates	6.1	0.1	1.9	1.9	333.5	127.8	5528.1	225
feldspar	6.1	0.1	1.3	1.3	141.7	42.4	1773.4	4
silicate-other	6.1	0.1	1.5	1.6	332.3	114.6	6523.5	75
quartz	6.1	0.1	1.5	1.5	265.1	87.3	5231.3	20
corundum	6.1	0.1	0	0	0	0	0	0
monazite	6.1	0.1	1.8	1.8	242.1	93.8	2612.7	3
xenotime	6.1	0.1	0	0	0	0	0	0
phosphate	6.1	0.1	2.5	1.7	125.9	47.6	731.3	1
carbonate	6.1	0.1	0	0	0	0	0	0
pyrite	6.1	0.1	0	0	0	0	0	0

Weight percent and average grain parameters on a mineral basis								
unclassified	6.1	0.1	1.8	1.8	248.4	96.1	4298.8	126

Garnet Report - Page 2/3
Sample GEUS #: 2003662
Sampler's sample#: 16
Description: Active dune. Fine-grained Buff coloured. Ca 1 km wide dunefield of active dunes ca 15 m high. Rich in hesvy minerals
Potengi
Country: BRAZIL
This document was created on: Wed Feb 04 15:50:52 CET 2009

Average Content

Mineral	Na2O	MgO	Al2O3	SiO2	SO3	K2O	CaO	TiO2	Cr2O3	MnO	Fe2O3	NiO	CuO	ZrO2	Nb2O5	P2O5	Y2O3	Ce2O3	SnO	Particles
ilmenite	0.0	0.5	1.53	3.03	0.17	0.09	0.35	57.26	0.12	1.74	34.29	0.09	0.1	0.19	0.22	0.16	0.02	0.05	0.09	317
leucoxene	0.01	0.28	3.7	6.42	0.24	0.2	0.25	76.97	0.25	0.34	9.77	0.09	0.1	0.31	0.42	0.47	0.07	0.02	0.08	105
rutile	0.0	0.11	1.01	1.76	0.18	0.06	0.12	93.57	0.27	0.08	1.67	0.11	0.09	0.17	0.55	0.12	0.01	0.03	0.09	40
Ti magnetite	0.18	2.56	2.62	5.01	0.23	0.17	0.66	27.66	0.37	0.62	58.44	0.07	0.11	0.61	0.28	0.24	0.08	0.0	0.09	62
magnetite	0.1	2.35	4.6	7.38	0.26	0.27	0.19	8.46	0.44	0.45	74.4	0.1	0.11	0.14	0.11	0.46	0.03	0.01	0.12	75
chromite	1.44	7.61	4.32	0.73	0.05	0.05	0.08	12.22	22.57	0.69	49.74	0.25	0.07	0.0	0.09	0.07	0.0	0.01	0.0	3
spinel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
zircon	0.04	0.06	0.23	31.17	0.07	0.02	0.05	0.23	0.06	0.07	0.87	0.16	0.02	59.96	6.58	0.0	0.01	0.16	0.25	75
sphene	0.0	0.16	1.55	11.93	0.23	0.06	31.59	50.43	0.15	0.06	2.44	0.18	0.02	0.01	0.36	0.18	0.09	0.44	0.12	18
garnet	0.0	3.19	21.13	36.79	0.62	0.07	3.17	0.41	0.08	1.98	30.46	0.05	0.0	0.0	0.65	1.0	0.25	0.12	0.03	15
sillimanite-kyanite	0.13	0.12	55.04	37.86	0.85	0.17	0.06	0.25	0.08	0.08	1.0	0.08	0.05	0.09	0.83	2.4	0.72	0.18	0.03	10
staurolite	0.3	1.82	46.56	34.03	0.84	0.14	0.17	0.71	0.08	0.18	12.47	0.08	0.05	0.02	0.71	1.36	0.31	0.1	0.08	25
mica	1.06	0.27	34.5	44.11	1.23	5.93	0.0	3.29	0.24	0.0	3.71	0.22	0.0	0.0	1.46	2.38	0.0	1.49	0.11	1
mafic silicates	0.41	6.55	13.73	44.07	0.75	0.46	13.72	0.95	0.2	0.47	16.84	0.1	0.07	0.02	0.62	0.44	0.28	0.05	0.26	225
feldspar	2.49	0.0	23.37	55.39	1.16	7.9	4.89	0.37	0.11	0.04	1.56	0.05	0.06	0.07	0.83	0.53	0.6	0.0	0.6	4
silicate-other	1.61	4.43	34.15	43.81	1.12	0.13	1.53	0.88	0.09	0.1	8.8	0.08	0.05	0.03	1.16	1.36	0.48	0.09	0.1	75
quartz	0.05	0.03	0.21	90.05	2.98	0.0	0.0	0.31	0.05	0.06	0.62	0.17	0.06	0.02	2.71	0.51	0.13	0.21	1.84	20
corundum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
monazite	0.0	0.69	2.79	6.33	1.38	0.0	1.9	9.15	0.0	0.0	10.28	0.05	0.09	7.46	0.0	32.55	1.97	25.38	0.0	3
xenotime	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
phosphate	0.0	0.0	39.16	6.84	5.33	0.3	1.58	0.0	0.0	0.0	3.01	0.0	0.0	7.93	0.0	30.51	0.0	4.81	0.53	1
carbonate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pyrite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
unclassified	0.18	1.09	7.32	43.98	2.52	0.61	3.45	13.74	0.19	0.31	9.74	0.26	0.21	7.6	3.8	1.43	2.32	0.47	0.78	126



GEOLOGICAL SURVEY OF DENMARK AND GREENLAND

Sample GEUS #: 2003662
Sampler's sample#: 16
Description: Active dune. Fine-grained Buff coloured. Ca 1 km wide dunefield of active dunes ca 15 m high. Rich in hesvy minerals
Potengi
Country: BRAZIL
This document was created on: Wed Feb 04 15:50:52 CET 2009

Weight percent and average grain parameters on a mineral basis								
Category	Heavy mineral concentrate wt %	Raw sand wt %	Aspect ratio	Circularity	Perimeter	Length	Area	Total grains
ilmenite	-	-	1.5	1.6	227.1	77.3	2996.5	317
leucoxene	-	-	1.6	1.6	286.8	101.4	4862.9	105
rutile	-	-	1.5	1.5	213.2	70.4	3016.0	40
Ti magnetite	6.1	0.1	1.7	1.7	262.3	95.9	3868.4	62
magnetite	6.1	0.1	1.6	1.6	238.3	83.6	3501.8	75
chromite	6.1	0.1	1.5	1.5	243.9	83.2	3254.0	3
spinel	6.1	0.1	0	0	0	0	0	0
zircon	6.1	0.1	1.2	1.3	198.9	59.2	2657.9	75
sphene	6.1	0.1	1.6	1.6	230.9	82.6	3116.9	18
garnet	6.1	0.1	1.7	1.7	155.8	58.3	1549.3	15
sillimanite-kyanite	6.1	0.1	1.8	1.8	286.0	104.8	4097.6	10
staurolite	6.1	0.1	1.5	1.6	268.0	91.2	4376.2	25
mica	6.1	0.1	2.4	2.4	172.1	72.2	1001.0	1
mafic silicates	6.1	0.1	1.9	1.9	333.5	127.8	5528.1	225
feldspar	6.1	0.1	1.3	1.3	141.7	42.4	1773.4	4
silicate-other	6.1	0.1	1.5	1.6	332.3	114.6	6523.5	75
quartz	6.1	0.1	1.5	1.5	265.1	87.3	5231.3	20
corundum	6.1	0.1	0	0	0	0	0	0
monazite	6.1	0.1	1.8	1.8	242.1	93.8	2612.7	3
xenotime	6.1	0.1	0	0	0	0	0	0
phosphate	6.1	0.1	2.5	1.7	125.9	47.6	731.3	1
carbonate	6.1	0.1	0	0	0	0	0	0
pyrite	6.1	0.1	0	0	0	0	0	0

Weight percent and average grain parameters on a mineral basis								
unclassified	6.1	0.1	1.8	1.8	248.4	96.1	4298.8	126