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CHARACTERISATION OF SOME INDUSTRIAL MINERALS FROM ZAMBIA

C J Mitchell

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 British Geological Survey, Keyworth, Nottingham NG12 5GG, UK

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Characterisation of some Industrial Minerals from Zambia

C J Mitchell

1. INTRODUCTION

In March 1991 a visit to Zambia was made by C J Mitchell and D A Briggs, Mineralogy and Petrology Group, for the BGS/ODA project "Minerals for Development" (see BGS Technical Report No. WG/91/20R). This was a follow up to the previous year's visit by D A Briggs and continued the project's aim to offer assistance in the development of the industrial minerals resources of Zambia. The Geological Survey Department cooperated in discussions with the Ministry of Mines, Mineral Exploration Department (Minex), Mindeco Small Mines and the National Council for Scientific Research (NCSR). In addition an industrial minerals workshop was held in which local companies, as well as representatives of the institutions named above, discussed their use of, and queries concerning, industrial minerals. A field visit to the Lochinvar gypsum deposit was conducted, courtesy of the GSD and Minex. As a result, of these discussions and field visit, samples of various industrial minerals were despatched to BGS for analysis. This report describes the work carried out on these samples of potential industrial minerals and presents the results.

2. METHODS

Bulk mineralogy was determined by X-ray diffraction (XRD), using a Phillips PW 1700 X-ray diffractometer, operating with Co-Kα radiation at 45 kV and 40 mA, and scanning over a range of 3 - 50°2θ. The traces were interpreted with reference to the JCPDS database. Quantitative mineralogy was carried out by thermogravimetric analysis (TG), where the weight losses of samples heated to 1100°C are recorded and interpreted as mineral percentages, including gypsum, kaolinite, talc (all dehydroxylation reactions) and calcite (decarbonation reaction). Determination of graphite content was carried out by loss-on-ignition (LOI) which is essentially the percentage weight loss of a sample (initially dried at 105°C) fired at 1000°C for 2 hours. The volatile, carbon and ash content of graphite samples was also carried out by TG. The major element chemistry was determined by X-ray fluorescence (XRF) analysis of fused glass discs using a Phillips PW 1480 X-ray fluorescence spectrophotometer. A non-quantitative indication of the trace elements present was also provided.

Particle-size distributions were determined by wet screening and/or X-ray sedigraph analysis, which provide, respectively, the percentages of +63 µm and -63 µm diameter particles present. Brightness determination was carried out using reflectance spectrophotometric analysis to measure the whiteness of the samples, unfired and fired (2 hours at 1050°C), using a barium sulphate standard (at a wavelength of 4700Å). Viscosity was determined using a Brookfield viscometer and several properties were determined in order to assess end-use suitability (mainly paper manufacture), including, flowability (solids content at which a slurry just begins to flow), deflocculant demand, (minimum amount of deflocculant required to obtain minimum viscosity) and viscosity concentration (solids content of a slurry with a viscosity of 5 poise). Plasticity of clay was determined by the Atterberg liquid and plastic limits. Transmission electron microscopy (TEM) was used to study the morphology of the Chilulwe kaolinite, with metal shadowing used to determine the thickness of the kaolinite plates.

Several methods of beneficiation were applied. Air classification, which is essentially a dry sizing method, was used to separate minerals based on differences in density and shape of closely-sized feed material. Low density, flaky material (eg graphite) was separated from higher density, granular material (eg quartz and feldspar). Hydrocycloning, a wet sizing method, was used to produce clay concentrates using a small glass hydrocyclone to separate material at approximately 10 µm, producing an underflow (material mainly >10 µm) and an overflow (material mainly <10 µm). Heavy liquid separation, a gravity separation method, was carried out using a heavy liquid with an SG of 2.45 g/cm^3 (a mixture of bromoform, 2.9 g/cm^3, and triethyl ortho phosphate, 1 g/cm^3) to separate gypsum (2.3 g/cm^3) from quartz (2.65 g/cm^3). Froth flotation, a separation method utilizing differences in surface properties, was used to upgrade graphite preconcentrates.

3. MINERALS

3.1. Clays

3.1.1. Chilulwe kaolinite

A sample of Chilulwe kaolinite (similar to that examined previously, see Report WG/91/5R) was submitted by Minex for testing. The kaolinite is very white in hand specimen, consisting mainly of coarse feldspar with a small amount of mica and kaolinite (17%). The current investigation repeated the work carried out previously, with the addition of fired brightness, viscosity testing, chemical analysis and transmission electron microscopy (TEM). The sample was attrition scrubbed for 2 hours prior to wet screening (2mm to 63 µm) and each of the size fractions was assayed for kaolinite. The +2mm fraction consists almost entirely of microcline feldspar, with only 4% kaolinite and chemical analysis indicates it to be a highly potassic feldspar, with 15.3% K_2O and little in the way of impurities. The brightness of the feldspar, as previously determined is 86%. The <63 µm fraction has a grade of 63% kaolinite, at a recovery of 78% kaolinite in the original sample and shows 51% of particles <10 µm and 24% <2 µm in size.

The <63 μm fraction was used as the hydrocyclone feed material. The overflow product contains 79% kaolinite, at a recovery of 20%, and 96% of the particles are <10 μm and 58% <2 μm in size. The brightness of the unfired kaolinite is 73% and the fired is 86%. The flowability is 65%, deflocculant demand 2.3 ml and the viscosity concentration 68%. The chemical analysis indicates it to be very pure with only 0.03% TiO_2 and 0.2% Fe_2O_3. TEM shows the Chilulwe kaolinite overflow to consist of subhedral to rounded plates and rods of kaolinite. The particles range in diameter from 0.1 - 0.44 μm (averaging 0.26 μm) and 0.02 - 0.05 μm in thickness (averaging 0.05 μm), with an average aspect ratio of 6.1. The underflow product contains 60% kaolinite, at a recovery of 78% and 33% of particles are <10 μm and 10% <2 μm in size.

The physical properties are listed in Table 1, the mineralogy in Table 2, chemical analysis in Table 9, viscosity plots in Figures 1 - 3, particle-size distribution curves in Figure 5, TEM photomicrographs in Figures 6 - 9 and X-ray diffraction traces in Figures 10 and 11. The Chilulwe overflow compares very favourably with paper coating-grade kaolinites, especially in its chemical and rheological properties (see Appendix A for the properties of commercial-grade kaolinite products). An improvement in the hydrocyclone separation (by using a finer cut point) to produce a higher proportion of clay in the overflow product could possibly result in a high-quality coating-grade kaolinite. The underflow product has a high kaolinite content and reasonably fine particle-size distribution and could be used as a filler. The +2 mm fraction is a pure potash feldspar with a white colour and would be suitable for use in ceramics, as a filler or as a mild abrasive.

3.1.2. Serenje kaolinite

The Serenje kaolinite, submitted by Moore Pottery, as used in their ceramics, is an off-white, fine-grained material composed of friable lumps. The sample consists mainly of quartz, microcline feldspar and kaolinite (23%), with minor amounts of albite feldspar and muscovite mica. Chemical analysis confirms that there is a high silica content, 80.9% SiO_2, but also relatively high Fe_2O_3 (1.5%) and TiO_2 (0.3%) (see Tables 2 and 9).

3.1.3. Solwezi ball clay

The Solwezi ball clay, submitted by Naluta Stationery (used in the production of their pencils) is a light brownish-grey material composed of friable lumps. It contains mainly quartz and kaolinite (21%), with a trace of muscovite mica and K-feldspar. Chemical analysis shows it to have 73.9% SiO_2, 15.7% Al_2O_3, 1.6% TiO_2 and 1.7% Fe_2O_3 (see Tables 2 and 9). The ball clay contains about 38% sand (>63 μm), 21% silt (2-63 μm) and only 41% clay (<2 μm), making it a sandy clay. The plasticity was found to be low, with a liquid limit of 31%, plastic limit of 16% and a plasticity index (PI) of 15. Therefore the sample is a non-plastic kaolin (as ball clays, or plastic kaolins, have PI's in the range 30 - 50). The presence of a large proportion of sand and silt is probably the cause of the low plasticity.

3.1.4. Kapiri Mposhi ball clay

This Kapiri Mposhi ball clay, submitted by Moore Pottery as used in their ceramics, is a blackish-brown, fine grained material composed of brittle lumps. It consists mainly of kaolinite (57%), quartz and microcline feldspar, with a trace of albite feldspar. The chemical analysis shows it to have comparatively high Fe_2O_3 (3.3 %) and TiO_2 (0.7%) (see Tables 2 and 9).

3.2. Lochinvar gypsum

The Lochinvar gypsum occurs as a dambo (a small, flat, broad grassy depression or channel) deposit in an alluvial plain in the Lochinvar National Park and is present, at the surface, as coarse crystals in a dark-brown sticky clay, down to 1 metre in depth. The gypsum is dug, wet screened on 2mm (in two stages) to remove the clay and allowed to air dry. Mindeco Small Mines (the operator), which sells the gypsum on an ad hoc basis to small consumers (for example school chalk manufacturers and Moore Pottery) is keen to supply larger consumers, such as plaster and cement manufacturers, eg Sanpoo Industries and the Chilanga cement factory. However the presence of a significant quantity of quartz in the final product prevents its use by these consumers and therefore a method of eliminating the impurities was required. Several samples of gypsum were collected by the author (see Report WG/91/20R), four samples as dug and three from various stages of processing, and beneficiation trials were carried out.

The Lochinvar gypsum samples, which were excavated in pits, have been numbered 1 - 5. Samples from pits 1 - 3 are as dug, the samples from pit 4 include as dug material, material from the initial screening and the final product, and sample 5 also represents the final product. The as dug samples contain 50 - 57% gypsum, the remainder being mainly quartz, with clay (a mixture of illite and kaolinite) and trace amounts of calcite, K-feldspar and iron oxides (ilmenite and magnetite). The processed samples contain more gypsum, 84% at the initial processing stage and 87 - 91% for the final product, with only traces of impurities (see Table 2).

Each of the samples was wet screened (2mm down to 63 μm) and additionally the No. 4 samples were attrition-scrubbed prior to screening (see Table 3 and Figure 6). The weight percentage of the +2 mm material present in the as dug samples varies from 29 - 49% and the gypsum content varies from 90 - 92%. The amount of gypsum present in the size fractions decreases with decreasing grain size and the amount of quartz and clay increases accordingly. The initially processed material contains 84% +2 mm (which contains 91% gypsum) and the final products contain between 89 - 95% +2 mm (containing 90 - 92% gypsum).

Heavy liquid separation was carried out on the +2mm size fractions from each sample to separate gypsum from quartz and other impurities. The 'heavy' fraction (>2.45 g/cm^3) ranges from 1% for the as dug samples to 2 - 4% for the processed samples (see Table 3). The 'heavy' fractions contain mainly quartz, with a small amount of calcite and iron oxides, and are mainly <4 mm in diameter. There is a discrepancy between the gypsum content determined by TG and that indicated by heavy liquid separation, with up to 8% more in the latter. Some gypsum aggregates reported to the 'heavy' fraction, possibly due to quartz inclusions and / or calcite pseudomorphing gypsum and this produced particles with a combined density >2.45 g/cm^3. This could partly explain the discrepancy, as some quartz and calcite would probably be carried into the 'light' fraction but in such quantities that did not produce a combined density >2.45 g/cm^3.

The beneficiation trials carried out suggest that gravity separation alone would not produce a significant improvement in the quality of the gypsum, unless some form of crushing was used to liberate further impurities from the gypsum. An improvement in wet screening efficiency, coupled with an increase in the screen size from 2 to 4 mm, should eliminate a large proportion of the impurities present, although this would reduce the gypsum recovery.

3.3 Phosphates and carbonatites

3.3.1. Luangwa carbonatite

The Luangwa carbonatite is formed of large irregular lumps of a salmon-pink, coarsely crystalline calcite (75%), with inclusions of quartz and feldspar. Chemical analysis shows it to contain 17% SiO_2, 44.2% CaO and 1.5% Al_2O_3 (see Tables 2 and 9).

3.3.2. Luangwa carbonatitic clays and silts

The Luangwa carbonatitic clays and silts sample consists of hard lumps of creamy-white, fine grained calcite (90%) with inclusions of quartz (see Table 2).

3.3.3. Phosphate rock No.1, Sugar Loaf

The phosphate rock No.1, from Sugar Loaf, Mumbwa North, contains lumps of heavily altered and weathered material, white in colour, with occasional mica flakes and iron oxide coating. This sample is from an apatite-rich pegmatite, thought to contain >35% apatite, but is not representative of the deposit. It contains mainly quartz and apatite, plus minor amounts of mica and plagioclase feldspar and a trace of goethite (?). The chemistry indicates 33.5% SiO_2, 2.3% TiO_2, 16.1% Fe_2O_3 and 18.2% P_2O_5, equivalent to 40-45% apatite (Tables 2 and 9).

3.3.4. Phosphate rock No.2, Sugar Loaf

The phosphate rock No.2, Sugar Loaf, Mumbwa North, is a light coloured, coarsely crystalline material, with a light coloured matrix, with dark greenish-brown and light green phenocrysts. This sample was taken as representing the 'average' phosphate ore from 'veins' in syenite country rock. It contains mainly quartz and apatite, with a minor amount of amphibole (tremolite?) and a trace of plagioclase feldspar. The chemistry indicates 43.3% SiO_2 and 20.55% P_2O_5, equivalent to about 45 - 50% apatite (Tables 2 and 9).

3.3.5. Phosphate orebody No.2, Chilembwe

The phosphate orebody No.2, Chilembwe, Sinda West, is a dark coloured, coarsely crystalline material, containing roughly equal proportions of dark green and yellowish-white phenocrysts. This sample is from apatite-bearing veins in syenite country rock and was submitted as 'apatite contained in a quartz-feldspar matrix'. It contains mainly apatite, amphibole (tremolite?) and pyroxene (augite?), with a trace of K-feldspar. The chemical analysis indicates 36.8% SiO_2 and 12.1% P_2O_5, equivalent to about 25 - 30% apatite (Tables 2 and 9).

3.3.6. Phosphate orebody No.4, Chilembwe

Phosphate orebody No.4, Chilembwe, Sinda West, is a pegmatitic apatite of a light whitish-pink colour. This sample is from apatite-bearing veins in syenite country rock and was submitted as 'apatite in an amphibolite'. It contains mainly apatite, plus traces of quartz, K-feldspar and amphibole (?). The chemistry indicates only 2.1% SiO_2 and 41.9% P_2O_5, equivalent to 95 - 100% apatite (Tables 2 and 9).

3.3.7. Phosphate-rich soil, Nkombwa Hill

This phosphate-rich soil, Nkombwa Hill, was submitted as consisting of 'secondary carbonatitic material enriched in phosphate'. It contains mainly apatite and quartz, with a minor amount of mica (phlogopite?). There are also traces of iron oxides (magnetite and/or hematite), goethite (?), K-feldspar, amphibole (?) and pyroxene (?) (Table 2).

3.3.8. Phosphate-rich soil, Kaluwe

This phosphate-rich soil, Kaluwe, was submitted as consisting of 'secondary carbonatitic material enriched in phosphate'. It contains mainly iron oxides (magnetite and hematite), quartz and apatite, plus traces of K-feldspar, pyroxene (augite?) and goethite (?) (Table 2).

3.4. Graphite

3.4.1. Njoka graphite

Two samples of graphite schist were collected from Njoka, Eastern Province, the first sample (A) is mainly unconsolidated, rubbly material and the second sample (B) is more consolidated. Both samples are weathered and friable, but appeared to be promising samples of graphite. Njoka A consists mainly of albite feldspar, with a small amount of mica and graphite (16%), and a trace of quartz. Njoka A has a volatile content of 4%, a carbon content of 11% and an ash content of 85%. A thin section of Njoka B was made to examine the fabric of the schist and attempt to gauge the liberation size of the graphite. The graphite flakes, about 150 µm to 5 mm long and often intercalated with mica, occur in a matrix of calcic plagioclase feldspar (about 100 µm to 1.2 mm in diameter) and quartz. Njoka B contains 18% graphite (see Table 4) and has a volatile content of 7%, a carbon content of 14% and an ash content of 79%.

Preparation.

Both samples of Njoka graphite were split to produce a fraction for particle-size analysis by dry screening (2mm down to 125 µm). The size fractions were assayed for their graphite content and examined by binocular microscope to gauge the liberation size of the graphite flakes, which was found to be about 1mm. The remainder was processed, initially by jaw crushing and disc milling, then screened on 1mm and any oversize reduced in a cone grinder. The nature of the crushing and grinding reduced the granular quartz and feldspar whilst preserving the flaky graphite. This produced graphite-rich +1 mm grinding products and these were retained as graphite concentrates (containing 41% graphite in Njoka A and 47% graphite in Njoka B). The <1 mm material was screened down to 125 µm.

Air classification .

The -1mm +500 μm and -500 +250 μm fractions were preconcentrated by air classification and this produced graphite concentrates, middling and tailing products, which were all assayed for their graphite content (see Appendix A and Tables 5 - 7). Air classification was partially successful, with the combined Njoka A concentrates grading at 53% graphite and an overall recovery of 41%, whereas the combined Njoka B concentrates grade 70% graphite with a recovery of 42%. The low grade of Njoka A and low recovery of both samples is probably due to the close association of mica with graphite and, as both are flaky, the mica has been preconcentrated with the graphite during air classification. Combination of air classification concentrates and middlings plus the -250 +125 μm fraction would, for Njoka A, produce a froth flotation feed grading 27% graphite, with a recovery of 86% and contain 45% of the original sample weight. For Njoka B it would grade 38% graphite, with a recovery of 72% and contain only 35% of the original sample weight.

Froth flotation .

The products of air classification of the -1mm +500 μm and -500 +250 μm fractions and the -250 +125 μm fractions were upgraded by froth flotation. This produced graphite concentrates, middling and tailing products, which were all assayed for their graphite content (see Appendix A and Tables 5 - 7). Froth flotation of Njoka A produced combined concentrates grading 78% graphite, with a recovery of 70% and Njoka B produced combined concentrates grading 73% graphite, with a recovery of 74%. The main impurity present in the concentrate was mica, which occurs closely intercalated with and not fully liberated from the graphite, and is separated with the graphite during froth flotation. The concentrates have low grades for flake graphite, commercial grades usually contain more than 85% graphite, although further processing could possibly improve the grade.

The current investigation has shown that air classification, as a method of graphite preconcentration, has limited use in upgrading the Njoka graphite and therefore froth flotation alone would be required to produce graphite concentrates. The flake graphite would be useful, with further upgrading, in refractory (such as Magnesia-carbon bricks and Alumina graphite refractories) and other applications (such as in dry cell batteries) (see Appendix C for the properties of commercial-grade graphite products).

3.4.2. Petauke graphite

The Petauke graphite-schist deposit is located close to the main road that runs through Eastern Province. Although the schist is of variable grade some parts contain about 10% graphite, which appeared to be of good quality flake, and a bulk sample was collected. Inspection of the schist under the microscope revealed the flake liberation size to be approximately 1mm. It contains mainly albite feldspar and mica, with a small amount of graphite (6.4%) and traces of quartz (see Table 4). It has a volatile content of 5%, a carbon content of 3% and an ash content of 92%. The material was processed in a similar fashion to the Njoka graphite, except that the -250 +125 μm fraction was air classified and the products upgraded by froth flotation. The results are given in Table 8 and Appendix A.

The air classification of the Petauke graphite was not successful, the combined concentrates grade only 25% graphite and have a low recovery (40%). This is probably due to the presence of a large amount of mica in the sample which has been preconcentrated with the graphite. Combination of air classification concentrates and middlings would produce a froth flotation feed grading 18% graphite, with a recovery of 45% and contain 17% of the original sample weight. Froth flotation results in a combined concentrate grading 87% graphite and a recovery of 39%; this is a good grade but poor recovery. This suggests that air classification is unsuitable for preconcentrating the graphite, but that a reasonable graphite concentrate can be produced by froth flotation alone but with a low recovery. The grade of this graphite concentrate is similar to that used in refractory and other applications.

3.4.3. Matala graphite

The Matala graphite was collected from a band of amorphous graphite found associated with a disseminated sulphide ore, Central Province in a locality being developed by ZCCM. The sample contains lumps of a friable amorphous graphite (40%) with disseminated sulphide minerals (see Table 4). It has a volatile content of 9%, a carbon content of 32% and ash content of 59%.

3.4.4. Chama graphite

The Chama graphite, Eastern Province was submitted by Nalutta Stationery and consisted of ball milled material containing mainly powder and some lumps of a graphite-rich schist (that has fine laminations and iron oxide coating). The sample contains mainly graphite (72%), with minor amounts of quartz and mica (see Table 4). It has a volatile content of 3%, a carbon content of 71% and ash content of 26%.

3.5. Miscellaneous industrial minerals

3.5.1. Lufunsa silica

The Lufunsa silica, as supplied by Moore Pottery and used in their ceramics, is a creamy-white powder. It contains mainly quartz and feldspar, with 94.1% SiO_2, 3.4% Al_2O_3, 0.7% CaO, 0.7% K_2O and 0.2% Fe_2O_3, and this suggests the feldspars present are K-feldspar and anorthite (Tables 4 and 9).

3.5.2. Naluama quartzite

The Naluama quartzite, Munali Hills, submitted by the GSD, is a white, sugary-textured quartzite with brown staining and consists mainly of quartz with a trace of mica (Table 4).

3.5.3. Siavonga feldspar

Two samples of Siavonga feldspar from Southern Province were submitted, a very white, coarsely crystalline (pegmatitic) feldspar and ground feldspar as used in ceramic manufacture (Moore Pottery). It contains mainly microcline and albite feldspar, quartz and a trace of mica. Chemical analysis shows it to contain 68% SiO_2, 17.8% Al_2O_3, 1.1% CaO, 3% Na_2O and 9.2% K_2O, consistent with the mineralogy, and the feldspar content is estimated to be 85 - 95% (see Tables 4 and 9).

3.5.4. Mpande kyanite

Samples of Mpande kyanite were submitted by the GSD and Mindeco. They consist of coarsely crystalline, interlocking kyanite (bluish-brown colour) with a flaky, micaceous cleavage, a small amount of muscovite mica and a trace of kaolinite (see Table 4).

3.5.5. Lilayi talc

The Lilayi talc sample, submitted by Mindeco, consists of lumps of white to pale-green, coarsely crystalline talc (87%), with occasional reddish-brown patches and black specks, calcite (5%) and a trace of serpentine (?) (see Table 4).

3.5.6. ZCCM talc

A sample of talc was submitted by Mr A Chisembele on behalf of ZCCM. This material, of unknown locality, is silvery white, with a friable texture and contains reddish-brown inclusions. It consists mainly of talc (79%) and quartz, plus traces of kaolinite (6%), K-feldspar and smectite (?) (see Table 4).

3.5.7. Industrial beryl

Beryl from the Old Mkushi Boma was submitted by the GSD. It consists of pegmatitic beryl, with an almost euhedral hexagonal form (with typically anhedral terminations), deep aquamarine colour and a trace of quartz (see Table 4).

3.5.8. Serenje 'diatomite'

This 'diatomite', submitted by the GSD, was in fact pumice with a typical pumiceous texture, porosity and lightweight density. It is white to green and brown in colour, has pervasive porosity, is hard, friable and has occasional phenocrysts of mica. It consists mainly of anorthite feldspar and sillimanite (see Table 4).

3.5.9. Corundum

This sample of corundum was submitted by the GSD on behalf of a local supplier who currently uses the GSD's jaw crusher for processing and consequently has worn out the crusher plates. The corundum consists of large, roundish lumps (obviously chipped out of the host rock) of a coarsely crystalline corundum with a pink to pinkish-purple colour. The question of how best to process such a hard material was answered by BGS sample preparation supervisor, Mr M Allen. He suggested an initial size reduction of the lumps, possibly with a percussion mortar down to 0.5 - 1 cm diameter, prior to jaw crushing in order to alleviate wear on the plates.

3.5.10. 'Tantalite'

This 'tantalite' sample was from the Kamanga Mission and was submitted by the GSD. It is formed of coarse crystals (up to 1 cm in diameter) with an anhedral to subhedral hexagonal shape, black colour, striated faces and sub-metallic lustre. It was found to consist mainly of tantalian columbite and a trace of quartz (see Table 4).

3.6. Metallic minerals

3.6.1. Mpande hematite

A specular hematite, was submitted by the GSD, from Mpande Hill. It consists of irregular, 'warped' sheets of coarsely crystalline hematite (with a 'polished' metallic lustre and striated faces) and a trace of magnetite (see Table 4).

3.6.2. Sanje iron ore

An iron ore, submitted by the GSD, consisting mainly of coarse hematite and quartz intergrowths, with a trace of apatite (hydroxylapatite) (see Table 4).

3.6.3. Nambala iron ore

An iron ore, submitted by the GSD, consists of finely crystalline, specular hematite (bluish-steely grey in colour) and quartz (see Table 4).

3.6.4. Mansa manganese

A manganese ore, submitted by the GSD, with a smooth, grape-sized botryoidal texture, a brownish-black colour and the freshly broken surfaces reveal a fine-grained steely-grey material, with layering concentric to the botryoidal nodules. It consist mainly of a manganese mineral, romanechite and quartz (see Table 4).

3.6.5. Petauke ilmenite

Petauke ilmenite, submitted by the GSD, consists of coarsely crystalline ilmenite (black in colour with a steely lustre) and hematite, plus a trace of rutile and goethite (see Table 4).

4. CONCLUSIONS

4.1. Kaolinite

The Chilulwe kaolinite is probably the most promising industrial mineral from Zambia that has been examined by BGS to-date. This kaolinite is an excellent potential source of paper-coating grade kaolin and ceramic-grade potash feldspar. The kaolinite can be processed to produce material with particle-size distribution, brightness and viscosity values comparable to those of fillers and with an improvement in beneficiation could be further upgraded for use as a paper coating and ceramic raw material. The Serenje kaolinite as used by Moore Pottery appeared to be similar to the Chilulwe kaolinite but was used without separation of kaolinite from quartz and feldspar. This is not unduly deleterious as its individual mineral components are those normally used in ceramics, but a consistent feed mineralogy would be required to avoid problems in ceramic manufacture.

4.2. Ball clay

The Solwezi ball clay is a sandy non-plastic kaolinite and further investigation of the deposit would be required to identify less sandy kaolins (which may be more plastic). The Kapiri Mposhi is a black ball clay with a high kaolinite content and further testing would be required to determine its plasticity.

4.3. Lochinvar gypsum

The Lochinvar gypsum, as currently produced, contains only a small amount of impurities, mainly quartz but enough to discourage many potential end-users. Gravity separation would not provide the solution, unless more complex processing was involved; however the level of impurities could be reduced by improving the screening efficiency and also by recovering a slightly coarser grade of gypsum (by increasing the screen mesh size from 2 to 4 mm).

4.4. Phosphates and carbonatites

The Luangwa carbonatites were found to consist mainly of carbonate. The Sugar Loaf phosphates have apatite contents in the region of 40 - 50%, whereas Chilembwe No.2 contains only 25 - 30% apatite and Chilembwe No.4 contains 95 - 100% apatite.

4.5. Graphite

The Njoka graphite-schists contain about 16 - 18% graphite and air classification was used as a means of producing a graphite preconcentrate, prior to froth flotation. However, probably due to the presence of mica, the concentrates produced had low graphite contents (40 - 70%) and low graphite recoveries (41 - 42%). Froth flotation resulted in concentrates grading 73 - 78% graphite with recoveries in the range 70 - 74%. The Njoka graphite schist is a potential source of flake graphite for use in refractories and other applications. Air classification would not be appropriate as a method of concentrating the graphite, due to the presence of mica resulting in low recoveries, and froth flotation would be more appropriate in producing graphite concentrates.

Table 1. Chilulwe kaolinite, Zambia.

Size fraction	Weight %	Kaolinite (Wt %)	Kaolinite recovery (Wt %)
+2 mm	22.4	4.0	5.4
-2 +1mm	19.4	4.0	4.7
-1mm +500 µm	14.3	5.0	4.3
-500 +250 µm	11.4	3.0	2.1
-250 +125 µm	6.9	5.0	2.1
-125 +63 µm	5.0	10.0	3.0
-63 +10 µm	10.1		
-10 +2 µm	5.6	63.0	78.4
-2 µm	4.9		
Total	100.0	(17.0)	100.0

Hydrocyclone separation products	Wt %	Kaolinite		Particle-size (Wt %)	
		Wt %	recovery	<10 µm	<2 µm
Underflow	79	60	58.1	33	10
Overflow	21	79	20.3	96	58

Brightness	4700Å	4900Å	5500Å	5800Å
Unfired	73	74	77	76
Fired	86	87	87	87

Viscosity	Flowability (Wt %)	Deflocculent demand (ml 10% Calgon)	Viscosity concentration (Wt %)
Overflow	65.1%	2.31 ml	67.7%

(N.B. See Appendix A for the properties of commercial-grade kaolinite products).

Table 2. Mineralogy of Zambian clays, gypsum, phosphate and carbonatite

Clays	Kaolinite	Quartz	K-feldspar	Mica	Other
Chilulwe kaolinite	17%	-	****	*	-
Chilulwe +2mm	4%	-	****	-	-
Chilulwe overflow	79%	*	**	*	-
Serenje kaolinite	23%	****	***	**	Albite **
Solwezi ball clay	21%	****	*	*	-
Kapiri Mposhi ball clay	57%	***	**	-	Albite *

Lochinvar gypsum	Gypsum	Quartz	Calcite	Iron oxides	Clay	K-feldspar
Pit 1 (as dug)	54%	***	*	*	*	*
Pit 2 (as dug)	50%	**	*	*	*	*
Pit 3 (as dug)	55%	***	-	*	*	*
Pit 4 (as dug)	57%	**	*	*	*	*
Pit 4 (1^{st} wash)	84%	*	*	*	-	-
Pit 4 (Final product)	87%	*	-	-	-	-
Pit 5 (Final product)	91%	*	-	-	-	-

Phosphate/Carbonatite	
Luangwa carbonatite	Quartz **, calcite 75%, plagioclase *
Luangwa carbonatitic clays and silts	Quartz**, calcite 90%
Sugar Loaf No.1	Apatite ***, quartz ***, mica **, plagioclase **, goethite *
Sugar Loaf No.2	Quartz ****, apatite ***, amphibole **, plagioclase *
Chilembwe No.2	Apatite ***, amphibole ***, pyroxene ***, K-feldspar *
Chilembwe No.4	Apatite ****, quartz *, K-feldspar *, amphibole *.
Nkombwa soil	Apatite ****, quartz ***, mica *, goethite *, K-feldspar *, pyroxene *, amphibole *.
Kaluwe soil	Magnetite/hematite ****, quartz ***, apatite ***, K-feldspar *, pyroxene *, goethite *.

Key: **** = Major (> 50 weight %) *** = Appreciable (20-50 weight %) Minor (7-20 weight %)
* = Trace (< 7 weight %)

Table 3. Lochinvar gypsum, Zambia.

Size fraction	Pit 1 As dug Wt %	Pit 2 As dug Wt %	Pit 3 As dug Wt %	Pit 4 As dug Wt%	Pit 4 As dug Gypsum	Pit 4 1st washing Wt%	Pit 4 1st washing Gypsum	Pit 4 Final product Wt%	Pit 4 Final product Gypsum	Pit 5 Final product Wt%	Pit 5 Final product Gypsum
-15 +10mm	6.5)	-	-	4.7)		3.0)		4.9)		2.1)	
-10 +5mm	20.7) (90)	7.8) (90)	12.6) (90)	19.5)	92	24.2)	91	41.3)	90	40.5)	(92)
-5 +2mm	17.5)	21.2)	24.6)	24.7)		56.5)		42.8)		52.2)	
-2 +1mm	5.7	6.7	10.4	3.9	77	4.2	79	1.9	79	3.22	85
-1mm +500 µm	3.6	3.9	4.7	1.9	50	2.1	53	0.6	64	0.37	52
-500 +250 µm	2.2	2.5	3.0	2.0	25	1.5	41	0.3	56	0.35	-
-250 +125 µm	1.7	2.5	2.2	1.9	8	0.7	31	0.4	76	0.25	19
-125 +63 µm	2.0	2.8	1.5	2.0	2	0.6	34	0.4	71	0.25	5
-63 µm	40.2	52.5	41.0	39.4	19	7.3	32	7.5	57	0.87	30
Total	100.1 (54)	99.9 (50)	100.0 (55)	100.0	57	100.1	84	100.1	87	100.01	91
Gypsum recovery in +2mm fraction	74.5	52.2	60.9	78.9		90.7		92.1		95.9	
'Heavy mineral' contents (>2.45 g/cm³)											
Quartz	0.4	0.5	0.5	0.6		1.6		1.2		2.8	
Calcite	0.1	0.1	-	0.2		0.4		0.3		0.8	
Iron oxides	-	-	-	<0.1		<0.1		<0.1		0.1	
Total	0.5	0.6	0.5	0.8		2.1		1.5		3.7	

(NB. The gypsum figures are weight % and the figures in brackets are back-calculated gypsum weight %. The heavy mineral figures are weight %)

Table 4. Mineralogy of Zambian graphite, miscellaneous industrial minerals and metallic minerals

Graphite	
Njoka A	Albite ****, mica **, graphite (16%), quartz *
Njoka B	Albite ****, mica **, graphite (18%), quartz *
Petauke	Albite ****, mica ***, graphite (7%), quartz *
Matala	Graphite (39.5%)
Naluta	Graphite (72%), quartz **, mica *
Miscellaneous industrial minerals	
Lufunsa silica	Quartz ****, albite *
Naluama quartzite	Quartz ****, mica *
Siavonga feldspar	Microcline ***, albite ***, quartz ***, mica *
Mpande kyanite	Kyanite ****, muscovite **, kaolinite *
Lilayi talc	Talc (87%), calcite *, serpentine *
ZCCM talc	Talc (79%), quartz ***, K-feldspar *, kaolinite *, smectite (?) *
Industrial beryl	Beryl ****, quartz *
Serenje 'diatomite'	Anorthite ***, sillimanite ***
'Tantalite'	Tantalian columbite ****, quartz *
Metallic minerals	
Mpande haematite	Hematite ****, magnetite *
Sanje iron ore	Hematite ****, quartz ***, apatite *
Nambala iron ore	Hematite ****, quartz *
Mansa manganese	Romanechite ****, quartz *
Petauke ilmenite	Ilmenite ****, hematite **, rutile *, goethite *

Key: **** = Major (> 50 weight %) *** = Appreciable (20-50 weight %) Minor (7-20 weight %)
* = Trace (< 7 weight %)

Table 5. Particle-size distribution and graphite content of Njoka graphite, Zambia.

Size fraction	Njoka A		Njoka B	
	Wt %	Graphite %	Wt %	Graphite %
+2mm	25.0	18.0	72.0	18.9
-2 +1mm	16.8	23.0	10.4	19.3
-1mm +500μm	28.5	14.9	9.4	20.2
-500 +250 μm	18.2	10.9	5.3	16.0
-250 +125 μm	7.7	8.2	1.9	11.9
-125 μm	3.9	8.2	1.0	10.7
Total	100.0	13.3	100.0	18.7

Table 6. Air classification and froth flotation grade and recovery of Njoka A graphite, Zambia.

Product	Air classification			Froth flotation		
	Wt %	Graphite %	Recovery	Wt %	Graphite %	Recovery
+1 mm	2.8	40.7	7.2	-	-	7.2
-1mm +500µm	51.0	18.2	58.3	-	-	58.3
Concentrate	(10.8)	52.8	33.8	6.5	85.3	(28.8)
Middling	(14.2)	18.9	15.9	3.4	66.9	(13.3)
Tailing	(26.0)	5.6	8.6	1.1	73.2	(4.9)
-500 +250 µm	28.4	12.8	22.8-	-	-	22.8
Concentrate	(2.1)	54.4	7.0	1.2	90.3	(6.4)
Middling	(7.5)	22.9	10.3	2.0	77.8	(8.9)
Tailing	(18.8)	4.8	5.5	0.8	53.2	(3.1)
-250 +125 µm	10.6	9.8	6.5	-	-	6.5
	-	-	-	1.0	81.5	(4.7)
-125 µm	7.2	11.5	5.2	-	-	5.2
Total	100.0	15.9	-	-	-	100.0

Product		Wt %	Grade (Wt %)	Recovery (Wt %)
Air classification	- concentrates	12.9	53.1	40.8
	- conc. & mid.	45.2	27.2	86.0
Froth flotation	- concentrates	16.0	78.2	70.1

(N.B. Weight percentage and graphite recovery figures are all related to the head material. Only the data for the froth flotation concentrates are used in the table and the full froth flotation results are given in Appendix B. The air classification 'conc. & mid.' refers to a combination of the concentrates, middlings and -250 +125 µm fraction.)

Table 7. Air classification and froth flotation grade and recovery of Njoka B graphite, Zambia.

Product	Air classification			Froth flotation		
	Wt %	Graphite %	Recovery	Wt %	Graphite %	Recovery
+1 mm	1.2	47.3	3.1	-	-	3.1
-1mm +500µm	54.9	16.9	51.1	-	-	51.1
Concentrate	7.4	72.2	28.1	5.9	86.8	(27.0)
Middling	9.8	25.7	13.3	3.5	52.8	(10.6)
Tailing	37.7	4.9	9.7	7.1	70.9	(7.5)
-500 +250 µm	23.1	20.3	25.9	-	-	25.9
Concentrate	3.6	67.7	13.6	2.7	88.8	(13.0)
Middling	4.2	32.3	7.6	1.5	72.3	(6.4)
Tailing	15.3	5.5	4.7	1.1	31.7	(2.1)
-250 +125 µm	10.1	17.0	9.5	-	-	9.5
	-	-	-	1.5	82.1	(6.9)
-125 µm	10.8	17.5	10.4	-	-	10.4
Total	100.0	(18.1)	-	-	-	100.0

Product	Wt %	Grade (Wt %)	Recovery (Wt %)
Air classification - concentrates	11.0	70.7	41.7
- conc. & mid.	35.1	38.1	72.1
Froth flotation	23.3	73.2	73.5
Froth flotation of -1mm +500 µm fraction without air classification			
Concentrate	11.7	72.1	41.6
Middling	0.9	25.8	1.1
Tailing	2.3	4.0	8.4

(N.B. Weight percentage and graphite recovery figures are all related to the head material. Only the data for the froth flotation concentrates are used in the table and the full froth flotation results are given in Appendix B. The air classification 'conc. & mid.' refers to a combination of the concentrates, middlings and -250 +125 µm fraction.)

Table 8. Air classification and froth flotation grade and recovery of Petauke graphite, Zambia.

Product	Air classification			Froth flotation		
	Wt %	Graphite %	Recovery	Wt %	Graphite %	Recovery
-1mm +500μm	46.9	4.8	32.3	-	-	32.3
Concentrate	6.2	18.3	16.4	1.0	92.4	(13.3)
Middling	2.9	3.0	1.2	0.01	68.6	(0.1)
Tailing	37.8	2.7	14.7	0.08	52.5	(0.7)
-500 +250 μm	25.0	8.5	30.5	-	-	30.5
Concentrate	3.4	36.4	17.9	1.0	95.4	(16.5)
Middling	1.9	8.7	2.4	0.1	86.6	(1.6)
Tailing	19.7	3.6	10.2	0.2	30.9	(1.0)
-250 +125 μm	11.3	7.9	12.8	-	-	12.8
Concentrate	1.6	26.1	5.9	0.3	92.2	(4.6)
Middling	1.2	8.8	1.6	0.06	89.6	(0.9)
Tailing	8.5	4.4	5.3	0.03	50.7	(0.3)
-125 μm	16.8	10.1	24.4	-	-	24.4
Total	100.1	(7.0)	-	-	-	100.0

Product	Wt %	Grade (Wt %)	Recovery (Wt %)
Air classification - concentrates	11.2	24.9	40.2
- conc. & mid.	17.2	18.3	45.4
Froth flotation	2.3	87.1	39.0

(N.B. Weight percentage and graphite recovery figures are all related to the head material. Only the data for the froth flotation concentrates are used in the table and the full froth flotation results are given in Appendix B. The air classification 'conc. & mid.' refers to a combination of the concentrates and middlings fractions.)

Table 9. Chemical analyses of Zambian industrial minerals

Mineral	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K2O	P_2O_5	LOI	Total
Chilulwe kaolin	46.24	0.03	36.99	0.23	0.004	0.03	0.17	0.07	1.55	0.08	13.19	98.58
Serenje kaolin	80.86	0.29	12.06	1.48	0.015	0.03	0.05	0.00	1.02	0.02	3.78	99.61
Solwezi ball clay	73.89	1.55	15.66	1.67	0.011	0.14	0.13	0.00	0.56	0.06	5.83	99.50
Kapiri Mposhi ball clay	54.66	0.72	24.83	3.26	0.02	0.36	0.52	0.06	1.14	0.04	13.59	99.20
Luangwa carbonatite	16.95	0.08	1.46	0.63	0.032	0.30	44.22	0.09	0.38	0.04	33.67	97.85
Sugar Loaf phosphate 1	33.50	2.28	3.84	16.01	0.379	0.36	19.07	0.27	0.72	18.23	2.82	97.48
Sugar Loaf phosphate 2	43.30	0.10	1.37	1.56	0.087	1.37	23.04	0.33	0.36	20.55	1.22	93.29
Chilembwe phosphate 2	36.76	0.34	1.75	6.75	0.226	8.80	26.55	0.66	0.12	12.09	0.90	100.13
Chilembwe phosphate 4	2.09	0.01	0.33	0.41	0.013	0.01	33.44	0.25	0.01	41.89	0.44	78.89
Chilulwe feldspar	64.32	0.01	19.14	0.04	0.003	0.09	0.03	0.71	15.27	0.24	0.28	100.13
Siavonga feldspar	68.04	0.03	17.82	0.35	0.017	0.12	1.07	2.95	9.22	0.03	0.93	100.58
Commercial products (for comparison)												
Paper-grade kaolin	47 - 49	0.03	36 - 38	0.7 - 0.9	-	0.1 - 0.2	0.05 - 0.07	0.08 - 0.14	1.5 - 2.7	-	11 - 13	100.00
Ceramic-grade kaolin	47- 50	0.02 - 0.06	34 - 38	0.4 - 1	-	0.2 - 0.3	0.02 - 0.1	0.1 - 0.15	0.8 - 4	-	10 - 13	100.00
Ceramic-grade feldspar	66 - 67	0.01	18.2 - 18.6	0.03 - 0.1	-	0.01 - 0.05	0.1 - 0.15	3 - 3.3	1.3 - 11.5	-	0.2 - 0.3	100.00

N.B. Figures are all weight percentages determined by XRF analysis using a Phillips PW 1480 X-ray fluorescence spectrometer.

The low totals, <99%, are caused by elements present not analysed on fused beads and scans of the samples showed the following elements are present:

Luangwa carbonatite Cl, S, Sr, Y.

Sugar Loaf phosphate 1 Cl, high S, Sr, Y, Ce, La, Nd, Pr, Gd.

Sugar Loaf phosphate 2 Cl, S, Sr, Y, Ce, La, Nd, Pr, Gd.

Chilembwe phosphate 2 Cl, S, Sr, Y, Ce, La, Nd, Pr, Gd.

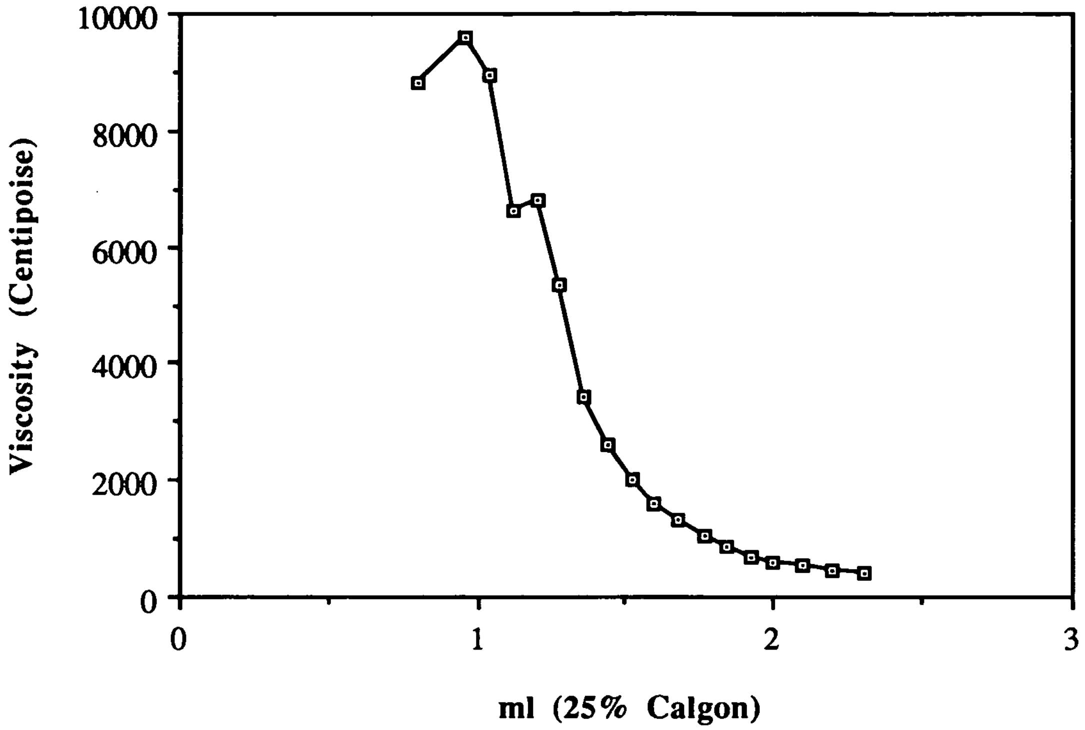

Figure 1. Deflocculant demand of Chilulwe kaolin, Zambia.

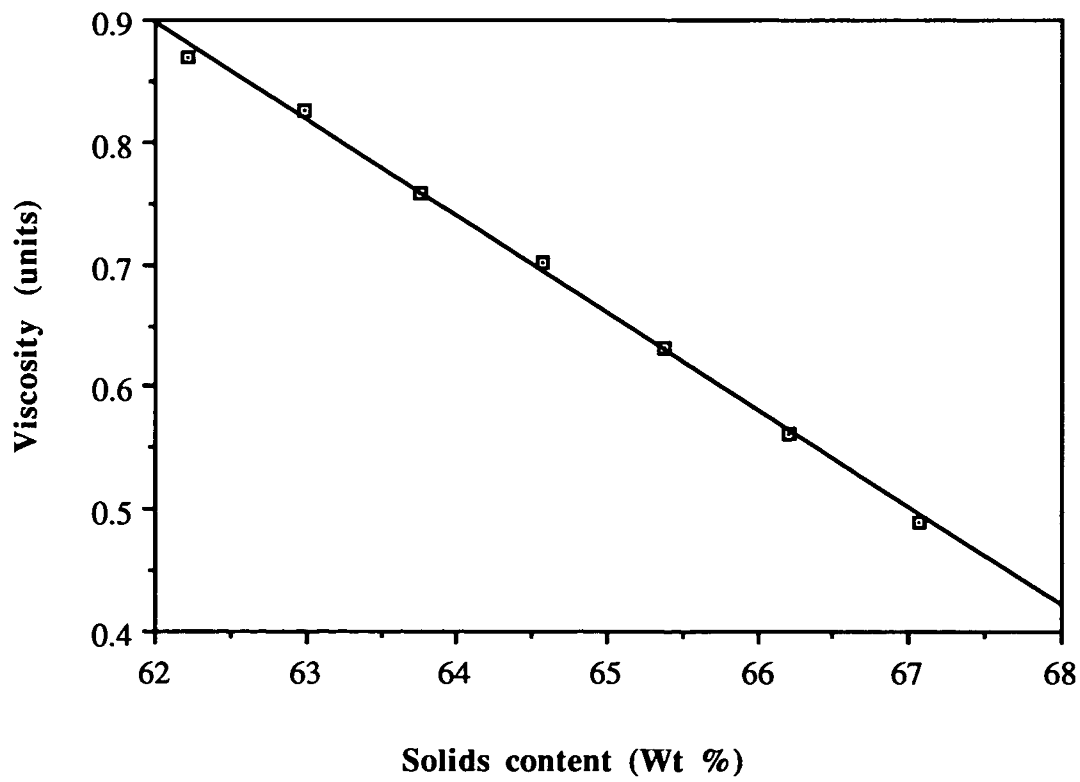

Figure 2. Viscosity concentration of Chilulwe kaolin, Zambia.

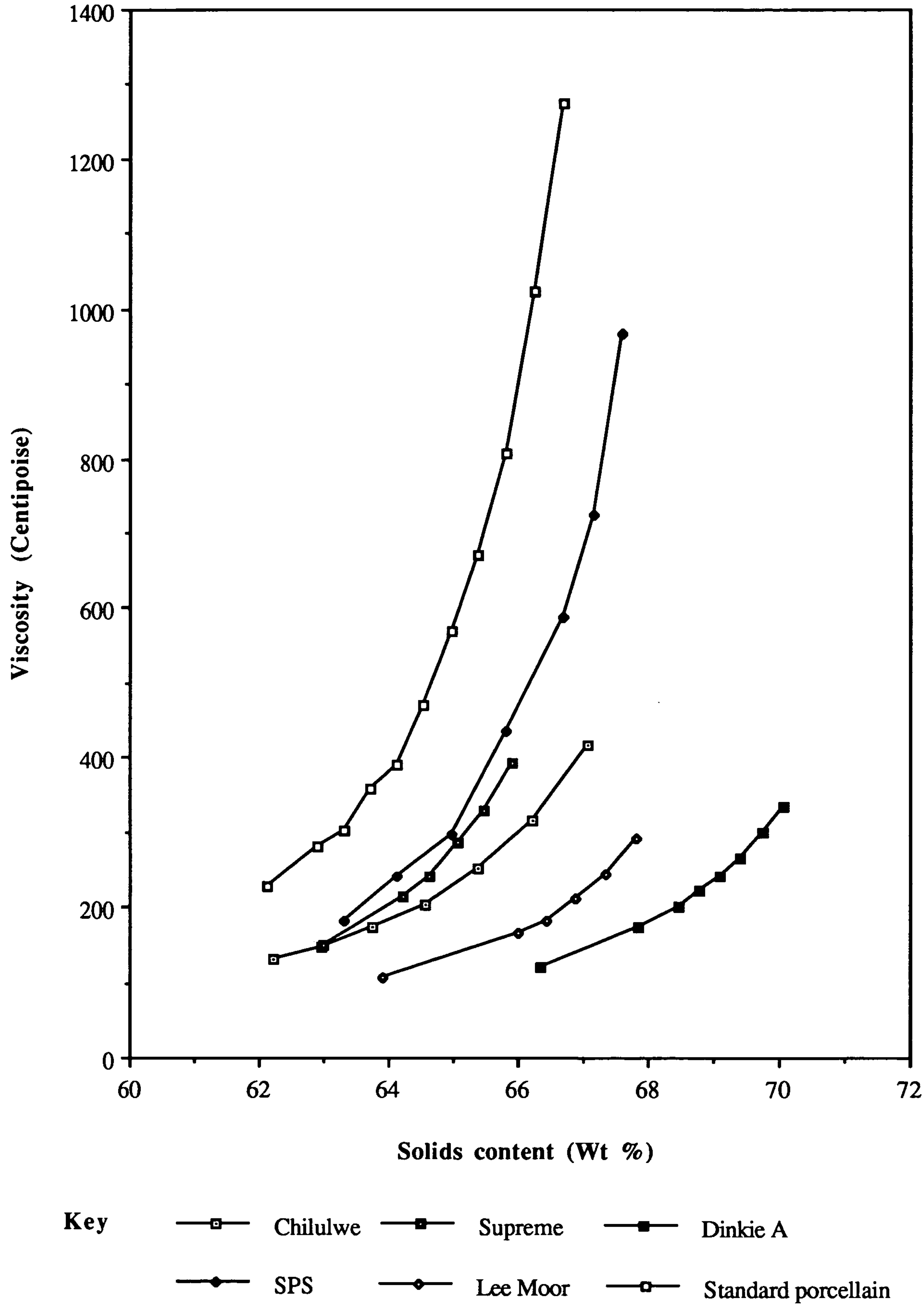

Figure 3. Viscosity concentration of Chilulwe kaolin (Zambia) and some commercial kaolins

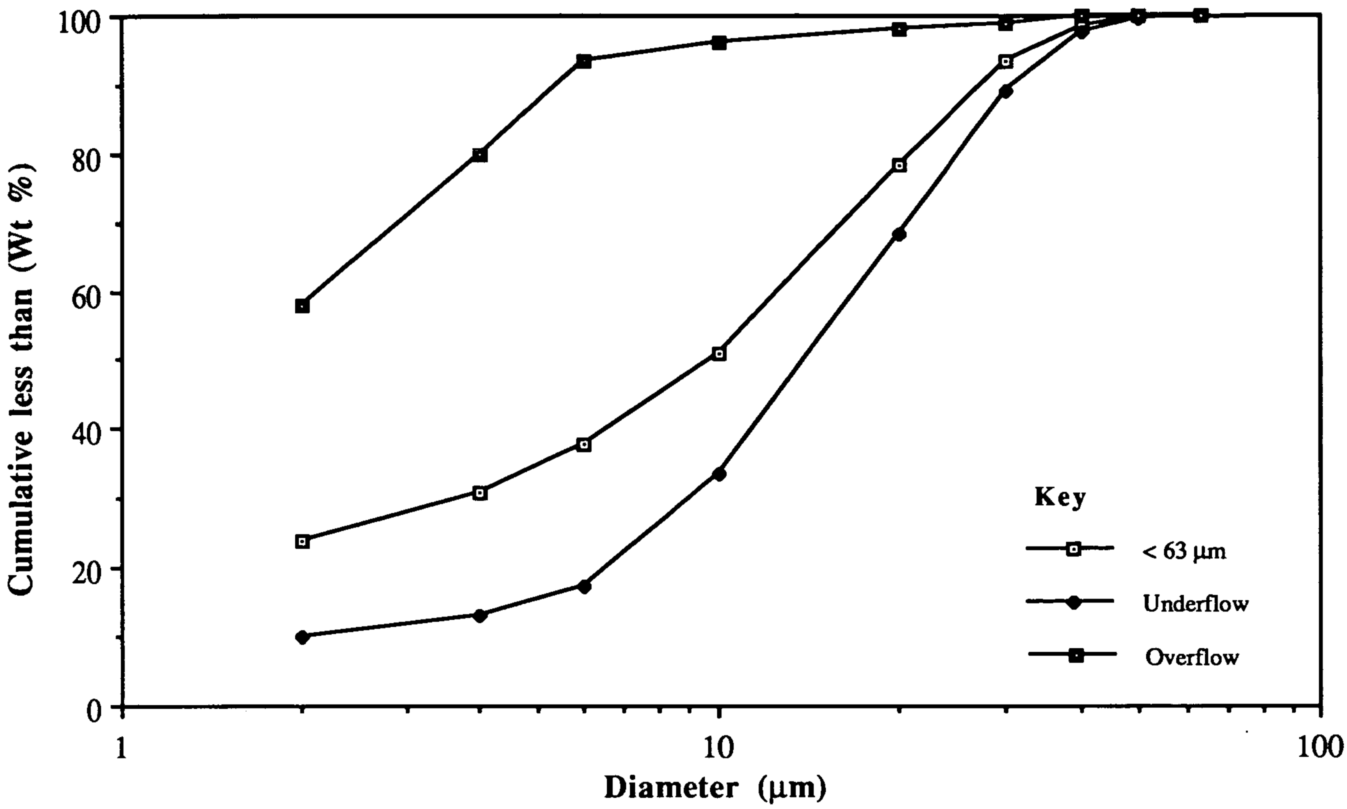

Figure 4. Hydrocycloning particle-size distribution of Chilulwe kaolinite, Zambia.

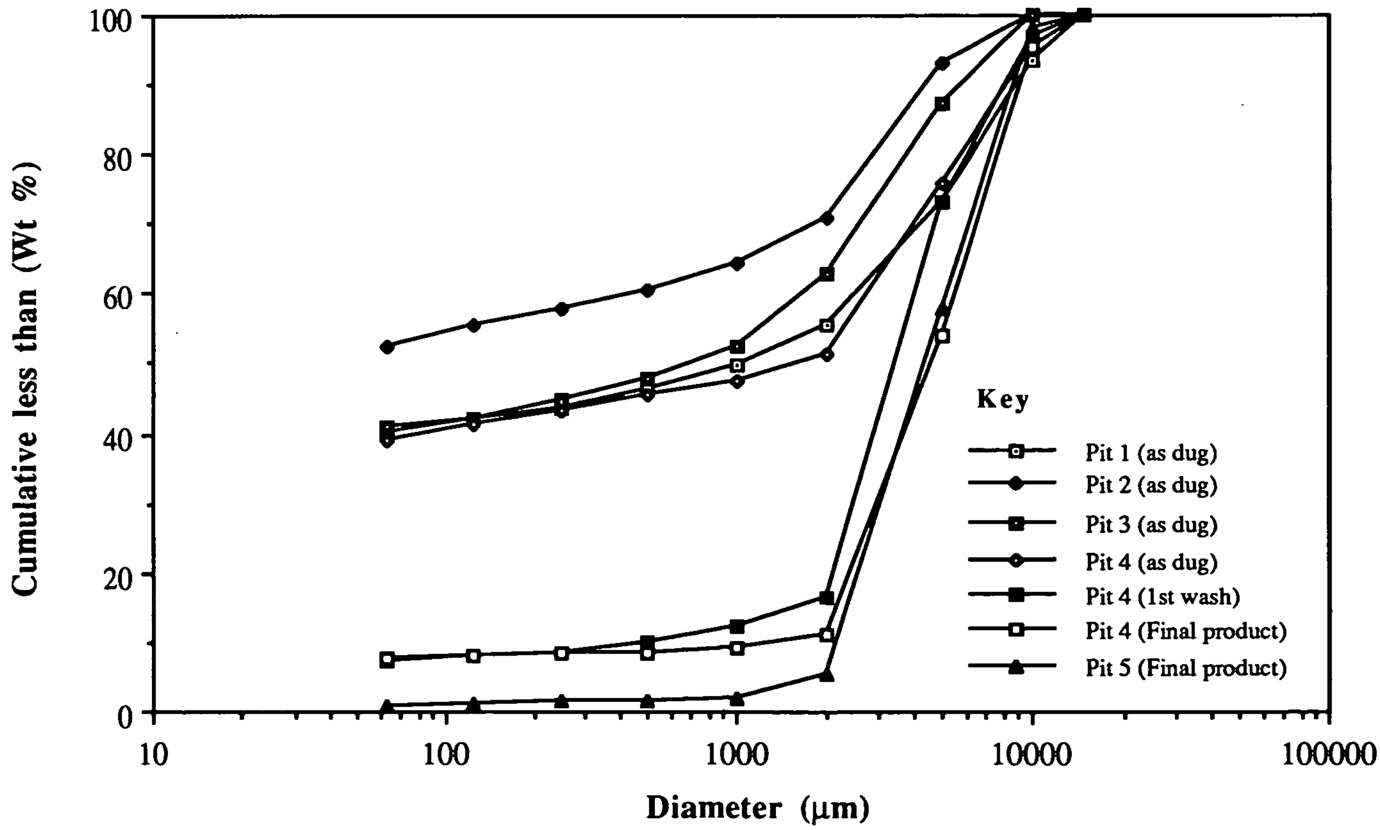

Figure 5. Grain size distribution of Lochinvar gypsum , Zambia.

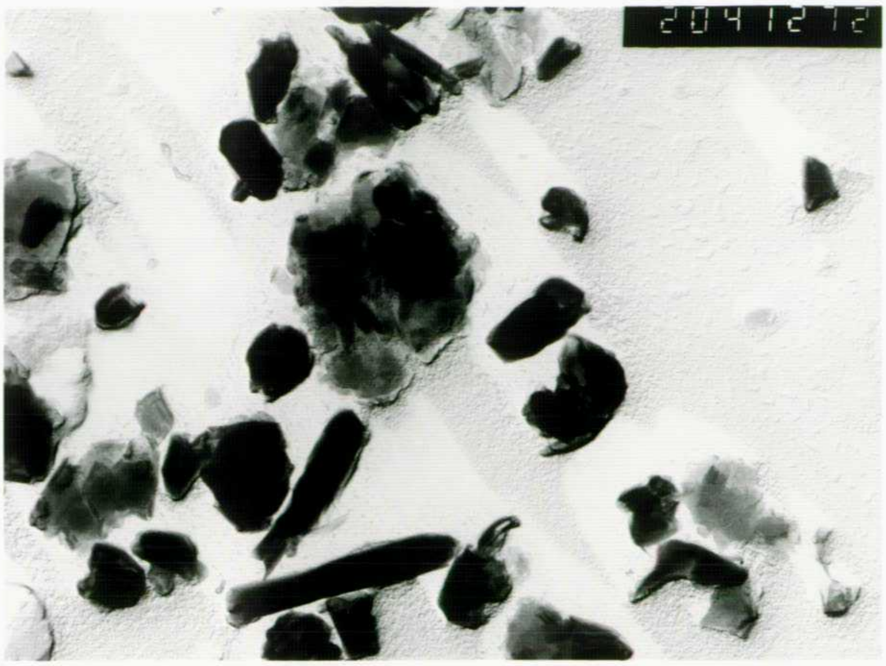

Figure 6. TEM photomicrograph (Mag x 31,000) showing subhedral and rounded hexagonal plates and halloysitic rods, Chilulwe kaolinite, Zambia.

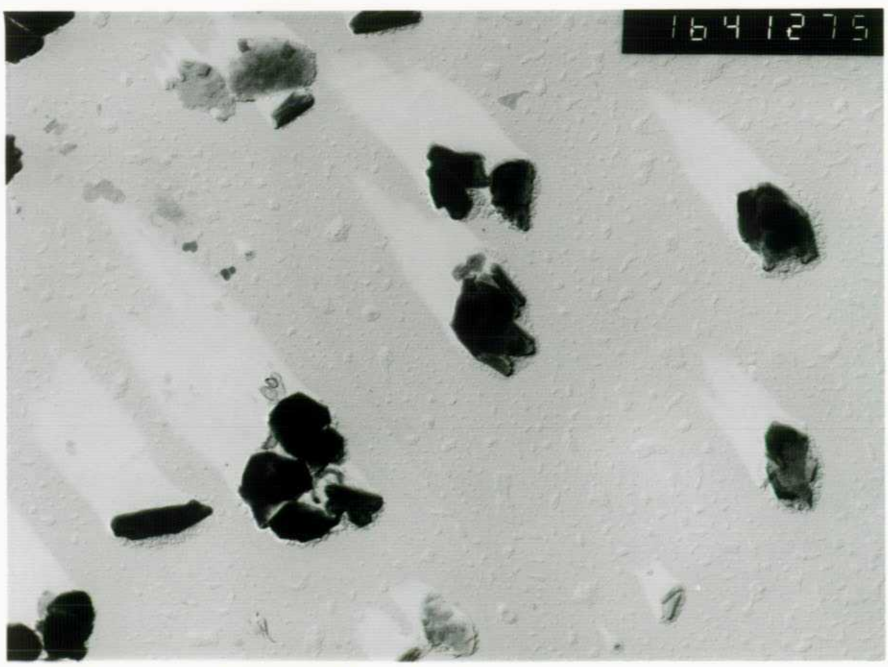

Figure 7. TEM photomicrograph (Mag x 24,800) showing subhedral and rounded kaolinite plates with metal shadowing, Chilulwe kaolinite, Zambia.

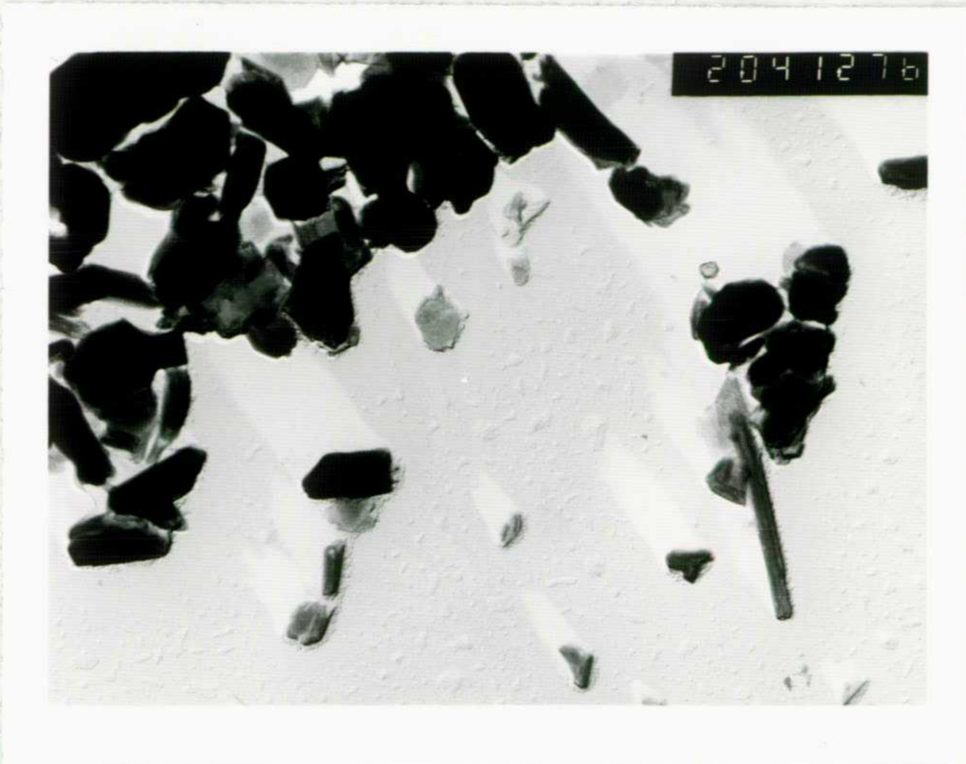

Figure 8. TEM photomicrograph (Mag x 31,000) showing subhedral and rounded hexagonal plates and halloysitic rods, Chilulwe kaolinite, Zambia.

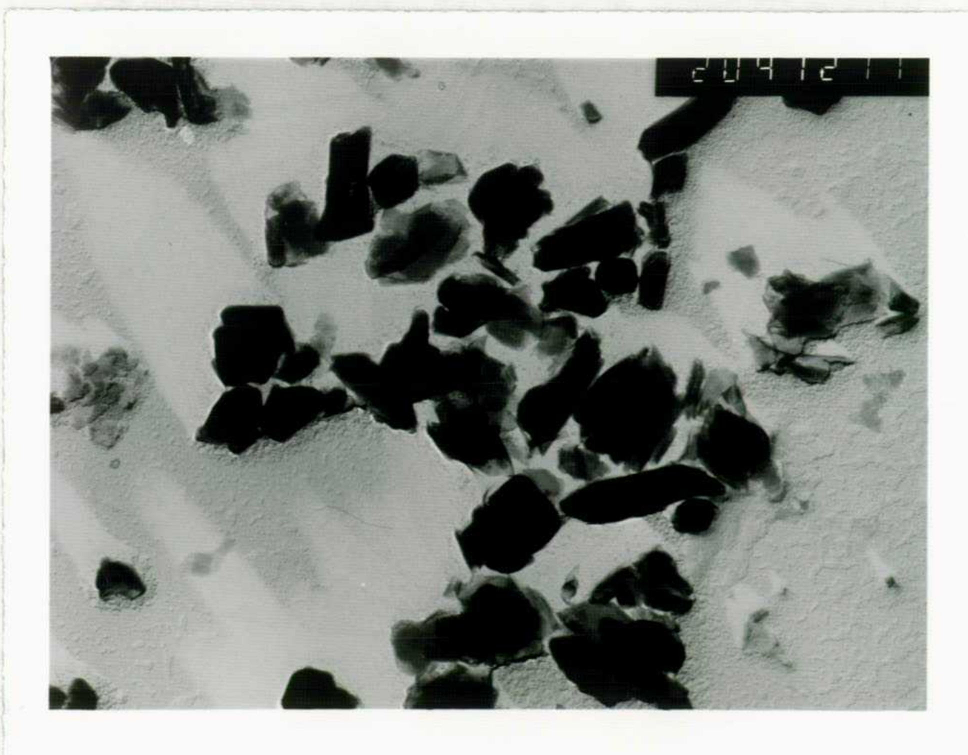

Figure 9. TEM photomicrograph (Mag x 31,000) showing subhedral and rounded kaolinite plates, Chilulwe kaolinite, Zambia.

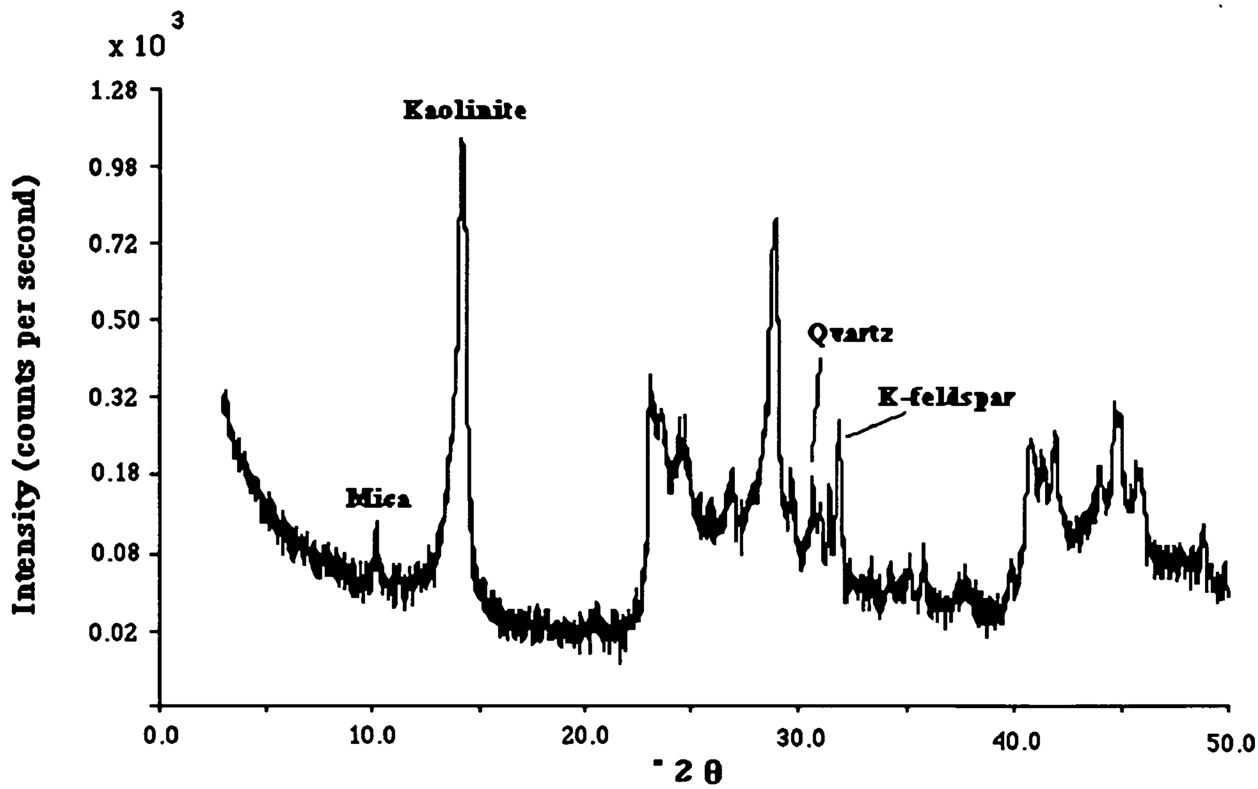

Figure 10. X-ray diffraction trace of Chilulwe kaolinite, Zambia.

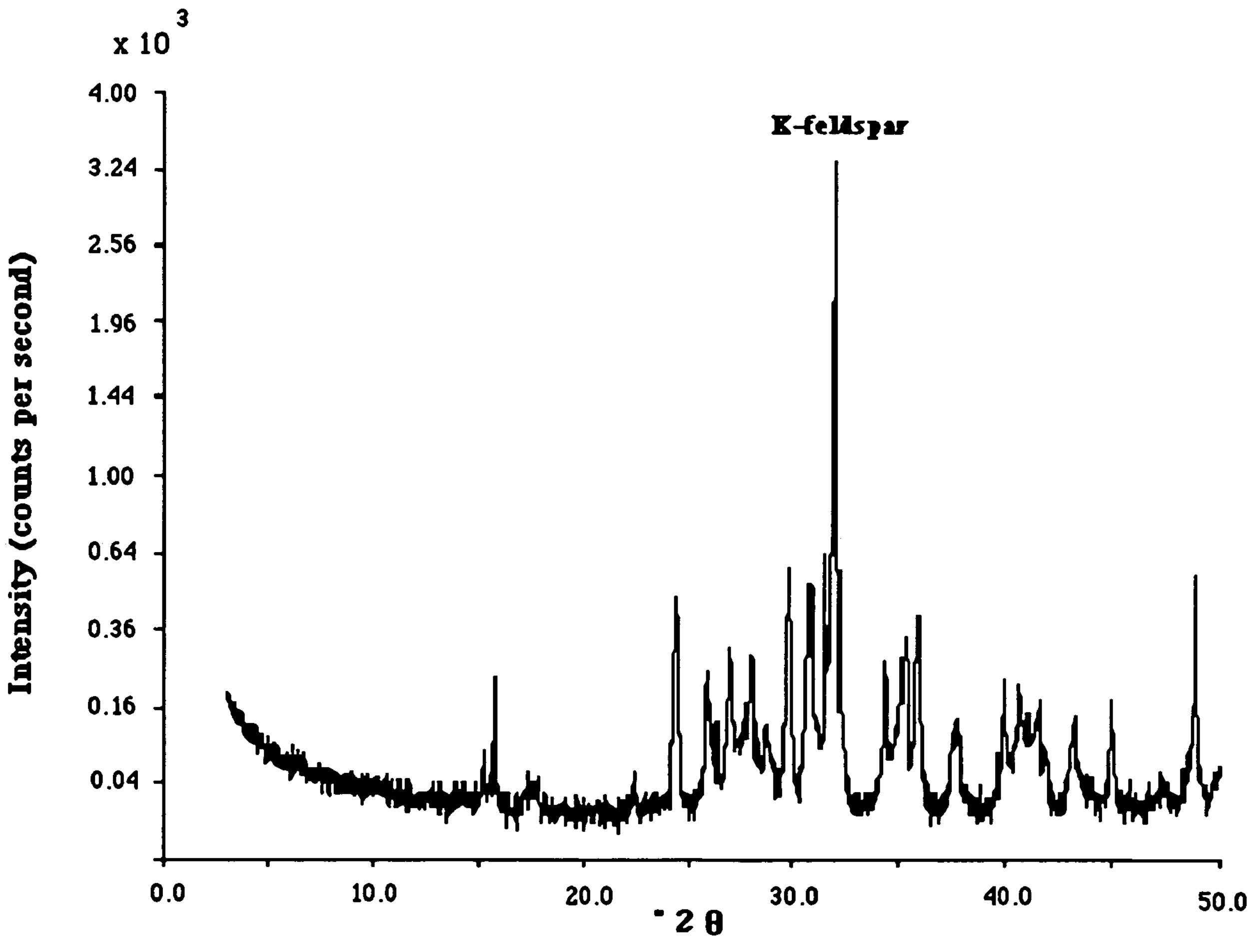

Figure 11. X-ray diffraction trace of Chilulwe feldspar, Zambia.

Appendix A. Commercial-grade kaolinite properties

Application	Kaolinite Wt %	< 2 μm Wt %	> 10 μm Wt %	Brightness (4570 Å)
Paper				
Coating grade	93 - 100	78 - 97	0.2 - 1.5	78 - 93
	(Flowability 67 - 70 wt %, deflocculant demand 0.7 - 1 ml calgon and viscosity concentration 67 - 70 wt %)			
Filler grade	89 - 97	30 - 78	3 - 41	70 - 90
Ceramic grade	87 - 97	39 - 70	2 - 18	86 - 91 (Fired 1180°C)
	(Flowability 64 - 66 wt %, deflocculant demand 0.6 - 4 ml calgon and viscosity concentration 58 - 64 wt %)			
Filler				
Paint	High grade	25 - 80	0.5 - 25	76 - 91
Plastic	High grade	17 - 90	0 - 22	70 - 92
Rubber	High grade	20 - 80	As above ?	As above ?
Agricultural	Low - medium	As fillers ?	As fillers ?	Not applicable

Paper-grade and ceramic-grade figures from Bristow CM (1987) World kaolins - genesis, exploitation and application, *Industrial Minerals*, **July**, pp.45 - 59. Paint figures from Toon S (1985) Minerals for paint, *Industrial Minerals*, **December**, pp. 49 - 75. Plastic figures from Katz HS & Milewski JV (Editors) (1987) Chapter 7. Kaolin, in *Handbook of Fillers for Plastic*, pp.143 -155. Rubber and agricultural figures from Highley DE (1984) *China Clay*, Mineral Dossier No. **26**, Mineral Resources Consultative Committee, HMSO.

Appendix B. Assay figures for the Njoka and Petauke graphite, Zambia.

Product	Njoka A Wt %	Njoka A Graphite %	Njoka B Wt %	Njoka B Graphite %
+2mm	25.04	17.97	72.0	18.89
-2 +1mm	16.75	23.02	10.4	19.30
-1mm +500 µm	28.45	14.93	9.4	20.21
-500 +250 µm	18.21	10.92	5.3	16.03
-250 +125 µm	7.69	8.23	1.9	11.94
-125 µm	3.85	8.16	1.1	10.69
Head	100	13.3	100	18.1

Njoka A

Size fraction	Air classification product		Froth flotation Concentrate	Froth flotation Middling	Froth flotation Tailing
-1mm +500 µm	Concentrate	21.24 (52.77)	59.7 (85.3)	3.3 (17.7)	37.0 (5.4)
	Middling	27.91 (18.9)	23.9 (66.9)	3.3 (19.2)	72.8 (3.5
	Tailing	50.85 (5.6)	4.29 (73.2)	0.9 (9.0)	94.9 (2.4)
-500 +250 µm	Concentrate	7.51 (54.38)	55.7 (90.3)	4.6 (58.0)	39.7 (5.9)
	Middling	26.23 (22.89)	26.1 (77.8)	2.1 (13.9)	71.9 (4.0)
	Tailing	66.26 (4.77)	4.4 (53.2)	0.6 (6.4)	95.1 (1.9)
-250 +125 µm			9.1 (81.5)	1.7 (18.2)	89.2 (2.9)

Njoka B

Size fraction	Air classification product		Froth flotation Concentrate	Froth flotation Middling	Froth flotation Tailing
-1mm +500 µm	Concentrate	13.50 (72.2)	80.3 (86.8)	1.5 (25.9)	18.2 (14.2)
	Middling	17.90 (25.68)	36.0 (52.82)	5.9 (20.38)	58.1 (6.35)
	Tailing	68.60 (4.88)	1.88 (70.94)	0.3 (33.88)	97.8 (3.81)
-500 +250 µm	Concentrate	15.60 (67.59)	74.2 (88.8)	1.0 (26.37)	24.8 (10.5)
	Middling	18.30 (32.26)	35.6 (72.26)	3.1 (22.4)	61.6 (6.82)
	Tailing	66.10 (5.46)	7.4 (31.73)	3.2 (10.35)	89.3 (2.81)
-250 +125 µm			15.1 (82.09)	1.4 (33.41)	83.5 (5.18)

Petauke

Size fraction	Air classification product		Froth flotation Concentrate	Froth flotation Middling	Froth flotation Tailing
-1mm +500 µm	Concentrate	13.3 (18.3)	16.0 (92.4)	3.8 (35.8)	80.2 (2.6)
	Middling	6.1 (3.0)	0.2 (68.6)	0.8 (17.4)	99.0 (2.1)
	Tailing	80.6 (2.65)	0.2 (52.5)	0.5 (9.8)	99.3 (2.2)
-500 +250 µm	Concentrate	13.7 (36.4)	74.2 (95.4)	1.2 (41.2)	68.4 (3.0)
	Middling	7.7 (8.7)	6.3 (86.6)	1.4 (23.4)	92.3 (2.6)
	Tailing	78.6 (3.6)	1.0 (30.9)	0.3 (7.1)	98.7 (3.0)
-250 +125 µm	Concentrate	13.9 (26.1)	20.8 (92.2)	3.5 (75.1)	75.7 (3.8)
	Middling	11.0 (8.8)	5.0 (89.6)	1.4 (52.9)	93.6 (3.2)
	Tailing	75.1 (4.4)	0.4 (50.7)	2.6 (18.1)	97.0 (3.4)

N.B. The figures for the beneficiation are firstly weight percentages followed by the graphite assay in brackets. The air classification wt %s are of the products to their respective size fractions and those of the froth flotation are of the products to the respective air classification product (or size fraction in the case of the Njoka -250 +125 µm material).

Appendix C. Commercial-grade graphite properties

Application	Carbon content (Wt %)	Particle size (μm)	Comments
Refractories			
Magnesia-carbon	85 - 90	+150	Ash <2%, up to 10% often used.
Alumina graphite	Min. 85	+250	
Crucibles	80 - 90	+150	
Expanded graphite	Min. 90	+250	
Foundry additive	40 - 70	53 - 75	Sulphides deleterious, quartz and mica advantageous.
Foundry washes	70 - 90	~75	
Brake linings	Min. 98	<75	
Lubricants	98 - 99	53 - 106	
Batteries	88 - 98	5 - 75	No impurities such as Cu, Co, Sb and As allowable.
Recarburizing steel	98 - 99	~5	
Carbon brushes	95 - 99	<53	Less than 1% ash and /or silica.
Conductive coatings	50 - 55	<75	May contain up to 25% silica.

(N.B. Table summarized from Russell, A. (1988) Graphite - current shortfalls in flake supply. *Industrial Minerals*, Dec., p. 23-43).