The Moyale graphite deposit, southern Ethiopia

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Precambrian metamorphic rocks of southern Ethiopia, belonging to the Pan-African (Mozambique Belt), host the Moyale graphite deposit. The principal rock units are amphibole schists, quartz-feldspar-mica schists, granodiorites, quartzites and graphite schists. Graphite-bearing units are hosted by quartzites and quartz-feldspar-mica schists and generally form continuous bodies extending for hundreds of metres. A Regional variation in grade and flake size of the graphite is noted. From its lateral extent and mode of occurrence, the graphite is believed to be sedimentary in origin. According to image analysis, the average volume percentage of graphite is 7.9%; the average lengths of the shortest and longest axes of the graphite grains are 155 and 407 μm, respectively. Statistical analyses indicate that about 60% of graphite grains have their longest axes between 100 and 300 μm, the remaining 40% falling in the >300 μm size fraction. Preliminary flotation trials to concentrate the graphites in the <400 μm fraction resulted in a concentrate grade of 71 % with a recovery in excess of 90%.

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Introduction

Graphite occurs in most of the metamorphic rocks of Ethiopia. Some of the known occurrences (e.g. the Kibre Mengist area) are characterised by very fine flakes and contain sulphide minerals. Vein type graphite deposits have not so far been reported in Ethiopia. The present study concerns graphite from the Moyale area, located 750 km south of Addis Ababa, on the Kenyan border (Fig. 1). The graphite occurrence is about 6 km west of Moyale town. Investigations of the Moyale graphite have comprised mapping the graphite body by geological and geophysical methods, analysis of the graphite carbon content, and determination of the size and texture of the graphite grains. Preliminary efforts have also been made to concentrate the graphite by flotation techniques.

Geological setting

The northeastern branch of the Mozambique Belt, a major Proterozoic structural and metamorphic unit of East Africa, extends from Kenya through Ethiopia and the horn of Africa into southern Arabia (Warden & Horke 1984). In the Mozambique Belt of southern Ethiopia, three major divisions (Lower, Middle and Upper Complexes) have been differentiated by characteristic contrasts in lithology, metamorphism and structural style (Kazmin et al. 1978). Metasedimentary rocks (graphitic phyllites, biotite schists and metacalcareous rocks) in the Adola area form the uppermost unit of the Upper Complex of southern Ethiopia. On the basis of this scheme, the rocks of the Moyale region are correlated with the lower part of the Upper Complex, and are probably Neoproterozoic in age (Alene & Barker 1993). According to Hussien (1999), the rock association in the Moyale area is typical of a subduction complex consisting of metamorphosed mafic-ultramafic rocks, fore-arc and accretional wedge-derived metasediments and associated rocks. Hussien further suggested that the lithological association in the Moyale domain indicates the existence of oceanic crust prior to subduction.

The major orogenic belts of the Horn of Africa, Arabian Shield and Mozambique Belt intersect in the Moyale region (Kazmin et al. 1975, Vail et al. 1986). The local geology comprises polydeformed and metamorphosed mafic and ultramafic rocks, granodiorites and subordinate amounts of meta-

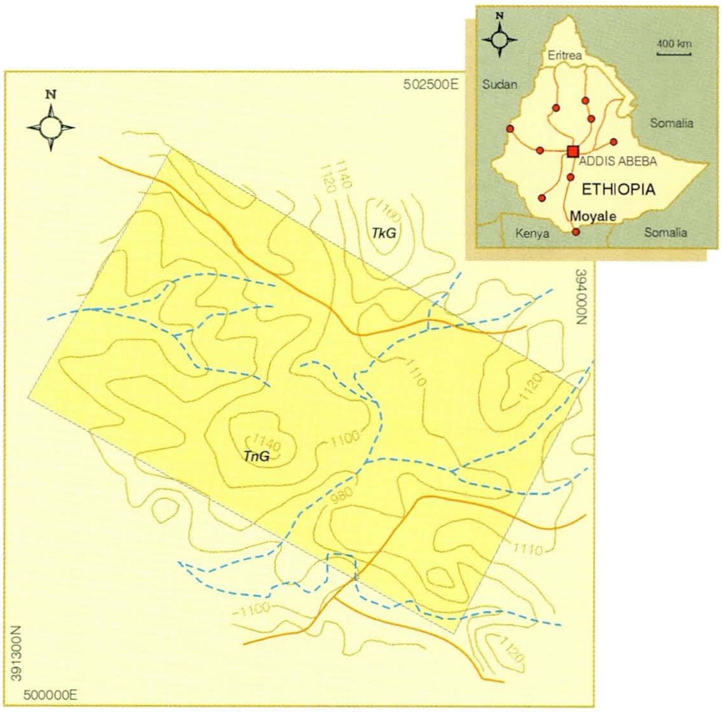

Fig. 1. Location map of the Moyale graphite deposits.

sedimentary rocks. The dominant rock units of the Moyale area are amphibole schist, quartz-feldspar-mica schist, granodiorite, quartzite and graphite schist.

The graphite occurrences

Graphite occurrences in the Moyale area are hosted by quartzite, quartz-feldspar-mica schist and rarely by amphibole schist. Pegmatitic graphite bodies, though less common, usually occur discordant to the main schistosity. Occurrences of graphite in the Moyale region can be divided into three areas. These show some differences in mode of occurrence as well as in the grade and flake size of the graphite.

Areas I and III (Fig. 2) contain nearly continuous graphite bands extending for several km. Such bands are dislocated by faults in the central region and show a tendency to pinch out towards the west. Area I consists of relatively thick graphite bands separated by feldspar-quartz-mica schists. All the graphite schist in this area dips towards NE at about 45° and has a relatively uniform graphite content (Fig. 3). Area II consists of short, discontinuous graphitic schists, hosted mainly by quartzites and pegmatites. Flake size of the graphite diminishes towards the east (Area III); very fine grained graphite dominates farther east from Area III. The association of graphite with rocks of medium metamorphic grade, their wide lateral extent and character in outcrop, as well as the grade and flake size of the graphite, suggests that they are, most probably, sedimentary in origin.

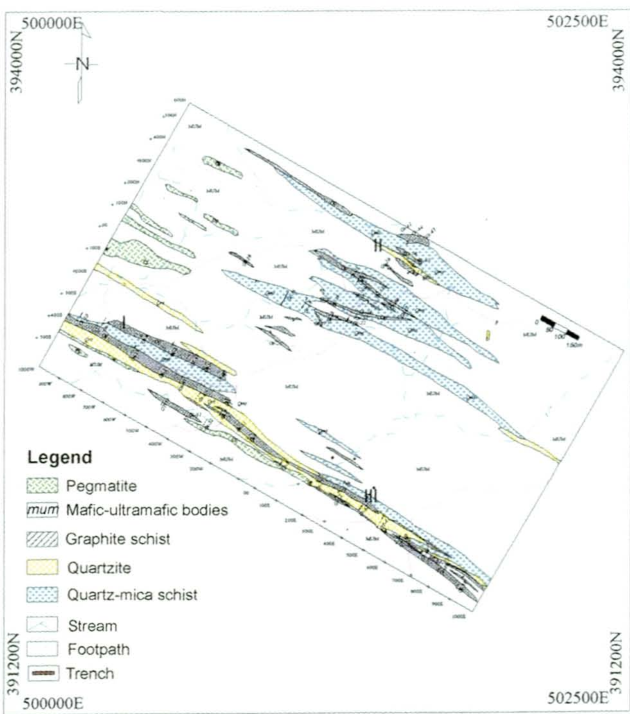

Fig. 2. Geological map of the Moyale graphite deposits

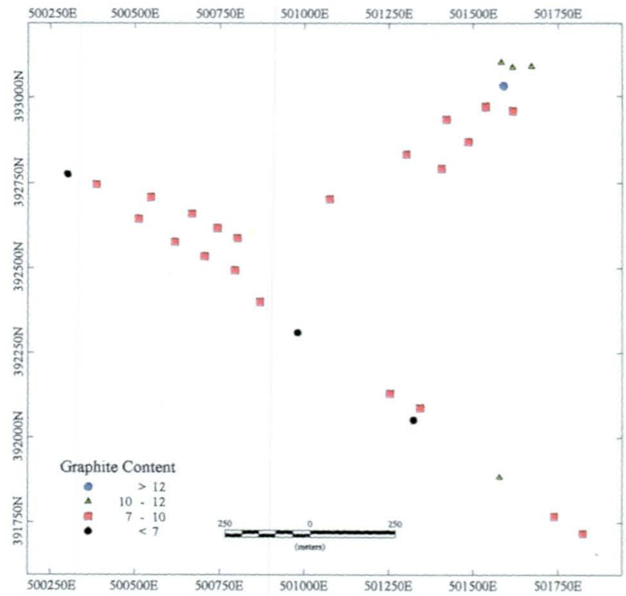

Fig. 3. Loaction and average graphite content of different trenches

Materials and experimental methods

Detailed geological mapping of the Moyale graphite was facilitated by a line survey spaced at 100 m and labelled every 20 m. The profile stretched NE-SW, nearly perpendicular to the regional schistosity. Trenches where dug almost parallel to the profile lines. The location and average graphite grades of the trenches are shown in Fig. 3. These grid lines were also used for collecting ground geophysical data. Scintrex TM-2 GENIE/horizontal loop portable electromagnetic transmitters and EGS-2/EM-4 receivers were used in the EM GENIE Survey.

Petrographic study was carried out by image analysis of representative thin-sections from graphite-bearing samples collected from trenches. By recording and processing the digital images, the volume percentage of graphite and the morphological features of graphite grains were determined. Graphite carbon content was determined by a loss of ignition (LOI) test. The material is ground to less than 500 µm and 1 g of the ground sample is heated in an oven (100° C) overnight and in a furnace for 2 hours at a peak temperature of 1000°C.

Graphite concentration was carried out in a laboratory-scale flotation cell using collectors and frothers including Pine Oil, MIBC and EKOFOL and combinations thereof. Fine (< 400 µm) fractions were subjected to flotation. Two to three drops of collectors were used for about 500 g of material. Concentrates were collected after a 3 minute spindle agitation. An inflow of air from an inlet at the side of the flotation cell facilitates flotation.

Results and discussion

Geophysics

Integrated geophysical exploration surveys confirmed geologically mapped graphite zones in the Moyale area. The

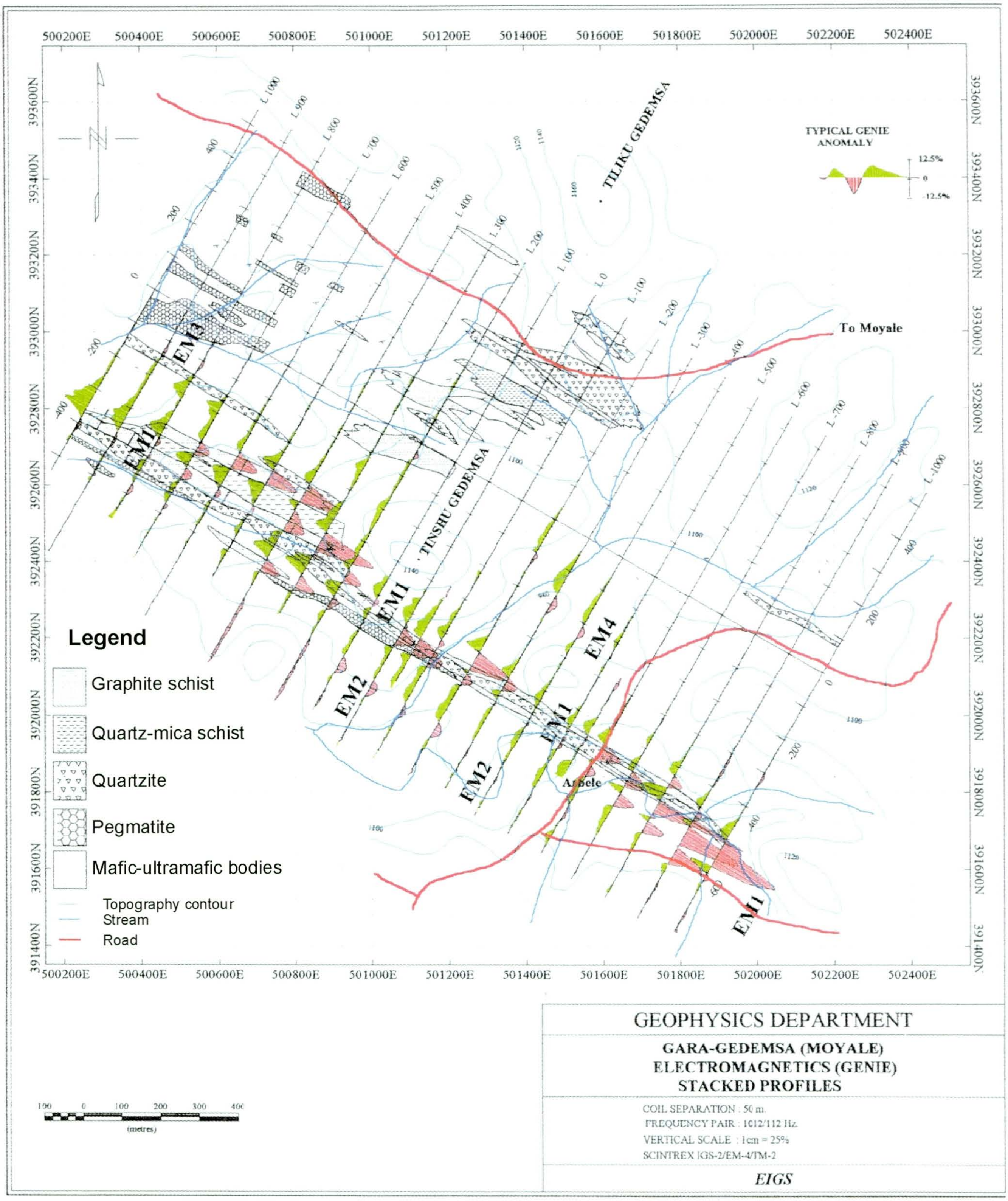

Fig. 4. EM GENIE electromagnetic survey. See text for discussion of the EM anomalies 1 to 4.

graphite-rich zones gave high-IP, low- resistivity, strong negative GENIE EM values and a moderately contrasting radiometeric response, in comparison with the surrounding barren rocks. EM GENIE stacked profiles using coil separations of 50 m and 100 m and three frequency pairs, show clear anomalies trending NW-SE in the Tinishu Gedemssa area (Fig. 4). The trends of the anomalies closely follow the geologically mapped graphite units, separated by quartz-mica schists. However, EM failed to pick out the graphite units of Area II. This is probably because the graphites in such an area are hosted by low-lying metasedimentary rocks. All geophysical anomalies continue towards the southeast, but as the graph-

Table 1. Aggregate statistical data obtained from image analysis of several representative thinsections of graphite, indicating selected morphological features.

	Area (μm^2)	Area (mm^2)	Perim (µm)	feretmin (µm)	feretmax (µm)	ellipsea (µm)	ellipseb (µm)
Average	36147.8	0.036	1471.9	155.8	407	172.4	57.8
Maximum	1382548	1.383	19290.7	1982.3	3836.5	1919.8	518.7
Minimum	3808.7	0.004	267.4	17.7	85.9	38	5.5

Note: Area =Area of grains, perim = length of grain perimeter; feretmin, feretmax = lengths of shortest and longest axes, ellipsea/ellipseb = lengths of longest and shortest axes of theoretical ellipses surrounding the grains.

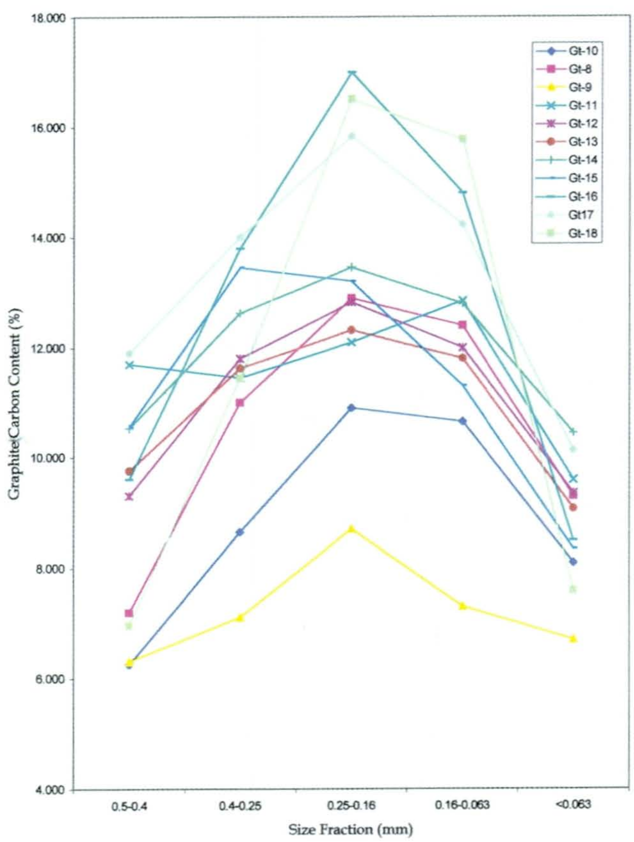

Fig. 5. Carbon content vs. size fraction of sieved samples.

ite is finer grained in this area this does not encourage further exploration. The Geophysical evidence strongly indicates that the graphite content of the rocks is the sole cause for the GENIE EM and IP/Resistivity responses (Sebhat 1998).

Petrographical analysis

The main purpose of petrographical study was to determine the volume percentage, grain size and morphology of the graphite. Such a study is viewed as a pre-requisite for evaluation of graphite beneficiation tests. During sieving, the shortest axis will be regarded as the maximum size that passes through the sieve. In other words, the shortest axis corresponds approximately to the liberation size of the graphite grains. From thin-section image analysis, volume % graphite and morphological data were recorded. To obtain as good statistical representative data as possible, aggregate values from several thin sections were recorded. The average volume percentage of graphite was found to be 7.9%. Statistical values for the size and dimensions of graphite are shown in Table 1. Average grain size in thin-section is 0.036 mm^2; the longest and shortest grain axes are 407 and 155 µm, respectively (Table 1, Gautneb 1997). Moreover, statistical analyses indicate that about 60% of graphite grains have their longest axis between 100 and 300 µm; the remaining 40% falling in the > 300 µm size fraction (Fig.5).

Graphite carbon analyses

Graphite carbon content was determined for both whole rock samples and the different size fractions. The average grade of the graphite for the whole rock ranges from 7 to 10% with a cumulative average of 9.01% (Fentaw & Mohammed 1998). The highest graphite concentration is confined between 400 and 63 µm, with the coarser and finer fractions having graphite carbon contents comparable with that of the whole rock. As can be seen in Fig. 3, samples from Area II are characterised by relatively higher graphite contents while those in Area I have nearly uniform graphite carbon contents.

Graphite beneficiation

Graphite concentration is dependent on the graphite morphology and liberation size. Graphite was concentrated by two stages of flotation. The first stage of flotation produced concentrates and tailings. A second flotation is carried out to clean the first graphite concentrates and results in three products: a concentrate, middling (material that sunk during the second flotation) and tails. As indicated in Table 2, it was possible to upgrade the graphite from 7 to 71%. The grade of the tailing is below 1%, suggesting that nearly all graphite in the head material is contained in the concentrates and that the collectors are particularly effective for the Moyale samples. This results in a high recovery of the graphite, even though the concentrates have only a moderate grade. The main reason for this is that the head material consists of coarse material (400 µm), whith a high incidence of interlocked quartz-graphite grains. Such grains are frothed along with the pure graphite and hence belong to the concentrates. High-grade graphite concentrates can best be achieved by stepwise grinding and flotation until all non-graphitic materials in the concentrate are liberated.

Table 2. Results from the flotation tests of the Moyale graphite.

Sample No.	Product type	Wt prod. (gm)	Weight (%)	Grade (%)	Wt.Grp (gm)	Recovery (%)	Collector
Gt 5-8	Concentrate	45.30	14.74	71.4	32.22	95.75	EKOFOL
Gt 5-8	Tailing	261	85.25	0.55	1.43	4.25	
		306.13	100	33.65	33.65	100	
Gt 13-4	Concentrate	34.6	11.51	70.2	24.28	95.82	EKOFOL
G[13-4	Tailing	266.00	88.48	0.4	1.06	4.18	
		300.6	100	25.34	25.34	100	
Gt 13-4	Concentrate	39.74	14.18	66.5	26.42	95.48	MIBC + EKOFOL
Gt 13-4	Tailing	240.4	85.81	0.52	1.25	4.52	
		280.14	100	27.67	27.67	100	
G t 12-3	Concentrate	69.39	17.7	52.2	36.22	94.47	MIBC + EKOFOL
Gt 12-3	Tailing	322.6	32.29	0.66	2.12	5.53	
		391.99	100	38.34	38.34	100	
Gt 12-3	Concentrate	5.8	1.89	42.4	2.45	9.04	MIBC
GL 12-3	Concentrate	4.7	1.53	57.2	2.68	9.88	MIBC+PINE
G[12-3	Tailing	296	96.57	7.43	21.99	81.08	
		306.5	100	27.12	27.12	100	
Composite	Concentrate	118.55	11.08	67.1	79.54	93.25	EKOFOL
Composite	Tailing (1st)	890	83.21	0.34	3.02	3.54	
Composite	Tailing (2nd)	61	5.7	4.5	2.74	3.21	
		1069.55	100		85.3	100	
Composite	Concentrate	132	11.61	60.8	8.25	92.8	MIBC+EKOFOL
Composite	Tailing (1st)	983	84.56	0.41	4.03	4.66	
Composite	Tailing (2nd)	44.5	3.82	4.94	2.19	2.54	
		1162.5	100	86.47	86.47	100	

Note: Tailing (2nd) = Middling; Composite = Mixed samples; Head grade 7-11%; Wt. Product = Weight of the product; Wt. Grade (%) = Weight percent of graphite

Conclusions

The economic potential of a graphite-bearing rock depends mainly on the graphite carbon content and flake size, since the market price for graphite reflects these two characteristics. The average grade of the Moyale graphite schist ranges between 7 and 11% (mean 9.1%). The Moyale graphite schists therefore have moderately low, graphite carbon contents. However, the graphite grains have their longest axes greater than 100 μm, which suggests that flake size is optimal and that it is technically feasible to produce graphite concentrates using the available technology. The Moyale area contains an indicated mineral resource of about 450 000 tonnes of graphite. With one or two exseptions the geomorphological conditions are also favourable for open pit mining.

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