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Description of a new howardite meteorite fall in southern Tanzania; proposed meteorite name Kilimani

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Introduction

This report summarizes laboratory and other data of a new meteorite that fell in southern Tanzania in July, 2003. This data is required by the Meteoritical Society for registration and approval of the proposed name. The rock fragments were originally collected by locals and later identified and studied in Geological Survey of Finland (GTK) during next years. Earlier contacts and previous scientific co-operation between University of Dar Es Salaam, the Geological Survey of Tanzania (GST) and GTK enabled this study. The meteorite was identified as polymict brecciated achondritic howardite. It is proposed that it should be named Kilimani according to the village in which it fell. The meteorite is the 10^{th} known from Tanzania. So far nine meteorites were known from Tanzania (see Grady 2000). Ivuna and Mbozi are the most widely known Tanzanian meteorites. Nine out of these now ten Tanzanian meteorites are witnessed falls.

Literature review on howardites

Howardites are achondritic meteorites that belong to the HED group (howardite, eucrite and diogenite). Howardites are polymict breccias and are composed of clasts and fragments of diogenites and eucrites. They have been considered as lithified "soil" regolith fragments with some resemblance to lunar soils. Latest studies show that only some of the howardites are regolithic. Most of them are fragmental breccias according to Warren et al. (2009). About 200 howardite meteorites are known and about 20 of them are observed falls. Many of these 200 meteorites seem to be paired and may represent only about 60 individual meteorites. Howardite fragments are together with the Mars meteorites among the most expensive meteorite specimens with prices ranging from 100 up to 1000 US dollars per gram.

Howardites are most likely impact ejecta from the Vesta 4 asteroid. Vesta 4 is the second largest asteroid (diameter 530 km) in the main asteroid belt between the orbits of Mars and Venus. However, howardites' resemblance to IIIAB irons and pallasites according to chemical and isotopical characteristics may suggest other asteroids as possible candidates as well. One strong argument to other possible asteroids is the topography of Vesta 4, which indicates that it was not cratered to the mantle depth to expose irons and pallasites.

Mineralogical, petrological, chemical and isotope compositions and spectroscopic properties of HED meteorites and their Vesta 4 connection have been reviewed by Takeda (1997), Mittlefehldt et al. (1998), Keil (2002) and Warren et al. (2009). Howardites have polymictic fragmental breccia texture. They represent impact breccia. Clasts and matrix both are composed of eucrite and diogenite fragments and of their fine-grained mineral fragments. Impact melt clasts, agglunites, are a common minor constituent. Most likely the agglunites represent impact melted eucrites. Many howardites contain fossil micrometeorites primarily composed of carbonaceous chondrite fragments (CM2). Consequently, the bulk chemical composition of howardites is essentially a mixture of eucrites and diogenites.

Clasts in howardites are fragments of igneous rocks formed in mantle fractionation 4.548 ± 0.009 Ma. According to ^{39}Ar-^{40}Ar impact-reset ages howardite were impact transported from Vesta 4 about 4.1 – 3.5 Gyr ago (Bogard and Garrison 2003). These fragments were the Vestoids and presumable some smaller particles. Cosmic-ray exposure ages 6 – 73 Ma indicate, that fragmentation of Vestoids may have formed the smaller bodies that finally drifted into Earth crossing orbits.

Vesta 4 asteroid with its HED meteorites (total mass 1147 kg) is one of the very few known planetary objects, from which there are concrete specimens. The others are Earth, Moon (lunar samples 382 kg), Mars (martian meteorites 94 kg) and comet Wild 2. In May 2012 Nasa's Dawn Probe shall launch Vesta 4 and study its mineral and chemical composition in more detail.

Figure 1. Location of the meteorite fall in southern Tanzania.

Circumstances of the meteorite recovery

On Thursday 10 July, 2003, about 10 am local time, several stones fell in the villages of Kilimani, Mbangamawe and in several other places in Mbinga District, Ruvuma region, southern Tanzania (Fig. 1). The villagers saw the smoke, sparks and they heard a sound, which resembled somebody fireing a gun, an artillery tank or riding a big motor cycle. Some people described the noise like a wind cyclone just before the stones fell down. A number of people heard the sound and observed smoke and something like lightning. The weather on that special morning was cloudy and chilly with some fog. The fall area is characterized by small scale farming and brick making.

In Mbangamawe village one meteorite fragment made a small pit on the ground. The dimensions of the hole were 3 inches (8 cm) deep and 5 inches (13 cm) wide.

The villagers reported the incident to the local police after hearing the strange sounds and witnessing sparks in the air. The police visited the area that same day, and they were able to collect one rock sample, which was later presented to the Mines Office in Songea for further investigations. The Mines Officer in Songea, Mr Karim Baruti, visited the area on 18th July, 2003, and managed to collect additional pieces of the strange material. Later two pieces of this material was taken to the museum of GST for further examination.

Reported eyewitnesses include Mr. Edwin Milinga, the Village Executive from the Mbangamawe village and other people residing in that area.

Identification of the specimen as a meteorite

The Geological Survey of Finland (GTK) implemented a geological project in Tanzania together with the Geological Survey of Tanzania (GST) during years 2003-2007. During the course of the project, Ms Augustina Rutaihwa, head of the museum of GST, showed the two pieces of the assumed meteorite to the project manager Kristian Lindqvist, who immediately was convinced about the meteoritic character and consequently brought one fragment of the largest object (Fig. 2) to Dr Kari A. Kinnunen in GTK, Espoo, for further examination. Kinnunen has experience in identification of meteorites and he has, among others, identified and studied the most recent meteorite find from Finland, i.e. Kivesvaara, CM2 (carbonaceous chondrite). Previously Kinnunen has identified potential Finnish meteorite samples which have been sent to GTK since the 1980's, about 10 pieces per year. In addition, assumed meteorite samples have been sent to him for identification from mainly tourist resorts in Spain including Canary Islands, Israel, Sweden, Saudi Arabia, South Africa, Siberia Russia and Arizona USA.

This probable meteorite fragment from Tanzania showed fusion crust in the form of a black glassy coating. The material did not show any chondrule-like grains. Instead it showed brecciated blackish and gray rock fragments in a light gray, very fine-grained matrix. Macroscopically the supposed meteorite fragment somewhat resembled a melted or burned piece of concrete. As a preliminary test very small fragments were prepared to an immersion grain mount using 1.6 RI immersion oil. This microscope study showed that the crystal fragments are mainly composed of pyroxene. The pyroxene grains contained glass inclusions and opaque metal-like spherules without any fluid inclusions typical of terrestrial pyroxenes. Some grains revealed under the microscope distinct shock-features. These observations suggested that the rock sample most probable is a new meteorite. These observations justified further studies with more sophisticated instrumental analytical methods and a careful selection of preparation methods in order to save as much material as possible was done. At this stage of the study, all remaining pieces of the meteorite material were brought to Finland (GTK) for detailed examination.

The preliminary microscopy study showed that the fragments most likely are pieces of a brecciated achondritic meteorite. The textures of the meteorite fragments resembled lunar regolithic breccias but similar textures are common in HED type basaltic achondrites, which at this stage seemed to be the most likely alternative.

Figure 2. The largest meteorite fragment, 308.6 g, 79 x 61 x 44 mm. Regmaglypts and black shiny fusion crust are diagnostic. Photos: Kari A. Kinnunen.

Laboratory studies

The meteorite pieces were weighed, measured, photographed and studied under the stereomicroscope. Petrophysical measurements including determination of the specific gravity were carried out. A polished thin section was prepared and the thin section photographed. The thin section was studied under the polarizing microscope and textures were observed and tentative mineral identifications were made. Image analyses were performed in order to analyze textures and grain sizes. Microprobe analyses with a Cameca SX 100 were made from both mineral grains and from the fusion crust. In total 149 point chemical analyses were made. The probe strength was 15 kV with the electron beam current 20 nA and a diameter 5 microns. The matrix material was studied and the relative abundance of the main minerals was calculated using data from X-ray diffraction analyses. The bulk chemical composition was determined in the chemical laboratory of GTK (presently Labtium Ltd.). Methods used for determination of the bulk chemical composition included grinding in an agate vessel and acid dissolution followed by analysis with the XRF pellet technique, ICP-MS method, sulfur analyzer and carbon analyzer.

Fall data

Proposed name of the meteorite: Kilimani

For what type of geographic feature the name stands for: Village name in southern Tanzania

Observed fall: Yes

Date of fall: 10th July 2003 (Thursday)

Time of fall: 10:00 am of local time (time zone GMT +3:0 Nairobi)

Nearest village to the recovery site: Kilimani and Mbangamawe villages (distance between the villages about 5 km)

County meteorite was recovered: Mbinga

State or province meteorite was recovered in: Ruvuma

Country meteorite was recovered in: Tanzania

Coordinates:

Kilimani village meteorite shower
Longitude 35 degrees, 01 minutes, 45 seconds E
Latitude 11 degrees, 00 minutes, 47 seconds S
Altitude 1302 m

Mbangamawe village meteorite shower
Longitude 35 degrees, 00 minutes, 51 seconds E
Latitude 11 degrees, 01 minutes, 47 seconds S
Altitude 1327 m above sea level

Total mass recovered: 586.12 g, (476.2 g remaining after the studies)

Bulk density: 3.03

Number of individual objects recovered: 2

Individual masses (and dimensions) of the objects: 308.6 g (79 x 61 x 44 mm, after cutting); 94.2 g (57 x 35 x 31 mm, intact and saved as type specimen); 73.4 g (small pieces of the largest object)

Nature of the recovery site: Countryside with small scale farming

Classification

On the basis of mineral composition, textures (Fig. 3) and chemical composition this meteorite is classified as an achondrite, and more specifically howardite.

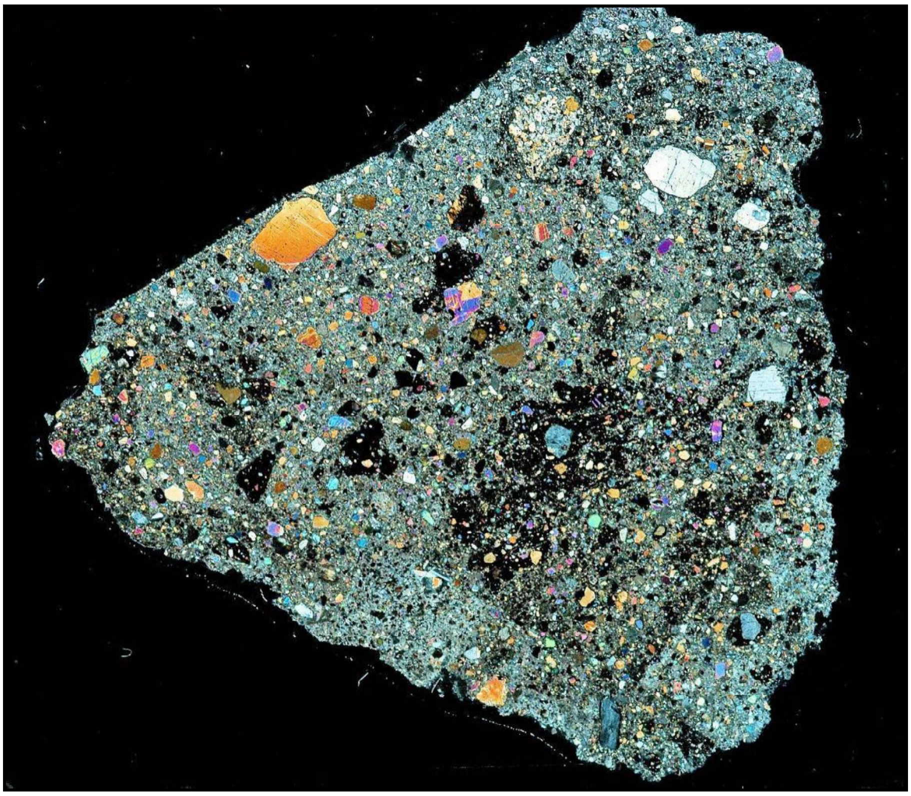

Figure 3. Polished thin section of the meteorite showing polymict breccia texture and a fine-grained matrix. Diogenetic polycrystalline fragments (grayish grains) and orthopyroxene grains are more abundant than eucritic fragments (blackish grains). Crossed polars. Dimensions of the section area: width 25 mm, height 27 mm. Photo: Jari Väätäinen.

The classification of basaltic achondrites is complex (see Mittlefeldt et al. 1998). These rocks are composed of diogenetic and eucritic material. In addition they may contain micrometeoritic spherules composed of carbonaceous chondrite material. Takeda (1997) has improved the classification criteria for basaltic achondrites, and his boundary values were used in this study. Furthermore, meteorite descriptions of similar achondrites, i.e. Lohawat and Kapoeta, were compared and used as reference material for the classification (see Pun et al. 1998, Sisodia et al. 2001).

The pyroxene grains in basaltic (eucritic) clasts of this studied meteorite are unzoned. This is typical of howardites. In polymict eucrites pyroxenes are mostly zoned.

Meteorite group: Howardite achondrite

Subtype: Polymict breccia type of howardite

The dividing line between polymict eucritic breccias and howardites is 9/1 ratio of diogenetic and eucritic pyroxenes. Howardites contain over 10% of diogenetic clasts (see Takeda 1997).

The clasts were studied and classified with the polarizing microscope from the polished thin section (Fig. 3). Microprobe analyses were made to confirm the identifications. The clast mode in volume percentages is: diogenite clasts 89 %, eucrite clasts 8 % and other clasts 3 % (modal analysis with point counting about 100 grains). In total 62 clasts with a diameter over 0.2 mm (Figs. 4 and 5) were classified and counted under the polarizing microscope. The result with a diogenite/eucrite ratio of about 9/1 classifies the meteorite as a diogenite-rich howardite.

Additional analytical results were obtained from a multicomponent X-ray diffraction analyses of the matrix material. It showed 70 % orthopyroxene and 30 % clinopyroxene from the pyroxene population.

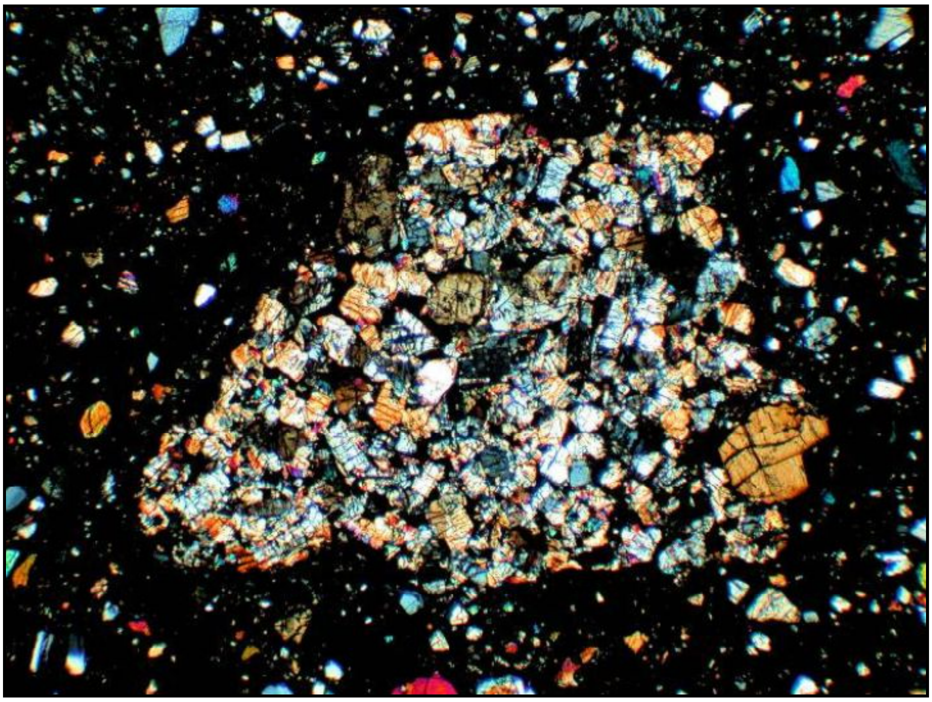

Figure 4. Diogenite clast in the meteorite. Crossed polars, picture width 5 mm. Photo: Kari A. Kinnunen.

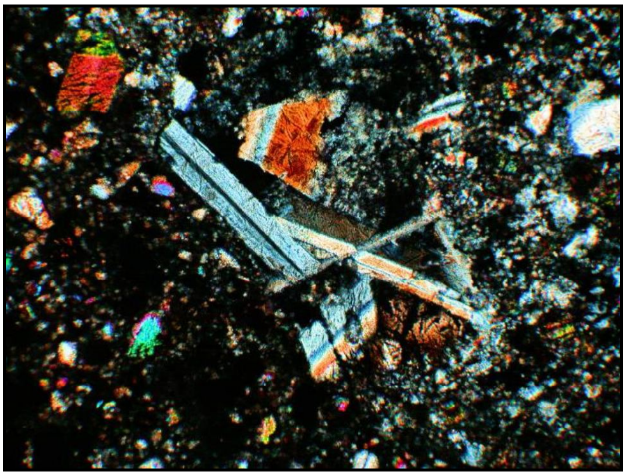

Figure 5. Eucrite clast in the meteorite. Crossed polars, picture width 2 mm. Photo: Kari A. Kinnunen.

Shock stage

The shock stage was determined from pyroxene and plagioclase grains. Criteria outlined by Stöffler et al. (1991) were used for this purpose. Olivine grains are rare in this meteorite and for this reason they could not be used for the determination. Large orthopyroxene clasts in the matrix material showed shock stages from S1 to S2 (Fig. 6). The degree of undulatory extinction and fracturing were mainly used as determination criteria. Plagioclase laths in eucrite clasts showed shock stages from S2 to S3 with a few clasts reaching the S4 stage. The degree of undulatory extinction was principally observed. Neither opaque shock veins nor melt pockets in the meteorite matrix material could be observed.

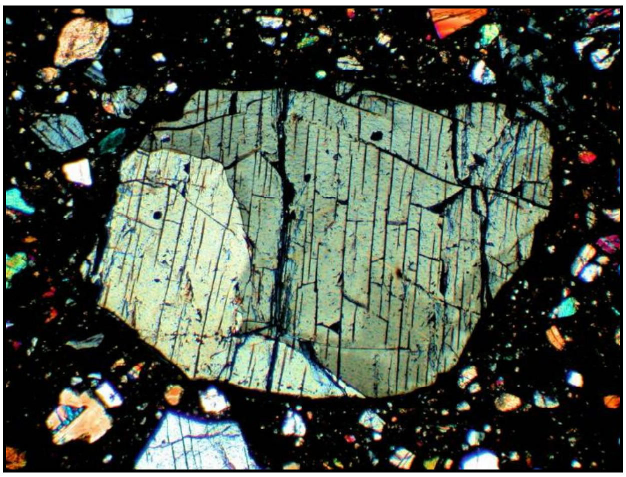

Figure 6. Orthopyroxene grain showing intense fracturing and weak undulatory extinction. Shock stage S2 (indicative of 5 – 10 Gpa). Crossed polars, picture width 4 mm. Photo: Kari A. Kinnunen.

The higher shock stage of eucritic clasts (Fig. 7) compared to diogenetic pyroxenes may suggest that the impacting was more severe on the lower level eucrites than on the deeper level diogenite layer.

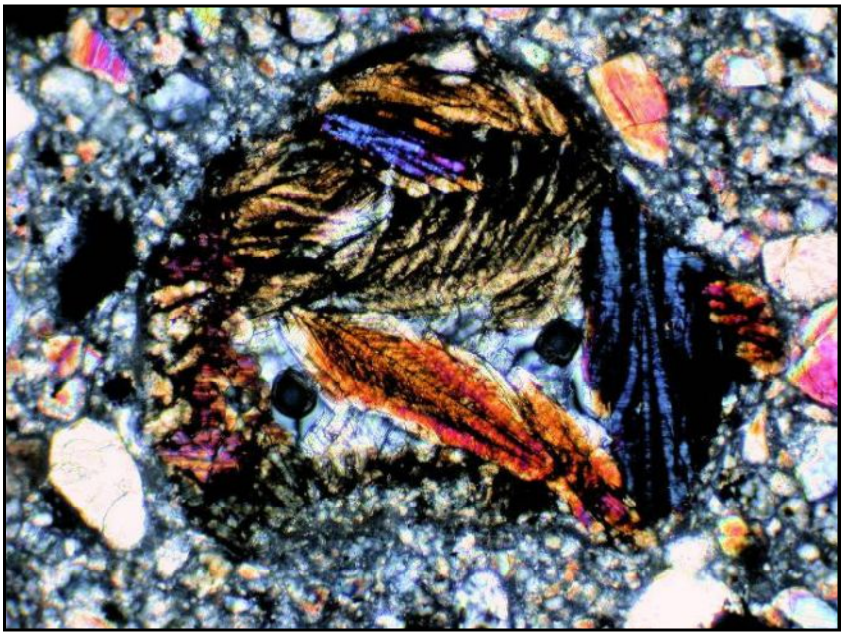

Figure 7. Impact (?) melted eucritic clast with dendritic clinopyroxenes. Shock stage S4 (indicative of 30 – 35 Gpa). Crossed polars, picture width 1.3 mm. Photo: Kari A. Kinnunen.

Weathering grade

The meteorite fragments were collected immediately after the fall. They were kept in plastic bags. The weathering grade classification is therefore 0.

Key information used for classification

Petrographic criteria

The meteorite is petrographically a polymictic breccia without any chondrules. The breccia clasts are mainly monomineralic orthopyroxene fragments of diogenetic type and more rarely roundish eucrite grains composed of plagioclase and pyroxene crystals in glassy material (Fig. 8). Some larger pyroxene grains contained glass inclusions.

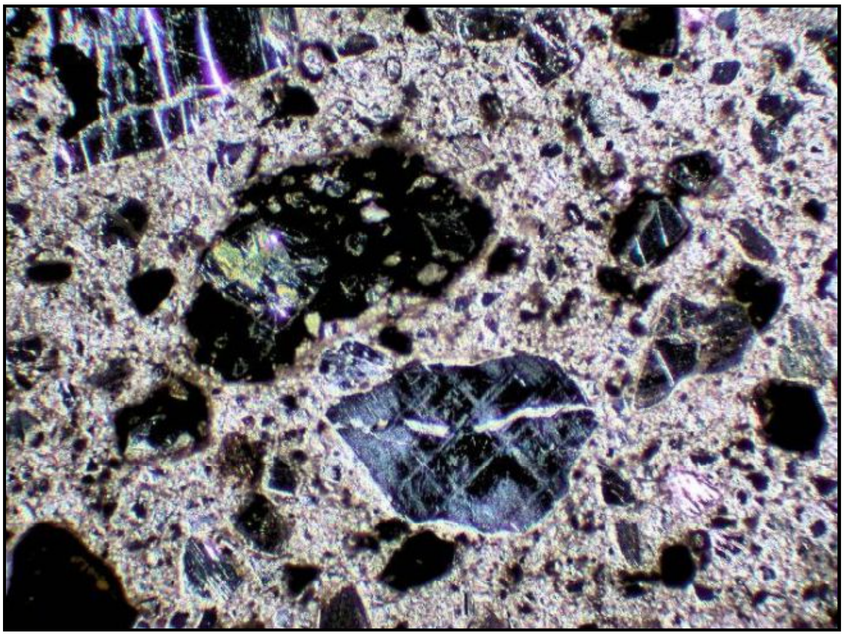

Figure 8. Polymictic breccia texture characterizing the meteorite. Crossed polars, picture width 4 mm. Photo: Kari A. Kinnunen.

Mineralogical criteria

Mineral chemical analyses were done with a Cameca SX100 electron microprobe. A typical diogenetic orthopyroxene fragment is composed of Wo 3.88, En 67.37, Fs 28.76, Ac 0.00, which corresponds to a hypersthene-like composition (Table 1). Eucritic pyroxene has a composition of Wo 15.01, En 39.61, Fs 45.39, Ac 0.00, which corresponds approximately to pigeonite (Table 2). The plagioclase composition in eucritic clasts lies is An_{79-87}, corresponding to bytownite (Table 3). Olivine ($Fa_{45.63-45.65}$) was analyzed only in one eucritic clast (Table 4). Troilites formed separate grains with the ideal composition (Table 5).

Table 1. Selected microprobe analyses showing the small compositional variation of one large (2.4 mm) diogenetic orthopyroxene grain.

SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	BaO	SrO	NiO	F	Cl	SO2	Total
51,14	0,14	0,88	0,76	20,83	0,64	17,93	5,79	0,00	0,02	0,04	0,12	0,00	0,13	0,02	0,00	98,43
51,34	0,25	0,91	0,61	20,80	0,81	17,97	5,59	0,00	0,01	0,00	0,10	0,00	0,14	0,02	0,00	98,54
51,00	0,22	1,10	0,76	21,53	0,75	18,00	4,49	0,00	0,00	0,03	0,21	0,00	0,12	0,00	0,02	98,23
51,39	0,11	0,85	0,58	23,62	0,72	18,53	2,37	0,01	0,04	0,00	0,09	0,03	0,18	0,00	0,03	98,56
53,98	0,08	0,66	0,87	14,13	0,31	26,84	0,89	0,00	0,00	0,00	0,20	0,00	0,10	0,00	0,00	98,05
54,33	0,10	0,55	0,74	14,47	0,32	26,95	0,83	0,00	0,01	0,00	0,20	0,07	0,13	0,01	0,04	98,74
54,14	0,17	0,61	0,73	14,50	0,35	26,94	0,90	0,00	0,00	0,03	0,11	0,00	0,15	0,01	0,02	98,64
54,01	0,02	0,60	0,65	14,60	0,41	26,84	0,94	0,00	0,02	0,00	0,07	0,01	0,21	0,01	0,00	98,39

Table 2. Selected microprobe analyses of eucritic clinopyroxene.

SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	BaO	SrO	NiO	F	Cl	SO2	Total
48,26	0,00	30,83	0,00	0,59	0,03	0,15	15,30	2,10	0,27	0,00	0,09	0,00	0,08	0,00	0,05	97,75
48,89	0,11	30,97	0,00	0,70	0,04	0,21	15,19	2,07	0,27	0,00	0,05	0,13	0,00	0,00	0,02	98,66
47,87	0,01	31,11	0,00	0,50	0,06	0,16	15,62	2,00	0,23	0,00	0,03	0,00	0,04	0,00	0,04	97,67
48,26	0,05	31,08	0,00	0,74	0,00	0,16	15,55	1,95	0,21	0,04	0,01	0,00	0,05	0,01	0,00	98,12
50,59	0,37	0,57	0,72	23,88	0,84	17,67	3,19	0,00	0,00	0,00	0,03	0,00	0,18	0,00	0,04	98,09
48,05	0,25	0,23	0,55	33,62	0,96	10,59	3,50	0,00	0,02	0,00	0,02	0,00	0,26	0,02	0,03	98,11
51,43	0,06	0,87	0,73	21,33	0,84	18,91	4,23	0,00	0,03	0,05	0,00	0,00	0,15	0,03	0,00	98,66
51,12	0,23	0,90	0,57	22,83	0,75	18,41	3,63	0,01	0,00	0,03	0,03	0,00	0,16	0,00	0,00	98,66
51,30	0,00	0,20	0,05	26,19	0,81	19,65	0,52	0,00	0,01	0,00	0,00	0,02	0,13	0,02	0,79	99,69
51,32	0,00	0,19	0,08	25,45	0,88	19,69	0,64	0,00	0,05	0,00	0,01	0,04	0,16	0,00	0,47	98,97

Table 3. Selected microprobe analyses of plagioclase crystals in a eucritic clast fragment.

SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	BaO	SrO	NiO	F	Cl	SO2	Total
48,26	0,00	30,83	0,00	0,59	0,03	0,15	15,30	2,10	0,27	0,00	0,09	0,00	0,08	0,00	0,05	97,75
48,89	0,11	30,97	0,00	0,70	0,04	0,21	15,19	2,07	0,27	0,00	0,05	0,13	0,00	0,00	0,02	98,66
47,87	0,01	31,11	0,00	0,50	0,06	0,16	15,62	2,00	0,23	0,00	0,03	0,00	0,04	0,00	0,04	97,67
48,26	0,05	31,08	0,00	0,74	0,00	0,16	15,55	1,95	0,21	0,04	0,01	0,00	0,05	0,01	0,00	98,12

Table 4. Selected microprobe analyses of olivine in a eucritic clast.

SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	BaO	SrO	NiO	F	Cl	SO2	Total
34,95	0,04	0,00	0,00	37,68	0,90	25,20	0,03	0,00	0,00	0,01	0,01	0,00	0,30	0,00	0,00	99,12
35,14	0,00	0,02	0,00	37,81	0,75	25,27	0,01	0,00	0,02	0,04	0,08	0,01	0,26	0,01	0,01	99,41

Table 5. Selected microprobe analyses of troilite aggregates.

Fe	S	Mn	Co	Ni	Cu	Zn	Te	As	Sb	Se	Ag	Cd	Total
63,14	35,89	0,01	0,00	0,01	0,00	0,05	0,05	0,05	0,00	0,00	0,02	0,00	99,22
62,48	35,77	0,04	0,00	0,00	0,00	0,00	0,11	0,00	0,04	0,00	0,00	0,00	98,44
63,12	35,64	0,01	0,00	0,00	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	98,84
64,47	35,73	0,00	0,00	0,03	0,00	0,00	0,05	0,05	0,00	0,01	0,00	0,00	100,33
63,58	36,13	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,00	0,02	0,00	0,00	99,75
63,43	36,05	0,01	0,00	0,00	0,00	0,00	0,04	0,00	0,00	0,00	0,05	0,00	99,58
63,71	36,12	0,03	0,00	0,00	0,00	0,03	0,00	0,01	0,00	0,00	0,00	0,00	99,90
64,14	36,59	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,01	0,03	0,00	0,00	100,81
63,34	36,55	0,00	0,00	0,00	0,01	0,06	0,08	0,00	0,00	0,00	0,00	0,02	100,05
62,97	36,12	0,00	0,02	0,02	0,01	0,00	0,00	0,04	0,00	0,02	0,00	0,00	99,19
63,52	36,12	0,00	0,00	0,00	0,00	0,00	0,00	0,11	0,00	0,00	0,00	0,00	99,75
62,97	36,42	0,00	0,00	0,00	0,00	0,02	0,07	0,00	0,00	0,00	0,00	0,00	99,48
63,05	36,33	0,00	0,00	0,00	0,03	0,02	0,00	0,00	0,00	0,00	0,03	0,00	99,46
63,95	36,46	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,01	0,00	100,43
62,83	36,69	0,01	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,03	0,00	0,00	99,59
63,26	36,45	0,01	0,00	0,01	0,00	0,03	0,00	0,00	0,00	0,01	0,05	0,00	99,80

Fusion crust

A glassy black fusion crust occurs on some surfaces of all meteorite fragments (Fig. 9). The thickness of the fusion crust varies from 0.2 to 0.3 mm (Fig. 10). In thin section the fusion crust is greenish brown and isotropic without any stress anisotropism. It is homogenous without any optically visible flow layers. The down part of the crust against the meteorite is principally composed of bubbles with thin walls between them. The upper part shows only a few bubbles. The mean bubble diameter is 0.1 mm. The chemical composition of the fusion crust in different analysis points is remarkably uniform, which indicates a very homogeneous nature of the glass material (Table 6). The main components show reasonable correlation with the chemical bulk composition (cf. Table 7).

Figure 9. A black fusion crust covered most of the meteorite samples. Picture width 4 cm. Photo: Kari A. Kinnunen.

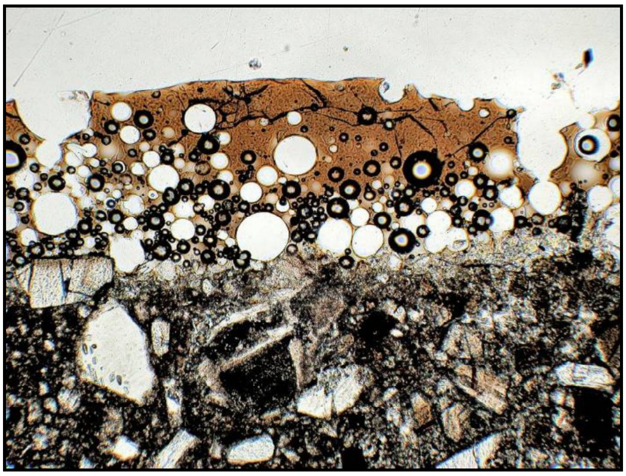

Figure 10. Cross section of the black fusion crust of the meteorite. The brownish glass layer is bubbly but rather homogeneous. Transmitted light, one polar, picture width 2 mm. Photo: Kari A. Kinnunen.

Table 6. Microprobe analyses of the fusion crust.

SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	BaO	SrO	NiO	F	Cl	SO2	Total
49,12	0,47	9,54	0,36	16,42	0,50	11,79	7,77	0,27	0,07	0,00	0,12	0,02	0,16	0,00	0,03	96,65
48,57	0,51	9,54	0,39	17,19	0,42	11,74	7,82	0,26	0,06	0,00	0,14	0,11	0,19	0,01	0,00	96,95
49,30	0,68	9,21	0,36	16,67	0,54	11,69	7,70	0,29	0,04	0,00	0,15	0,03	0,13	0,01	0,01	96,81
48,80	0,32	9,52	0,34	16,54	0,48	11,88	7,77	0,29	0,06	0,00	0,17	0,07	0,17	0,01	0,04	96,45
48,99	0,60	9,41	0,43	16,56	0,42	11,93	7,77	0,25	0,06	0,00	0,12	0,07	0,16	0,02	0,00	96,78

Matrix material, mineralogical composition

The matrix is friable and powdery without any glass impregnated cohesion (Fig. 8). The fine grain size made optical mineral identification very difficult. For this reason small fragments of the powdery matrix material were analyzed with the X-ray diffraction method. The mineral possibilities selected for peak measurements were selected according to microprobe data on minerals. They were ferroan enstatite, pigeonite and anorthite.

Bulk chemical composition

Homogeneous fragments without fusion crust were selected for the chemical analysis. The total weight of the analyzed material was about 10 g. The results are presented below in Table 7.

Table 7. Bulk chemical composition of the Kilimani howardite. Analytical techniques: (1) multielement determination by XRF technique (pellet), (2) elemental determination by the ICP-MS technique and (3) determination of C with carbon analyzer and S with sulfur analyzer.

Component and unit	**Contents**	**Technique**
SiO_2 (%)	48.3	1
Fe_2O_3 (%)	19.5	1
MgO (%)	12.9	1
Al_2O_3 (%)	10.2	1
CaO (%)	6.93	1
MnO (%)	0.506	1
TiO_2 (%)	0.468	1
Cr (%)	0.430	1
Na2O (%)	0.32	1
S (%)	0.174	1
C (%)	0.05	3
K_2O (%)	0.045	1
P_2O_5 (%)	0.041	1
Cl (%)	<0.006	1
Ni (%)	0.003	1
Cu (%)	<0.002	1
Zn (%)	<0.002	1
Ga (%)	<0.002	1
As (%)	<0.003	1
Sr (%)	0.006	1
Mo (%)	<0.001	1
Sn (%)	<0.002	1
Sb (%)	<0.01	1
Ba (%)	0.004	1

Component and unit	Contents	Technique
Pb (%)	<0.003	1
Bi (%)	<0.003	1
Ce (ppm)	5.14	2
Co (ppm)	10.2	2
Dy (ppm)	2.07	2
Er (ppm)	1.33	2
Eu (ppm)	0.41	2
Gd (ppm)	1.79	2
Hf (ppm)	0.84	2
Ho (ppm)	0.45	2
La (ppm)	2.07	2
Lu (ppm)	0.19	2
Nb (ppm)	2.39	2
Nd (ppm)	3.81	2
Pr (ppm)	0.77	2
Rb (ppm)	0.74	2
Sc (ppm)	24.1	2
Sm (ppm)	1.19	2
Ta (ppm)	<0.2	2
Tb (ppm)	0.33	2
Th (ppm)	<0.5	2
Tm (ppm)	0.19	2
U (ppm)	<0.2	2
V (ppm)	98.9	2
Y (ppm)	11.5	2
Yb (ppm)	1.15	2
Zr (ppm)	30.4	2

Interpretation of bulk chemical composition:

Gunn (2006) has compiled 263 HED meteorite bulk analysis and plotted the main oxides on MgO and CaO variation diagrams. In these diagrams the analysis of Kilimani fragments (Table 7) is placed on howardite field near pure eucrites (Fig. 11).

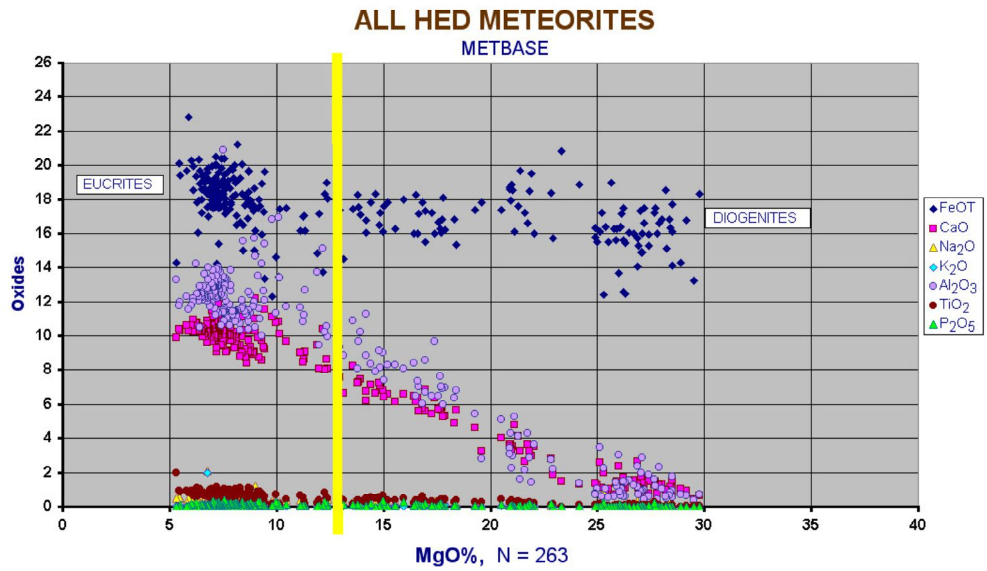

Figure 11. Yellow bar depicts the MgO contents of the new Kilimani meteorite. Other oxides in the bulk chemical analysis obeys the trends in the diagram. The background diagram is published by Gunn (2006). It summarizes the analysis of 263 HED meteorites.

Warren et al. (2009) have analyzed the bulk major and trace-element compositions of 104 HED meteorites including 30 howardites. Many of these were not previously analyzed and therefore not included in the analyses plotted in Figure 11. The analysis in Table 7 has many similarities to regolithic howardites, when compared to Figs. 1-3 in Warren et al. (2009). However, the element ratios are still on the side of ordinary howardites. Likewise, the absence of spheroidal turbid-brown glass masses indicates fragmental breccia origin with no petrographic indications of regolith origin.

Unusual properties

Because of the impact breccia origin of howardites, they may contain rare rock clasts. The samples studied are mainly monomict diogenetic breccia with only scanty eucritic clasts. The material represents a typical howardite. As indicated earlier the absence of petrographic features, indicating of regolithic origin (see Warren et al. 2009), points to fragmental breccia. Some rare types of rock clasts, however, can be observed. They are explained in the following.

Unusual components

In addition to the common diogenetic and eucritic rock and mineral clasts the meteorite contains shock melted mainly eucritic clasts. They have a glassy matrix and dendritic forms in the clinopyroxenes. Chondritic clasts were not observed in this howardite. One unusual spinel type was observed in the microprobe analyses (Table 8). It may represent interplanetary dust (IDP) or it may be some unusual chromite originating from diogenites.

Table 8. Microprobe analyses of an unknown spinel.

SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	BaO	SrO	NiO	F	Cl	SO2	Total
0,06	1,40	20,13	42,64	33,04	0,00	1,46	0,05	0,00	0,00	0,02	1,76	0,00	0,18	0,02	0,00	100,75
0,19	1,70	19,77	41,57	32,75	0,00	1,40	0,05	0,00	0,00	0,00	1,85	0,00	0,20	0,00	0,00	99,48
0,09	1,69	20,09	42,09	33,34	0,00	1,37	0,03	0,00	0,00	0,00	1,71	0,05	0,05	0,02	0,08	100,62

Most sulfides in the meteorite could be identified as troilite. One sulfide aggregate or clast was composed of pyrite type sulfide material (Table 9). This is unusual in brecciated HED achondrites.

Table 9. Microprobe analyses of a pyrite-like aggregate.

Fe	S	Mn	Co	Ni	Cu	Zn	Te	As	Sb	Se	Ag	Cd	Total
50,20	49,69	0,01	0,00	0,01	0,00	0,04	0,02	0,03	0,00	0,00	0,01	0,00	100,00
50,03	49,89	0,03	0,00	0,00	0,00	0,00	0,04	0,00	0,01	0,00	0,00	0,00	100,00
50,39	49,56	0,01	0,00	0,00	0,00	0,00	0,00	0,04	0,00	0,00	0,00	0,00	100,00
50,85	49,08	0,00	0,00	0,02	0,00	0,00	0,02	0,03	0,00	0,00	0,00	0,00	100,00
50,25	49,73	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,00	0,01	0,00	0,00	100,00
50,23	49,72	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,02	0,00	100,00
50,29	49,66	0,02	0,00	0,00	0,00	0,02	0,00	0,01	0,00	0,00	0,00	0,00	100,00
50,14	49,82	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,02	0,00	0,00	100,00
49,83	50,08	0,00	0,00	0,00	0,01	0,04	0,03	0,00	0,00	0,00	0,00	0,01	100,00
49,99	49,94	0,00	0,01	0,02	0,01	0,00	0,00	0,02	0,00	0,01	0,00	0,00	100,00
50,21	49,73	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00	100,00
49,80	50,16	0,00	0,00	0,00	0,00	0,02	0,03	0,00	0,00	0,00	0,00	0,00	100,00
49,88	50,07	0,00	0,00	0,00	0,02	0,02	0,00	0,00	0,00	0,00	0,01	0,00	100,00
50,17	49,82	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00
49,56	50,41	0,01	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,02	0,00	0,00	100,00
49,89	50,06	0,01	0,00	0,01	0,00	0,02	0,00	0,00	0,00	0,01	0,02	0,00	100,00
50,17	49,75	0,00	0,00	0,00	0,00	0,00	0,03	0,04	0,00	0,01	0,00	0,00	100,00
49,90	50,05	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	100,00
50,09	49,83	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,02	0,00	0,03	0,01	100,00
49,84	50,13	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,01	0,00	0,00	100,00

Personal information for meteoritical society

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Kristian Lindqvist, GTK (organizator of the rescue collecting of the meteorite specimens, X-ray diffraction studies)
Lassi Pakkanen, GTK (electron microprobe analytics)
Chemical laboratory of GTK (presently Labtium Ltd., Finland)
Augustina Rutaihwa (local contact person)

Institution where the type specimen has been deposited:
Geological Survey of Tanzania, Dodoma, Tanzania

Mass of type specimen: 94.2 g (original piece)

Main mass of the meteorite at: Geological Survey of Tanzania, Dodoma

Whom to contact to obtain specimens: Professor Abdulkarim Mruma, Geological Survey of Tanzania, Dodoma

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