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Meteorites from Botswana

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Abstract–In 1999, the first meteorites from Botswana were recovered. Most samples (seven) were purchased from natives in the small village of Kuke. We suggest that these samples were found close to Kuke in the Kalahari desert. As reported by the finder, the other four samples were recovered during geological field work in various areas of Botswana in April (Mabe), September (Kalahari 008 and 009), and November 1999 (Matisama). Kalahari 008 and Kalahari 009 were found close to the small village of Kuke and are chemically and petrographically different lunar rocks. However, we suggest that both samples represent distinct lithologies of one meteoroid and that the lunar sample broke apart at the find site. The other nine samples are H-group ordinary chondrites. Based on different petrologic types, the degrees of shock metamorphism and weathering pairing of most samples can be ruled out. We conclude that only Kalahari 004 and Kalahari 005 are paired.

INTRODUCTION

According to Grady (2000) and Koblitz (2003), no meteorites were known from Botswana until recently. In 1999, 11 meteorites were recovered from various locations in Botswana. The coordinates of the find locations are known for four samples (Kalahari 008, 009, Mabe, and Matisama). Seven samples were bought from natives in the small village of Kuke. We suggest that these meteorites were recovered within the Kalahari desert close to Kuke. Figure 1 shows the find locations and the town of Kuke in Botswana. Table 1 lists the coordinates and masses of all the samples.

In this study, we have investigated thin sections from all 11 Botswana meteorites to obtain a proper classification of these rocks. Classifications and preliminary data will be published in the Meteoritical Bulletin (Russell et al. 2005).

ANALYTICAL PROCEDURES

Polished thin sections of all the meteorites were studied by optical microscopy in transmitted and reflected light. A JEOL 840A scanning electron microscope (SEM) was used to resolve the fine-grained texture of the rocks. Mineral analyses were obtained with a JEOL JXA-8600 S electron microprobe operating at 15 kV and a probe current of 15 nA. For Kalahari 006 and 007 only, some mineral data were obtained with the JEOL 840A SEM equipped with a Pentafet-detector (Oxford Instruments) for energy dispersive analysis (EDS, INCA). Using the SEM for quantitative analysis, the samples and appropriate mineral standards were measured at an excitation voltage of 20 kV, and the beam current constancy was controlled by a Faraday cup. Repeated analyses of the same areas and the comparison with data obtained with the electron microprobe demonstrated the reproducibility of the system. All data were corrected using the ZAF correction procedures.

RESULTS

Based on petrographical and chemical studies, nine of the Botswana meteorites are ordinary chondrites. Table 2 summarizes the classification data of these rocks. The table includes the chondrite group, the petrologic types (Van Schmus and Wood 1967), the shock stages (Stöffler et al. 1991), and the weathering degrees (Wlotzka 1993), as well as the average compositions of olivine and pyroxene within the analyzed samples.

Two Botswana samples are lunar meteorites. Kalahari 008 is an anorthositic breccia, while Kalahari 009 can best be characterized as a brecciated VLT mare basalt. In addition to the data presentation, possible pairings of the samples will be discussed.

Mabe (H5)

Mabe is a single rock of 378 g and was found in April 1999 by an anonymous finder near the village of Mabe. It appears brownish and is heavily affected by terrestrial

Fig. 1. Find locations of meteorites from Botswana.

weathering. By far, the majority of metal has been removed and replaced by Fe-oxides/-hydroxide (W3; Wlotzka 1993).

Mabe is a typical type 5 ordinary chondrite with a partly recrystallized texture. The overall chondritic texture is hardly visible; only relics of chondrules are detectable.

According to the shock classification scheme of Stöffler et al. (1991), the rock is very weakly shocked (S2). Olivine shows undulatory extinction and contains irregular fractures. Planar fractures are not obvious in the large olivine grains. Based on the size of the studied thin section (~0.5 cm^2), Mabe is unbrecciated.

The main silicates are olivine, pyroxene, and plagioclase. All these phases are quite homogeneous in composition. For classification, 87 olivines and 47 low-Ca pyroxenes were randomly selected and analyzed (Figs. 2 and 3). The mean Fa content of olivine is 19.1 ± 0.5. Low-Ca pyroxene is also uniform in composition (Fs: 17.1 ± 0.5). The analyzed

Table 1. Find locations and masses of 11 meteorites from Botswana.[a]

Name	Latitude	Longitude	Weight (g)
Matisama	21.09°S	26.49°E	187
Mabe	21.30°S	24.10°E	378
Kalahari 001	Unknown	Unknown	150
Kalahari 002	Unknown	Unknown	141
Kalahari 003	Unknown	Unknown	827
Kalahari 004	Unknown	Unknown	87
Kalahari 005	Unknown	Unknown	220
Kalahari 006	Unknown	Unknown	157
Kalahari 007	Unknown	Unknown	72
Kalahari 008	20.98°S	22.98°E	598
Kalahari 009	20.98°S	22.98°E	13500

[a]The Kalahari 001–007 samples were purchased in Kuke in 1999.

plagioclases have an An content between 10.1 and 16.3 mol% (mean = 13.3 ± 1.8). Other present phases include Ca-rich pyroxene, troilite, and Fe, Ni-metal.

Matisama (H4/5)

Matisama was found as an individual rounded rock, covered by black fusion crust, 187 g in weight.

The essential mineralogy of the meteorite is dominated by olivine and low-Ca pyroxene. Plagioclase, Ca-rich pyroxene, troilite, and Fe, Ni-metal are also noted as major and minor minerals. Microprobe analyses gave a mean Fa content of olivine of 18.9 ± 0.8 mol% (n = 74) and a mean Fs content of low-Ca pyroxene of 16.7 ± 0.7 mol% (n = 31). These compositions are typical for H-group chondrites and the uniformity is consistent with the classification of equilibrated, metamorphosed chondrites (Figs. 2 and 3). Petrographically, the rock displays a few intact, sharp defined chondrules, and the matrix is partly recrystallized (H4/5).

Based on the shock classification scheme of Stöffler et al. (1991), the rock is weakly shocked (S3). The olivine shows undulatory extinction and contains obvious planar fractures. Undulatory extinction was also noted in plagioclase.

The degree of weathering (W2) was obtained according to the classification system of Wlotzka (1993). In thin section,

Table 2. Classification of the chondrites.[a]

Name	Class	Shock	Weathering	Fa	Fs	Comments
Matisama	H4/5	S3	W3–4	18.9	16.7	–
Mabe	H5	S2	W3	19.1	17.1	–
Kalahari 001	H4/5	S2	W2–3	18.8	16.7	–
Kalahari 002	H5	S2	W3–4	20.6	17.5	sv
Kalahari 003	H5/6	S1	W4	19.1	17.1	–
Kalahari 004	H5	S3	W3–4	18.8	16.9	sv
Kalahari 005	H5	S3	W3–4	18.9	17.0	sv, calc. v.
Kalahari 006	H5	S2	W3–4	18.0	16.0	–
Kalahari 007	H4	S2	W3–4	17.1	15.0	–

[a]Shock and weathering classifications are according to Stöffler et al. (1991) and Wlotzka (1993). The samples Kalahari 004 and Kalahari 005 are probably paired. sv = shock veins, calc. v. = severe calcite veining.

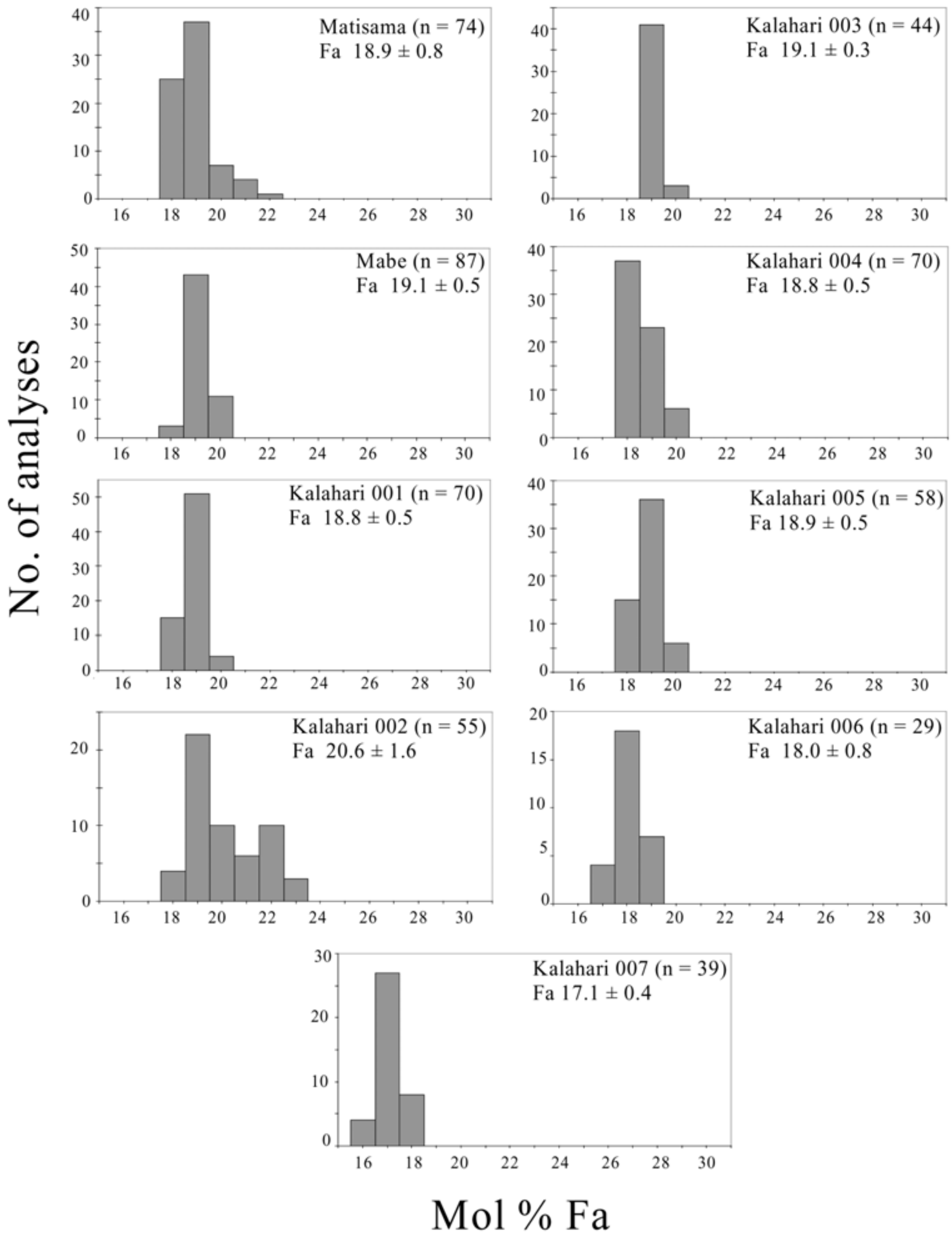

Fig. 2. Histograms showing the distribution of olivine composition in the classified chondrites (n = number of analyses, Fa = fayalite). The mean values and standard deviations are given for all individual chondrites.

the partial replacement of metal and, consequently, the formation of oxide/hydroxide veins is obvious; but, most of the metals are still preserved.

Kalahari 001–007

The seven meteorites Kalahari 001–007 are ordinary chondrites. According to the Fa content in olivine and the Fs content in pyroxene (Figs. 2 and 3), all of them can be assigned to the H chondrite group. Petrologically, they are slightly (Kalahari 007 [H4]; Fig. 4a) to moderately metamorphosed (mostly H5). The equilibrated chondrites from Kalahari exhibit the typical homogeneity of olivines and pyroxenes. Kalahari 002 has some significant differences. Although most olivines and pyroxenes have Fa and Fs contents of 18–20 and 16–18 mol%, respectively, olivines and pyroxenes with aberrant Fe/(Fe + Mg) ratios ($Fa_{21–23}$ and $Fs_{19–21}$, respectively) are detected. The standard deviations of the mean Fs and Fa values are more than five percent like those of unequilibrated (type 3) ordinary chondrites (Figs. 2 and 3). However, based on the texture, Kalahari 002 must clearly be assigned to a metamorphosed,

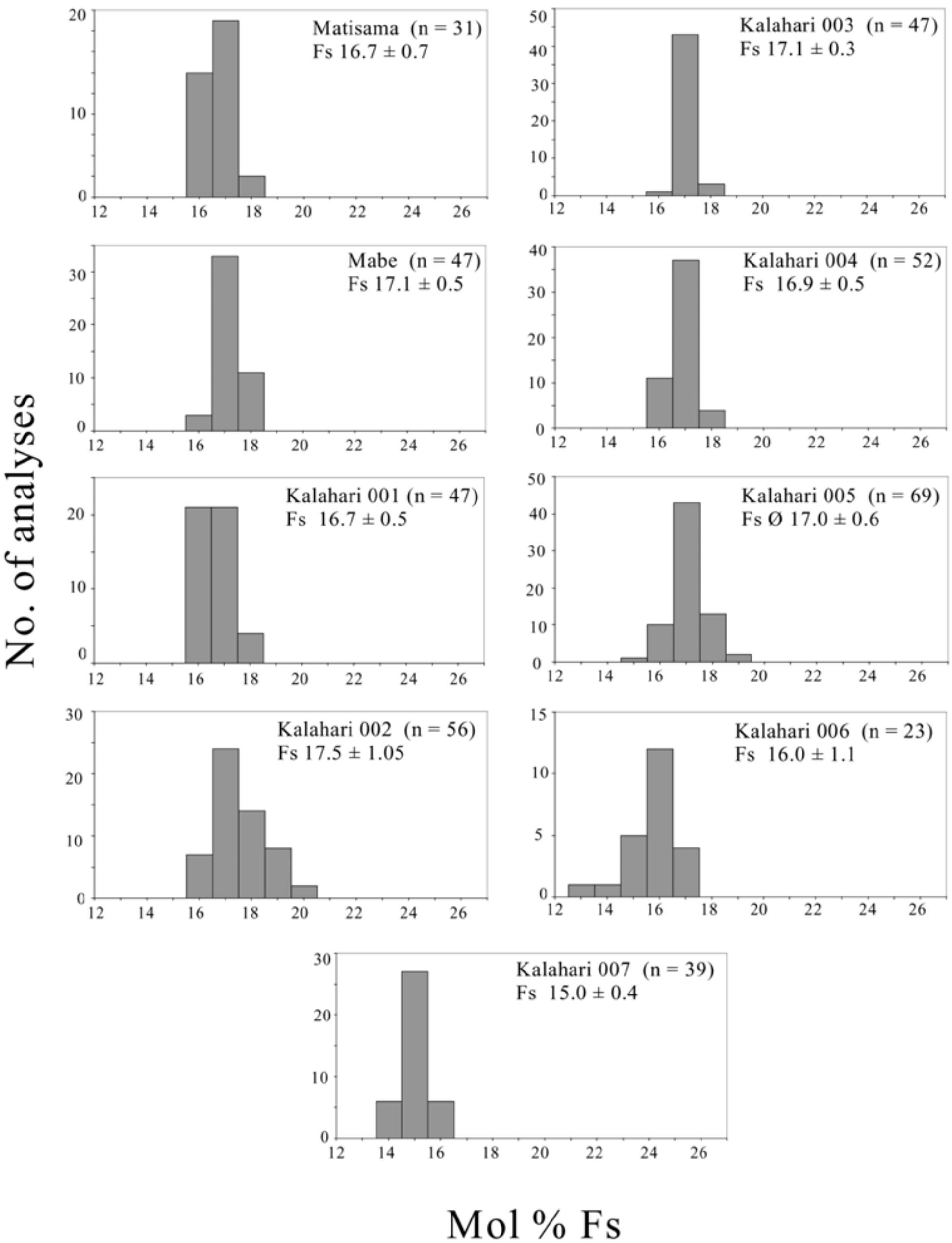

Fig. 3. Histograms showing the distribution of pyroxene composition in the classified chondrites (n = number of analyses, Fs = ferrosilite). The mean values and standard deviations are given for all individual chondrites.

type 5 ordinary chondrite. Since Kalahari 002 is unbrecciated in the studied thin section, the identification of specific clasts with silicates richer in FeO than in the host chondrite was impossible. According to Scott et al. (1985), some chondrites exist that are not obviously brecciated but have ingredients that have not experienced the same degree of metamorphism as the host material. These rocks may represent post-metamorphic, fragmental breccias (Scott et al. 1985).

The degree of shock metamorphism was obtained according to the classification system of Stöffler et al. (1991). The results are given in Table 2. Most chondrites are of shock stage S2; some others are S3 (Fig. 4b) and S1. No chondrite was observed that had experienced moderate to very strong shock metamorphism (S4–S6). Nonetheless, some of the meteorites contain shock veins (Fig. 4c).

Generally, the analyzed meteorites are moderately (W2) to heavily (W4) weathered. In thin section, the replacement of metals and (to lesser degree) troilite by Fe oxides and hydroxides is obvious. In many cases, cracks and mineral fractures are filled with oxides/hydroxides. In Kalahari 005, terrestrial weathering resulted in severe calcite veining.

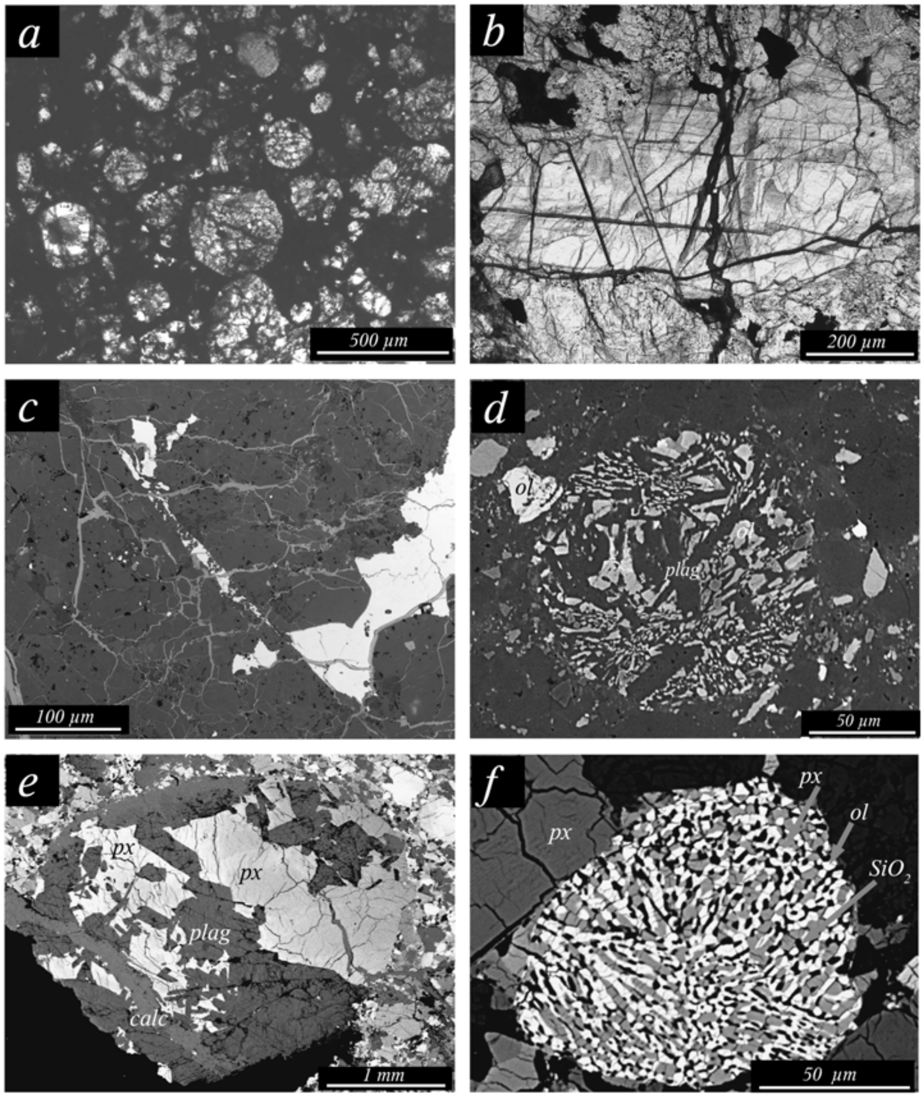

Fig. 4. a) Photograph of the ordinary chondrite Kalahari 007 (H4) showing the typical chondritic texture. Transmitted light; b) olivine with planar fractures in the weakly shocked H5 (S3) chondrite Kalahari 005. Transmitted light; c) reflected light image of an opaque shock vein cutting and shearing metal grains in the H5 (S3) chondrite Kalahari 004; d) backscattered electron image showing a devitrified glass spherule within the lunar regolith breccia Kalahari 008; e) backscattered electron image of a typical basaltic fragment in the sample Kalahari 009; f) backscattered electron image showing a symplectite within the sample Kalahari 009.

Kalahari 004 and Kalahari 005 belong to the same chemical class and petrologic type. They exhibit the same composition of olivine and pyroxene and show almost identical degrees of shock metamorphism and weathering. For these reasons and due to optical similarities in hand specimen and thin section, pairing of these samples is probable.

Kalahari 008

The finder reported that Kalahari 008 was found during geological field work in September 1999 close to Kalahari 009 (see below) in front of a small dune within the Kalahari desert near the village of Kuke (Fig. 1). This rock, 598 g in weight, is an anorthositic breccia having typical clasts of lunar highland breccias (e.g., feldspathic crystalline melt breccias, granulitic lithologies, cataclastic anorthosites, etc.) embedded within a well-lithified matrix. An impact melt spherule (Fig. 4d) indicates that this rock derives from the regolith. With respect to the rarity of melt spherules and to the low concentrations of solar wind implanted rare gases (L. Schultz, personal communication; Bischoff et al. Forthcoming), this meteorite appears to be a very immature surface sample.

In Kalahari 008, all clasts are shocked to almost the same degree. Characteristic shock features include mosaicism and planar fracturing in feldspar and olivine as well as localized impact melting. The transformation of plagioclase to maskelynite is visible in some locations. Such shock effects are typical for shock pressures of at least 15–20 GPa according to the calibration scheme of Stöffler et al. (1988) for ordinary chondrites (S4).

The analyzed phases within lithic and mineral clasts are plagioclase (n = 44), pyroxene (n = 31), and olivine (n = 32). Minor and trace minerals include ilmenite, troilite, Fe, Ni metal, chromite, and ulvöspinel.

Olivines are much less frequent and are, on average, smaller than pyroxene crystals and display a distinct bimodal distribution in composition (~$Fa_{42–66}$ and $Fa_{78–98}$; Fig. 5). The Fa-rich olivines exist as individual mineral fragments within the clastic matrix. Lithic clasts containing these olivines have not been observed. Pyroxenes show a wide range of compositions ($Fs_{14–77}Wo_{0.5–39}En_{8–76}$). Some pyroxene clasts have exsolution lamellae up to 8 μm wide. Most plagioclases in clasts and matrix are anorthites ($An_{92–99}$; Fig. 6), typical of lunar highland mineralogy. The major element compositions are determined by a combination of instrumental neutron activation analysis (INAA) and X-ray fluorescence technique (XRF; H. Palme, G. Weckwerth, personal communication; Bischoff et al. Forthcoming). The concentrations of selected elements are (in wt%): Al: 14.68; Si: 20.73; Mg: 2.68; Fe: 3.5; Ca: 11.1. The oxygen isotopes are as follows: $\delta^{18}O = +6.52$; $\delta^{17}O = +3.32$; $\Delta^{17}O = -0.07$ and are typical for lunar meteorites (R. N. Clayton, personal communication; Bischoff et al. Forthcoming). Further data on the chemistry and mineralogy of this rock will be published separately (Bischoff et al. Forthcoming).

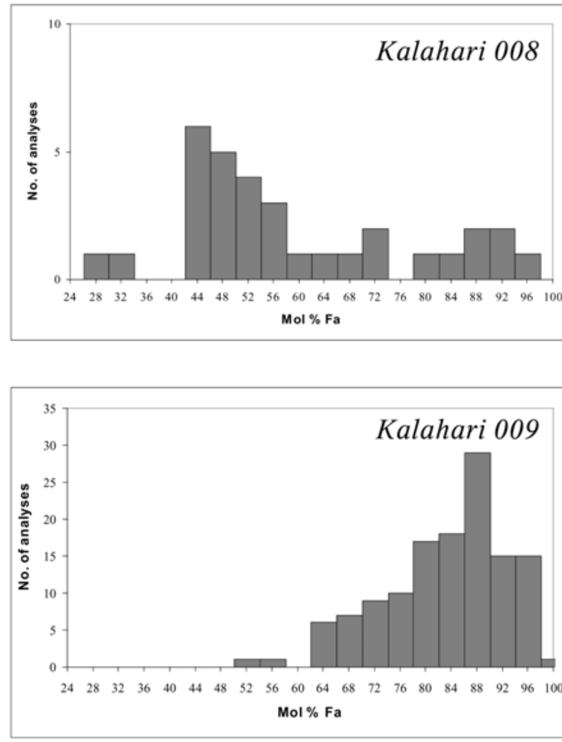

Fig. 5. Histograms showing the distribution of olivine composition in the anorthositic breccia Kalahari 008 and the VLT mare basalt Kalahari 009 (Fa = fayalite).

Kalahari 009

As reported by the finder, Kalahari 009 was found during geological field work roughly 50 m apart from Kalahari 008 in front of a small dune in September 1999 (Fig. 1). It is a single rock of about 13.5 kg. Compositionally and texturally, it differs from Kalahari 008. Kalahari 009 is a fragmental breccia consisting of fragments of basaltic lithologies embedded in a fine-grained matrix. The basaltic clasts have a coarse-grained subophitic texture (Fig. 4e). The clasts and matrix display the same composition. The main constituents are predominantly pyroxene followed by plagioclase. Olivine occurs less frequently. The accessory minerals are ilmenite, chromite, troilite, ulvöspinel, and Fe, Ni metal (having about 0.6 wt% Ni). Most pyroxenes display small exsolution lamellae (mostly <5 μm). "Bulk" pyroxene grains are composites of pigeonite and augite ranging in composition from $Fs_{22–67}En_{10–64}Wo_{6–41}$ (Fig. 7). Some grains without visible exsolution lamellae clearly show zonation from $Fs_{32–36}En_{48–56}Wo_{10–15}$ to $Fs_{49–52}En_{28–34}Wo_{16–20}$.

Most feldspars are anorthites ($An_{>90}$), but some are more sodic. In two clasts, An contents of plagioclase as low as 72 and 75 mol% have been measured (Fig. 6). The chemical composition of fine-grained olivine is FeO-rich, ranging

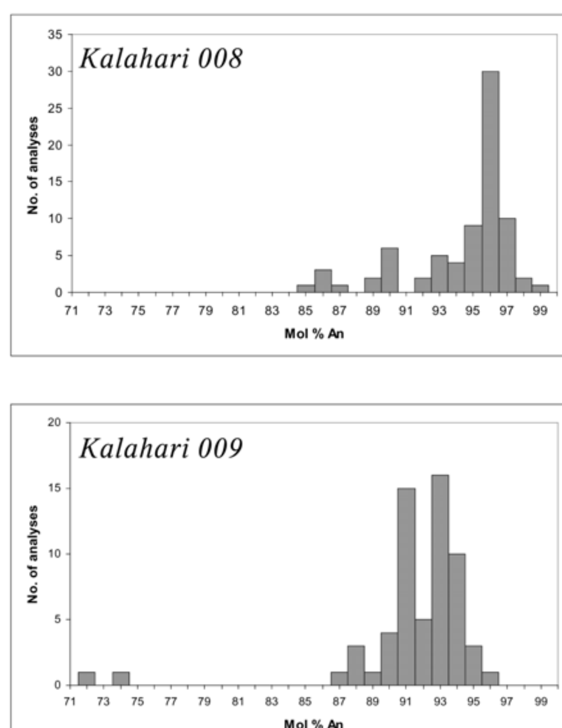

Fig. 6. Distributions of plagioclase compositions within Kalahari 008 and Kalahari 009 (An content in mol%).

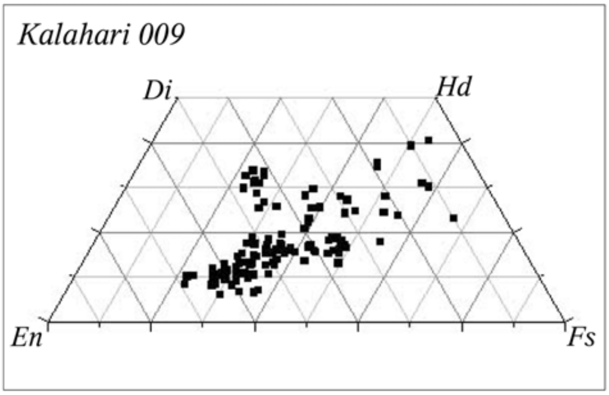

Fig. 7. Compositions of pyroxene in Kalahari 009. Please note that most pyroxenes contain small exsolution lamellae. Therefore, mixtures of augite and pigeonite were analyzed in most cases.

from $Fa_{50–99.9}$ (Fig. 5). Symplectitic intergrowths of hedenbergite + fayalite + SiO_2 are abundant in Kalahari 009 (Fig. 4f). Such symplectites have been reported in some other lunar and martian basalts, such as Asuka 881757 (Oba and Kobayashi 2001), Northwest Africa (NWA) 773 (Joliff et al. 2003), Los Angeles, and Queen Alexandria Range (QUE) 94201 (Armorovich et al. 2002). They are interpreted to be the result of pyroxferroite breakdown upon cooling (Papike et al. 1998).

In Kalahari 009, all fragments are shocked to almost the same degree. The characteristic shock features include mosaicism and planar fracturing in feldspar and olivine as well as localized impact melting. In some areas of the sample, the clastic matrix is shock melted leading to a strong lithification of the entire rock. The transformation of plagioclase to maskelynite is visible in some locations. Such shock effects are typical for shock pressures in excess of 15–20 GPa according to the calibration scheme of Stöffler et al. (1988) for ordinary chondrites (S4).

Calcite deposits are the most obvious terrestrial alteration, and they occur throughout the meteorite in the form of fracture fillings. The weathering grade of metals is W1, according to the classification scheme of Wlotzka (1993).

The major element compositions are determined by a combination of instrumental neutron activation analysis (INAA) and X-ray fluorescence technique (XRF; H. Palme, G. Weckwerth, personal communication; Bischoff et al. Forthcoming). The concentrations of the selected elements are (in wt%): Al: 6.76; Mg: 5.14; Fe: 12.47; Ca: 7.66; Ti: 0.27. Considering the bulk composition in combination with mineralogical observations, Kalahari 009 is compatible with a VLT lunar mare basalt. Zr/Hf = 30.2 and Nb/Ta = 17.4 are typical for lunar rocks (C. Münker, personal communication; Bischoff et al. Forthcoming). The oxygen isotopes are as follows: $\delta^{18}O = +6.87$; $\delta^{17}O = +3.45$; $\Delta^{17}O = -0.07$, which is consistent with a lunar origin (R. N. Clayton, personal communication; Bischoff et al. Forthcoming). Further data on the chemistry and mineralogy of this rock will be published separately (Bischoff et al. Forthcoming).

CONCLUSIONS AND SUMMARY

Nine of the Botswana meteorites belong to the H-group of ordinary chondrites. Based on the different find locations and/or similarities in mineral chemistry, the degree of shock metamorphism, texture, and terrestrial weathering effects, only pairing of Kalahari 004 and Kalahari 005 is probable. All the others appear to belong to separate meteorite falls. Based on textural appearance, Kalahari 007 has the most obvious chondritic texture with well-defined chondrules and cannot be paired with the type 5 chondrites or with Kalahari 003 (H5/6), which is the most recrystallized rock. In addition, Kalahari 007 also has the lowest Fa and Fs contents of olivine and pyroxene, respectively, among the ordinary chondrites from Botswana. Further, Kalahari 003 is unshocked (S1) and is certainly not paired with the weakly shocked chondrites (S3). Unfortunately, terrestrial weathering has severely affected the mineralogy of most the samples. The freshest chondrite is Kalahari 001 (H4/5), in which about half of the metal is preserved.

The most spectacular samples are the lunar meteorites Kalahari 008 and Kalahari 009. They were found about 50 m apart. Although they represent different rock types (anorthositic breccia versus basaltic breccia), we suggest that they belong to one meteorite fall. It would be very surprising to find two individual lunar meteorites this close to each other. The compositions of olivines in both samples also indicate some similarities. Most olivines in the basaltic rock Kalahari 009 have Fa contents above 80 mol% (Fig. 5). Such high Fe concentrations in olivine are uncommon in many other anorthositic highland breccias (e.g., Dar al Gani 262 [up to Fa_{71}; Bischoff et al. 1998], Dhofar 081 [up to Fa_{46}; Bischoff 2001]). As shown in Fig. 5, the olivine compositions of the anorthositic breccia Kalahari 008 show a bimodal distribution. Most olivines have Fa contents up to about 70 mol% (peak at about 46 mol% Fa), but several analyzed olivines have significantly higher Fa contents of about 90 mol% (Fig. 5). These grains, chemically similar to those in Kalahari 009, occur as individual mineral fragments within the clastic matrix. We conclude that the latter olivines in the Kalahari 008 anorthositic breccia were originally derived from fragmented basalts (like Kalahari 009). These fragments must have been incorporated into the Kalahari 008 breccia during impact-induced fragmentation, mixing, and relithification. This may indicate that the Kalahari 008 breccia was formed in close vicinity to the Kalahari 009 basalt and that both texturally different rock types were ejected from the Moon as one polymict meteoroid.

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