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REEXAMINATION OF MOCS AND TAUTI CHONDRITIC METEORITES: CLASSIFICATION WITH SHOCK DEGREE

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Abstract: The Mocs meteorite, which fell on February 3, 1882, in Transylvania over a large area (15 km by 3 km) has been reclassified from a L6 to a L5-6 chondrite in this study. Six fragments of the Mocs chondrite were observed by optical microscopy and measured using electron microprobe analyses and standard wet chemical analysis. Although the petrologic type of the 6 samples is almost the same, 2 fragments: Mocs-1 and Mocs-3 show heterogeneous features (opaque shock veins and melt pockets) due to different shock degrees (S-5 and S-4, respectively). Therefore the mean shock degree of the Mocs chondrite was found to be S3-5. The Tauti meteorite which fell in 1937 in Transylvania was previously classified as L6 chondrite using the bulk chemical analyses of H. SAVU (St. Cerc. Geol., **2**(IV), 272, 1959) (A. L. GRAHAM; Meteoritics, **14**, 1, 1979; A. L. GRAHAM *et al.*; Catalogue of Meteorites, London, British Museum, Natural History, 1985). The chemical compositions of olivines and orthopyroxenes determined by electron microprobe analyses, the bulk chemical analysis, along with textural characteristics classify Tauti shower as L6 chondrite with a shock degree of S-3.

1. Introduction

The purpose of this paper is to check the heterogeneity and the shock degree of the Mocs and Tauti meteorite showers using bulk chemical analysis and optical and electron microprobe analyses. Up to now 8 meteorites (7 falls and 1 find) have been registered and investigated in Romania (DEMETRESCU, 1928; MAXIM, 1968; BEDELEAN *et al.*, 1979; GRAHAM *et al.*, 1985) and are listed in Table 1.

The Mocs (syn. Moci) meteorite fell on February 3, 1882, 16.00 hrs, in Transylvania (Cluj District). After appearance of luminous meteor and detonations, a shower of stones fell over a large area (15 km by 3 km) which includes Moci, Ghiris, Vaida Camaras, Barai, Visea, Coasta, Tauseni, Palaica and Chesau villages (Cluj District). The number of fragments has been estimated at 3000 and the total weight at about 300 kg, the largest stone weighs about 56 kg. Samples are kept in thirty countries (*cf.* STANCIU and STOICOVICI, 1943; MAXIM, 1968; BEDELEAN *et al.*, 1979; GRAHAM *et al.*, 1985).

The Tauti meteorite fell in July or August, 1937, in Transylvania (Bihor

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Table 1. Meteorites fallen or found in Romania (cf. GRAHAM et al., 1985).*

No.	Name	Date of fall	Place of fall	Total weight	Class and type	Shock degree	Comments
1.	Mezö-Madaras (syn. Madaras)	1852, September 4, 16.30 hrs, shower	Madaras, Transylvania	22.7 kg	Chondrite L3, xenolithic		
2.	Kakowa (syn. Cacova)	1858, May 19, 08.00 hrs	Cacova, Banat	577 g	Chondrite L6, veined		
3.	Ohaba	1857, October 10, 00.15 hrs	Ohaba, Transylvania	16.25 kg	Chondrite H5, veined		
4.	Zsadáni (syn. Jadani)	1875, March 31, 15.00–16.00 hrs, shower	Jadani, Banat	552 g	Chondrite H5		
5.	Mocs (syn. Moci)	1882, February 3, 16.00 hrs shower	Wide area around Moci Transylvania	300 kg	Chondrite L5–6, veined	S3–5	In this study
6.	Sopot	1927, April 27, 12.00–13.00 hrs**, shower	Sopot, Oltenia	958 g	Chondrite, not classified		
7.	Tauti	1937, July or August, shower	Tauti, Transylvania	21 kg	Chondrite L6	S-3	In this study
8.	Tuzla	Found	Tuzla, Dobrogea	236 g	Chondrite L6		

* After 1918, when Transylvania unified with Romania, the Hungarian names of the meteorites changed to Romanian names, thus all Romanian papers on this subject (quoted as references) used "Moci", "Cacova", "Jadani" and "Madaras" instead of "Mocs", "Kakova", "Zsadany" and "Mezö-Madaras". All Romanian Museums which keep samples from these chondrites (see MAXIM, 1968), use the Romanian names also.

** These data follow the original paper (DEMETRESCU, 1928) where is written: 12–1 hrs during a suny day.

District). After three explosions and a bright bolide, a 20 kg stone fell at Tauti and two other stones of about 0.5 kg each fell at Gura Suvelului, about 6 km South of Tauti (GRAHAM *et al.*, 1985). After discovery, the principal sample broke in several pieces. Samples are kept only in Romania (*cf.* MAXIM, 1968).

2. Samples

Seven samples representing the Mocs and Tauti meteorites were investigated in this study: Mocs-1, -2, -3, -4, -5, -6 and Tauti-1. Mocs-1, complete stone with fusion crust and shock veins, weighing 76.29 g was received from the Aiud Natural Sciences Museum, Romania. Fragments of this piece, 50 (0.601 g), 51 (0.182 g) and 52 (2.668 g), were used to make two polished thin sections and for bulk chemical analysis, respectively, at the National Institute of Polar Research (NIPR). Mocs-2, a small stone weighing 2.18 g was received from the Mineralogical Museum of Babes-Bolyai University, Cluj - Napoca, Romania. One fragment of this piece, 90 (0.656 g) was used to make a polished thin section at the NIPR. Mocs-3, -4, -5 and -6 are small

Table 2. Samples used in this study.

Samples	Size	Provenance
Tauti-1	80.35 g (2.5×5.0×3.0 cm)	"Tarii Crisurilor" Mus. Oradea, Romania
Mocs-1	76.29 g (3.0×4.0×4.0 cm)	Aiud Natural Sci. Mus., Romania
Mocs-2	2.18 g (1.5×1.2×0.5 cm)	Miner. Mus. of Cluj-Napoca Univ., Romania
Mocs-3	1.3 g (1.4×1.0×0.5 cm)	Naturhist Mus. Wien, Austria
Mocs-4	2.69 g (1.4×1.0×1.0 cm)	Naturhist Mus. Wien, Austria
Mocs-5	2.3 g (2.5×1.5×0.4 cm)	Naturhist Mus. Wien, Austria
Mocs-6	2.8 g (3.0×1.4×0.3 cm)	Naturhist Mus. Wien, Austria
Mezö-Madaras-1	Thin Section	Naturhist Mus. Wien, Austria

stones with fusion crust and two of them (Mocs-3 and -4) have shock veins and heterogeneous features. These weigh 1.30 g, 2.69 g, 2.30 g and 2.80 g, respectively and were received from the Naturhistorisches Museum Wien, Austria. Fragments from each of these stones (*i.e.* 0.950 g from Mocs-3, 1.010 g from Mocs-4, 2.173 g from Mocs-5 and 1.660 g from Mocs-6) were used to make four polished thin sections at Yamaguchi University. Tauti-1, a complete fragment with fusion crust and shock veins, weighing 80.35 g was received from the "Tarii Crisurilor "Museum Oradea, Romania. Fragments of this piece, 50 (0.622 g) and 51 (2.222 g) were used to make a polished thin section and for bulk chemical analysis, respectively, at the NIPR. One other fragment, B (0.51 g) was used to make one polished thin section at Yamaguchi University. The standard samples used for quantitative electron microprobe analyses were synthetic oxides for Si, Al, Mg, Fe, Mn and P and natural oxides for Na, K, Ca, Ni and S (MIURA and MATSUMOTO, 1982). To check the reliability of our data, we measured also by electron microprobe analyses one thin section of the Mezö Madaras chondrite received from the Naturhistorisches Museum Wien, Austria and the results (olivine with Fa=21 mole% and low-Ca pyroxene with Fs=14 mole%) are very similar with those of DODD *et al.* (1967). The samples used in this paper are listed in Table 2.

3. Analytical Methods

Nine polished thin sections (PTS) representing the Mocs and Tauti meteorites (*i.e.* Mocs-1,50; Mocs-1,51; Mocs-2,90; Mocs-3; Mocs-4; Mocs-5; Mocs-6; Tauti-1,50 and Tauti-1B) were studied under the microscope in both transmitted and reflected light. In order to determine the shock degree of the two meteorites, in every thin section, ten to twenty of the largest, randomly distributed olivine single crystals and the largest plagioclase grains were examined with 20×- or 40×- objectives and with the electron microprobe in order to recognize the shock effects. Quantitative chemical analyses of the constituent minerals were obtained on the carbon-coated, polished thin sections by using a JEOL JXM-50A electron probe microanalyzer and a JSM-5400 (with JED 2001 energy dispersive X-ray analysis) analytical scanning electron microanalyzer at the Yamaguchi University. Both instruments were operated at an accelerated voltage of 15 kV, a 38.5 nA beam current and 35 mm working distance (*cf.* MIURA and MATSUMOTO, 1982). During the analytical runs, standard minerals were regularly analyzed to check on instruments stability. About 30 points of both olivine and orthopyroxene were measured on each thin section. Two small interior chips, Mocs-1, 52 (2.668 g) and Tauti-1, 51 (2.222 g), removed from the specimens Mocs-1 and Tauti-1, were used for standard wet chemical analysis by one of the authors (H. H.) at the NIPR. The analytical method and the error in the measurements are those of HARAMURA *et al.* (1983).

4. Bulk Chemical Compositions

4.1. *Mocs meteorite*

The bulk chemical composition of the Mocs-1,52 is listed in Table 3. Due to their small weight, Mocs-2, -3, -4, -5 and -6 were not analyzed by wet chemical analysis. The iron contents of metal plus troilite and oxides were determined from the magnetic and non-magnetic fractions reported by HARAMURA *et al.* (1983) to be 11.43 and 11.73 (wt%), respectively. The ratio Fe (in metallic form)/Si or Fe (in oxide and sulfide form)/Si are 0.20 and 0.45 respectively, and the total Fe is 23.16 wt%, indicative of the L-group. The Mocs chondrite was also assigned to the L chemical group by KEIL and FREDRIKSSON (1964) based on the iron content in olivine and orthorhombic pyroxene.

Table 3. Bulk composition of the Mocs-1 meteorite by standard wet chemical analysis method in wt%**.*

Oxides/Elements	Mocs-1	Oxides/Elements	Mocs-1
SiO_2	38.40	$H_2O(-)$	0.00
TiO_2	0.10	$H_2O(+)$	0.00
Al_2O_3	2.20	P_2O_5	0.19
Fe_2O_3	0.00	Cr_2O_3	0.45
FeO	15.10	FeS	6.13
MnO	0.38	Fe	7.54
MgO	25.70	Ni	1.32
CaO	1.73	Co	0.046
Na_2O	0.69		
K_2O	0.07	Total	100.04

*Analyzed by H. HARAMURA.
**Analytical method and the error in the measurements are the same by HARAMURA *et al.* (1983).

4.2. *Tauti meteorite*

The bulk chemical composition of the Tauti-1,51 is listed in Table 4. The iron contents of metal plus troilite and oxides were determined from magnetic and non-magnetic fractions reported by HARAMURA *et al.* (1983) to be 11.29 and 11.64 (wt%), respectively. The ratio Fe (in metallic form)/Si or Fe (in oxide and sulfide form)/Si is are 0.21 and 0.44 respectively, and the total Fe is 22.93 wt%, consistent

Table 4. Bulk composition of the Tauti-1 meteorite by standard wet chemical analysis method in wt%**.*

Oxides/Elements	Tauti-1	Oxides/Elements	Tauti-1
SiO_2	38.32	$H_2O(-)$	0.00
TiO_2	0.11	$H_2O(+)$	0.00
Al_2O_3	2.26	P_2O_5	0.22
Fe_2O_3	0.00	Cr_2O_3	0.48
FeO	14.98	FeS	6.48
MnO	0.45	Fe	7.18
MgO	25.72	Ni	1.21
CaO	1.54	Co	0.05
Na_2O	0.74		
K_2O	0.08	Total	99.82

*Analyzed by H. HARAMURA.
**Analytical method and the error in the measurements are the same by HARAMURA *et al.* (1983).

with the L-group.

5. Petrologic Type of the Mocs and Tauti Meteorites

5.1. *Mocs meteorite*

Seven thin sections were studied using optical and scanning electron microscopy in order to determine the petrographic type of the Mocs meteorite. Although all the thin sections reveal similar textural characteristics of the matrix which is completely recrystallized, they show different textures in the chondrules. While Mocs-3 and Mocs-4 have poorly defined or have no chondrules visible, Mocs-5 has well defined and readily delineated chondrules (Figs. 1 and 2). Mocs-1, Mocs-2 and Mocs-6 have similar textures, with readily delineated and poorly defined chondrules. The internal textures of chondrules consist of barred olivine (Mocs-1, Mocs-5 and Mocs-6), barred orthopyroxene (Mocs-2 and Mocs-5), porphyritic - olivine (Mocs-1) and porphyritic - orthopyroxene (Mocs-2 and Mocs-6) types. Barred olivine chondrules are composed of parallel sets of prismatic olivine crystals and devitrified glass. Barred orthopyroxene chondrules are composed largely of parallel sets of orthopyroxene crystals and devitrified glass. Porphyritic-olivine chondrules and porphyritic-pyroxene chondrules consist mainly of fine-grained olivine or fine-grained orthopyroxene and olivine crystals and glassy materials of feldspar composition. All samples contain plagioclase-like small grains (10~20 μm), (An_{10-11}). Maskelynite (An_{12-19}) was seen only in Mocs-1. Pyroxenes are mainly orthopyroxenes but less than 10% of the grains are clinopyroxenes (Cpx) with Wo_{50} (mole percentage) which is similar to diopside composition. Diopside grains in Moci were also reported by TSCHERMAK (1885), STANCIU and STOICOVICI (1943) and by HUNEKE *et al.* (1968). The other minerals identified in the thin sections are troilite, kamacite, taenite and chromite. A phosphate mineral with chlorapatite composition was also seen in Mocs-1, Mocs-2,

Table 5. Petrographic type determined by textural characteristics of the Mocs meteorite (cf. MIURA et al., 1994).

Sample No.	Texture of chondrule	Texture of matrix	Igneous glass	Development of feldspar	Low-Ca pyroxene	PMD (avg.)	Petrologic type
Mocs-1	Readily delineated and poorly defined	Recrystallized	Devitrified (in chondrules) and absent	Small grains (10~20 μm)	Opx + cpx (~10%)	Fa: 0.78 Fs: 0.91	5–6
Mocs-2	Readily delineated and poorly defined	Recrystallized	Devitrified (in chondrules) and absent	Small grains (10→20 μm)	Opx + cpx (~10%)	Fa: 0.30 Fs: 0.74	5–6
Mocs-3	Poorly defined and no visible chondrules	Recrystallized	Absent	Small grains (10~20 μm)	Opx + cpx (~7%)	Fa: 2.70 Fs: 2.90	5–6
Mocs-4	Poorly defined and no visible chondrules	Recrystallized	Absent	Small grains (10~20 μm)	Opx	Fa: 3.00 Fs: 4.30	6–7
Mocs-5	Well defined and readily delineated	Recrystallized	Devitrified (in chondrules) and absent	Small grains (10~20 μm)	Opx + cpx (~10%)	Fa: 3.30 Fs: 2.10	4–6
Mocs-6	Readily delineated and poorly defined	Recrystallized	Absent	Small grains (10~20 μm)	Opx + cpx (~10%)	Fa: 3.50 Fs: 3.00	5–6
Total Mocs	Well defined, readily delineated and poorly defined	Recrystallized	Devitrified (in chondrules) and absent	Small grains (10~20 μm)	Opx + cpx (~10%)	Fa: 2.26 Fs: 2.33	5–6

Table 6. The estimation of shock stage for the Mocs meteorite (cf. STÖFFLER *et al., 1991).*

Sample No.	Olivine	Plagioclase	Effects resulting from local P-T-excursions	Shock stage	Shock pressure GPa
Mocs-1	Mosaicism (strong), planar fractures, planar deformation features	Maskelynite (by OM and EPMA)	Melt pockets, veins and dykes, opaque shock veins	S-5 strongly shocked	45–55
Mocs-2	Planar fractures, undulatory extinction, irregular fractures	Undulatory extinction	None	S-3 weakly shocked	15–20
Mocs-3	Mosaticism (weak), planar fractures	Undulatory extinction, partially isotropic, planar deformation features	Melt pockets, melt veins, opaque shock veins	S-4 moderately shocked	30–35
Mocs-4	Planar fractures, undulatory extinction, irregular fracture	Undulatory extinction	Opaque shock veins	S-3 weakly shocked	15–20
Mocs-5	Planar fractures, undulatory extinction	Undulatory extinction	None	S-3 weakly shocked	15–20
Mocs-6	Planar fractures, undulatory extinction	Undulatory extinction	None	S-3 weakly shocked	15–20
Total Mocs				Avg. S 3–5	20–30

Mocs-3 and Mocs-5. MASON and WIIK (1961) also indicated a small amount of apatite or merrillite in the Mocs meteorite. Analysis of 77 olivine grains in "matrix" from all thin sections, shows a variation in composition from Fa_{23} to Fa_{27} mole% fayalite (avg. Fa_{25}; PMD 2.3%) (Fig. 3; DODD, 1981 and Table 5). The fayalite content of olivine from chondrules ranges from Fa_{23} to Fa_{27} mole% fayalite (avg. Fa_{25}; PMD 1.74%) (Fig. 3). MASON (1963) and KEIL and FREDRIKSSON (1964) indicated also 24 and 24.4 mole% fayalite, respectively for the olivine from Mocs chondrite. Seventy-one orthopyroxene grains from "matrix" show a range in composition from Fs_{18} to Fs_{23} mole% ferrosilite (avg. Fs_{21}; PMD 2.3%) (Fig. 4 and Table 5). The iron content of orthopyroxene in chondrules shows a variation between Fs_{18} and Fs_{23} mole% ferrosilite (avg. Fs_{21}; PMD 0.94%) (Fig. 4). KEIL and FREDRIKSSON (1964) reported 20.8 mole% ferrosilite for the orthopyroxene from this meteorite.

Based on the petrographic data, the Mocs chondrite is classified as petrographic type 5-6 (*cf.* Table 5). Histograms of iron contents (by weight %) of olivine and orthopyroxene in the analyzed samples are given in Figs. 3 and 4.

The estimation of shock stage for the Mocs meteorite (as of STÖFFLER *et al.*, 1991) is shown in Table 6. While Mocs-2, -4, -5 and -6 are weakly shocked (S-3), {olivine with planar fractures (*cf.* Fig. 5) and undulatory extinction and plagioclase with

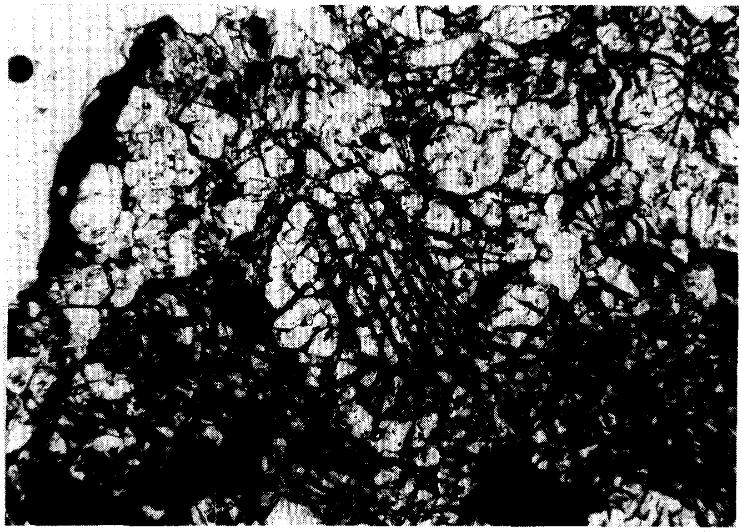

Fig. 1. Well defined barred olivine chondrule consisting of prismatic olivine crystals in the Mocs-5 chondrite. Plane polarized light. Long dimension of photograph=2 mm.

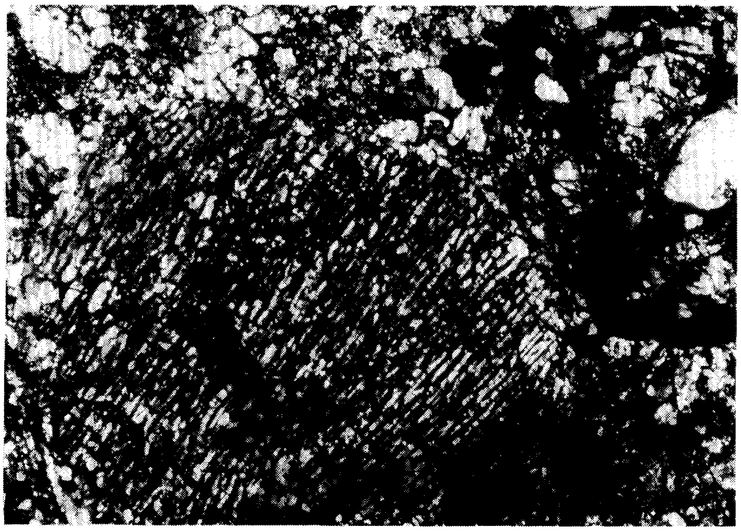

Fig. 2. Readily delineated barred orthopyroxene chondrule consisting of prismatic orthopyroxene crystals in the Mocs-5 chondrite. Crossed nicol. Long dimension of photograph=1.2 mm.

undulatory extinction}, Mocs-3 is moderately shocked (S-4), (melt pockets, melt veins, opaque shock veins, olivine with weak mosaicism and planar features and plagioclase partially isotropic with undulatory extinction and planar deformation features) and Mocs-1 (*cf*. Fig. 6) is strongly shocked (S-5), (melt pockets, veins and dykes, opaque shock veins, maskelynite and olivine with strong mosaicism, planar fractures and planar deformation features). By studying the metallic particles of Mocs chondrite, UREY and MAYEDA (1959) said this meteorite in many ways shows extreme crushing and distortion of all constituents. Although the Mocs meteorite is mostly homogeneous from the petrologic viewpoint, Mocs-1 and Mocs-3 have heterogeneous features due to their different shock degrees, thus we estimate the overall shock degree to be S 3-5.

5.2. *Tauti meteorite*

Two thin sections made from Tauti-1 were studied by optical and scanning electron microscopy in order to determine the petrologic type of the sample analysed in this study: Tauti-1,50 and Tauti-1,B. The chondrule texture is poorly defined and

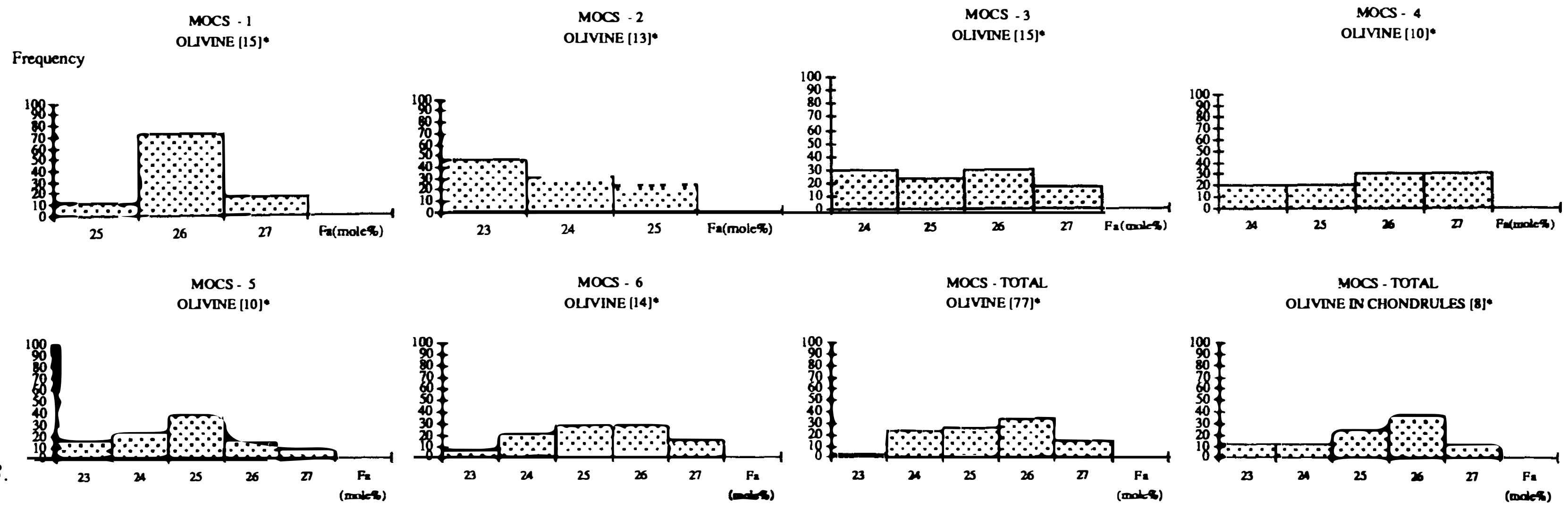

Fig. 3.

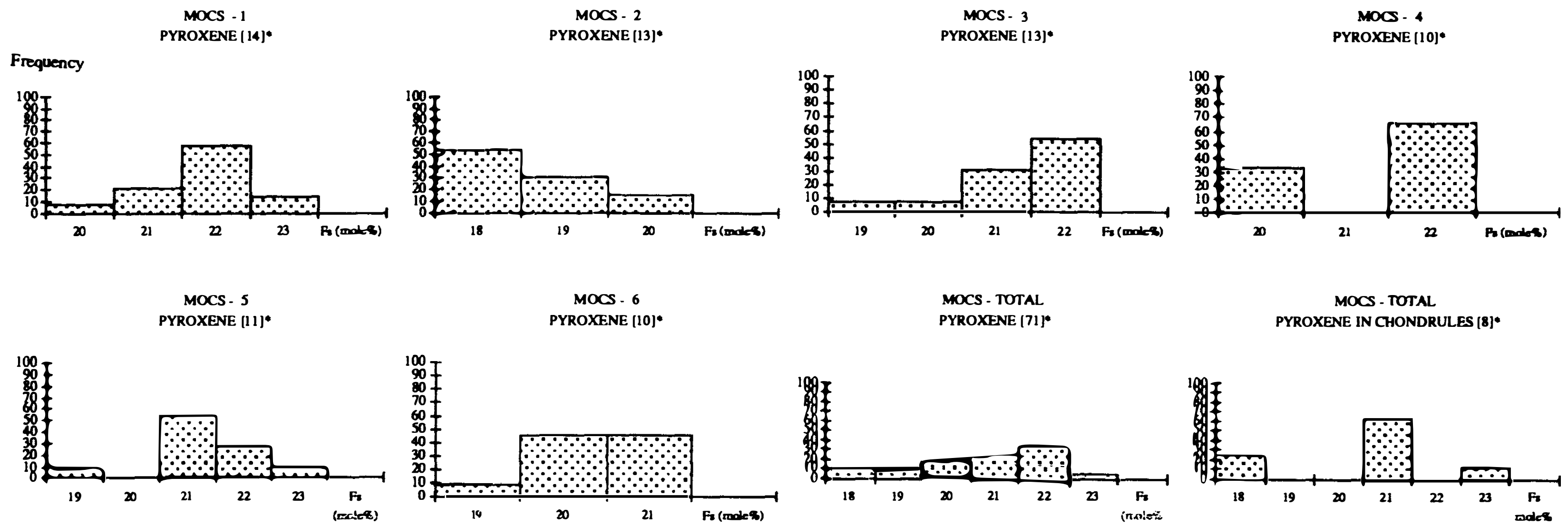

Fig. 4.

*Figs. 3, 4. Histograms of iron—contents of olivine (Fig. 3) and orthopyroxene (Fig. 4) in the Mocs chondrite. *Number of grains analyzed.*

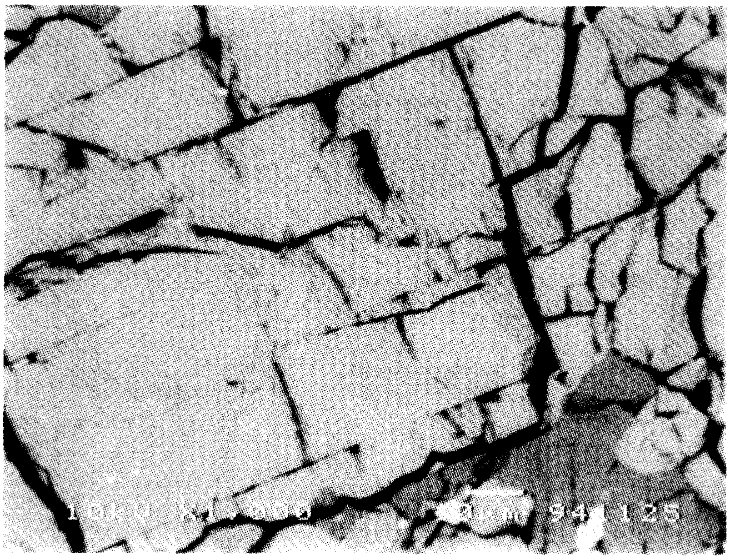

Fig. 5. Olivine (light gray) with two sets of paralel planar fractures by back scattered electron image (BEI) in the Mocs chondrite.

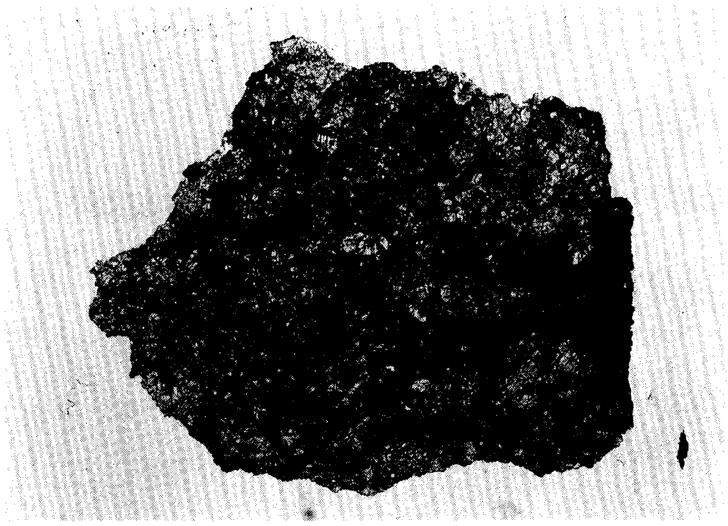

Fig. 6. Photomicrograph of the Mocs-1 chondrite, with shock veins and melt pockets (shock degree = S-5). Field of view is 12 mm.

the matrix is recrystallized. The feldspar (An_{10} Or_6) occurs in grains greater than 50 μm and igneous glass is absent. Pyroxenes are mainly orthopyroxenes but less than 5% of the grains are clinopyroxenes with Wo_{50} (mole percentage) which is similar to diopside composition. Other minerals identified in thin sections are kamacite, taenite, troilite and chromite. The merrillite identified by SAVU (1959) was not found in our fragment. Analysis of 31 olivine grains from all thin sections, shows a variation in composition from Fa_{23} to Fa_{26} mole% fayalite (avg. Fa_{24}; PMD 2.13%) (Fig. 7 and Table 7). Thirty-five orthopyroxene grains analyzed, show a range in composition from Fs_{18} to Fs_{23} mole % ferrosilite (avg. Fs_{20}; PMD 2.80%) (Fig. 8 and Table 7). Histograms of the fayalite contents of olivine and orthopyroxene in the analyzed samples are given in Figs. 7 and 8. Based on the petrographic data, the Tauti chondrite is classified as petrologic type 6 (*cf.* Table 7), consistent with the data printed in GRAHAM (1979) and GRAHAM *et al.* (1985). The fragment analyzed has a brecciated texture and a heterogeneous aspect due to the opaque shock veins (*cf.* Fig.

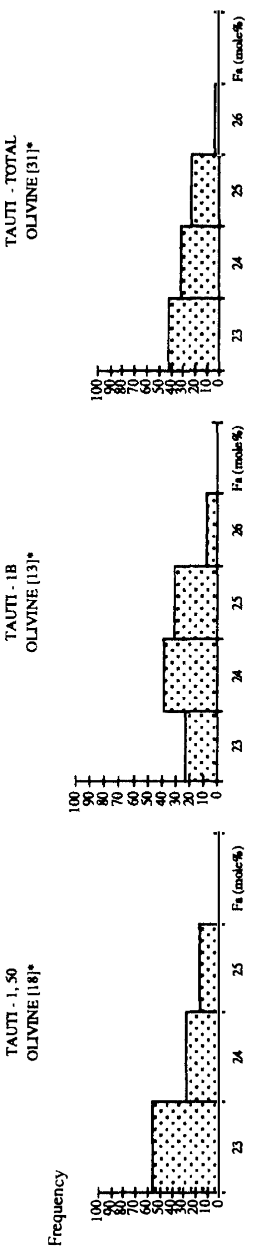

Fig. 7

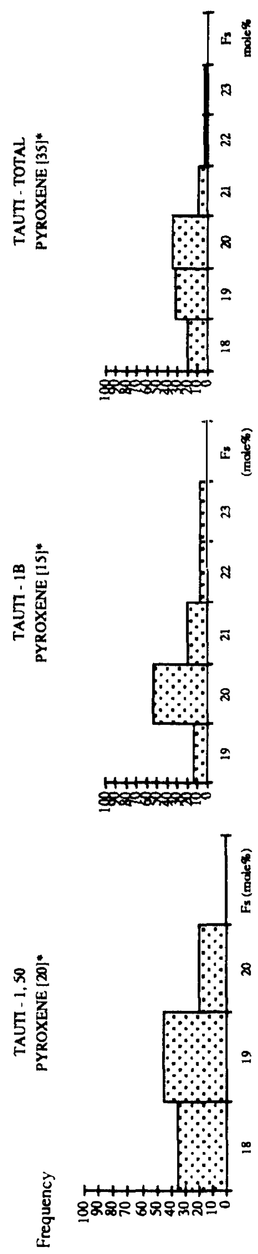

Fig. 8

*Figs. 7, 8. Histograms of iron—contents of olivine (Fig. 7) and orthopyroxene (Fig. 8) in the Tauti chondrite. *Number of grains analyzed.*

Table 7. Petrographic type determined by textural characteristics of the Tauti meteorite (cf. MIURA et al., 1994).

Sample No.	Texture of chondrule	Texture of matrix	Igneous glass	Development of feldspar	Low-Ca pyroxene	PMD (Avg.)	Petrologic type
Tauti-1	Poorly defined	Recrystallized	Absent	Grains >50 μm	Opx + cpx (~5%)	Fa: 2.13 Fs: 2.80	6

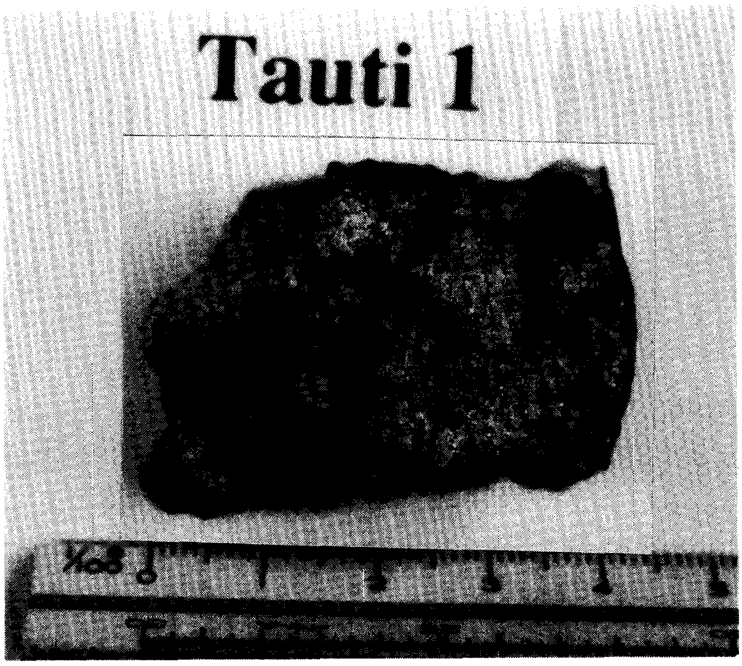

Fig. 9. Macroscopic features of the Tauti-1 chondrite, with shock veins (shock degree= S-3).

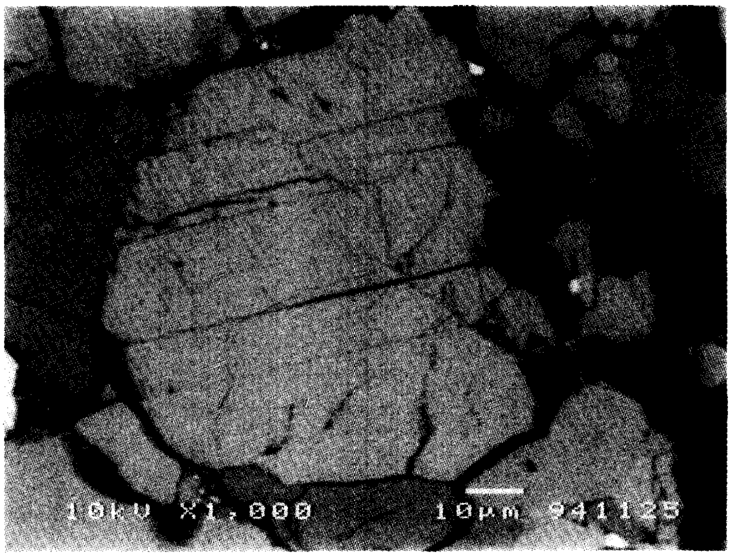

Fig. 10. Olivine (light gray) with one set of paralel planar fractures by back scattered electron image (BEI) in the Tauti chondrite.

Table 8. The estimation of shock stage for the Tauti meteorite (cf. STÖFFLER et al., 1991).

Sample No.	Olivine	Plagioclase	Effects resulting from local P-T-excursions	Shock stage	Shock pressure GPa
Tauti-1	Planar fractures, undulatory extinction, irregular fractures	Undulatory extinction	Opaque shock veins	S-3 weakly shocked	15–20

9). Because olivine shows planar fractures (*cf.* Fig. 10), undulatory extinction and irregular fractures and plagioclase has undulatory extinction, we estimate the shock degree of this chondrite as S-3, weakly shocked (*cf.* Table 8).

6. Conclusions

The results of this study are summarized as follows:

(1) Based on optical and electron microprobe analyses and bulk chemical analysis, the Mocs (syn. Moci) meteorite is reclassified as an L 5-6 chondrite. From the viewpoint of shock stage, Mocs meteorite looks heterogeneous because of the different shock degrees this meteorite experienced (S-3 to S-5).

(2) Based on electron probe microanalyses, optical microscopic study and bulk chemical analysis, the Tauti meteorite is classified as a typical L 6 chondrite. The result is consistent with the classification of this chondrite printed in GRAHAM (1979) and GRAHAM *et al.* (1985).

(3) The shock degrees of the Mocs and Tauti meteorites are S 3-5 (average) and S-3, respectively.

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