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The Zakłodzie enstatite meteorite:
Mineralogy, petrology, origin, and classification

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Abstract–The Zakłodzie meteorite was found in September 1998, about 40 km west of Zamość, in southeast Poland. Macroscopic and microscopic observations (in transmitted and reflected light), microprobe analyses, cathodoluminescence images, and X-ray diffraction data show that the meteorite is composed of clino- and orthoenstatite, two generations of feldspars, relict olivine (forsterite), a polymorph of SiO_2 (apparently cristobalite), and opaque minerals: Fe-Ni alloy (kamacite and taenite), troilite, schreibersite, graphite, and sulfide (Mg, Mn, Fe)S, which is probably keilite. The texture is fine- to inequigranular of cumulate type, locally intergranular. The MgS-FeS thermometer indicates that the sulfides crystallized at ~580–600 ºC. Thus, the Zakłodzie meteorite formed by the nearly complete melting of an enstatite chondrite protolith, probably at ~4.4 Ga; the process was likely caused by the decay of the ^{26}Al nuclide in the planetesimal interior. The second stage of its evolution, which could have happened at ~2.1 Ga, involved partial re-melting of most fusible components, probably due to collision with another body. The structure, composition, and origin of the meteorite and its relation to the parent rock indicate that Zakłodzie may represent a primitive enstatite achondrite.

INTRODUCTION

The Zakłodzie meteorite was found by Stanisław Jachymek in September 1998 while searching minerals and fossils on a country path near the village of Zakłodzie, which is located in SE Poland about 40 km west of Zamość (the site coordinates are 22º51′58″E, 50º45′46″N; Grossman 2000). One stone, weighing 8.68 kg and partly covered by fusion crust, was found. Based on ^{14}C data, which suggests a young terrestrial age of Zakłodzie, Patzer et al. (2002) defined the meteorite as a "recent fall."

The meteorite has a granoblastic texture and is mostly composed of orthoenstatite (~60 vol%), metal (~20 vol%), troilite and feldspar (~10 vol% each), with accessory schreibersite, silica phase, oldhamite, alabandite, and amphibole (Grossman 2000). The pyroxene forms subhedral to subrounded grains, 0.1–1.0 mm in diameter, and contains small amounts of Fs (<0.1–1.6 mol%) and Wo (~0.7 mol%). The feldspars comprise two populations: a) $Ab_{59-64}An_{36-41}Or_{0-0.5}$ and b) $Ab_{86-89}An_{0-5}Or_{9-12}$. The metal contains 6 to 16 wt% of Ni and 1.6 wt% of Si, while the troilite has considerable admixtures of Cr (4.7 wt%), Mn (1.4 wt%), and Ti (0.9 wt%) (Grossman 2000). F. Wlotzka, M. Stępniewski, and R. Bartoschewitz classified Zakłodzie as an ungrouped enstatite-rich meteorite (Grossman 2000).

In further investigations, Stępniewski et al. (2000) described Zakłodzie to be a "fossil stone" altered by weathering processes (W1/W2) during its residence (>100 yrs) within Quaternary loess deposits. The mineral composition of the stone is mostly typical of enstatite chondrites, with oval enstatite crystal aggregates, which can be interpreted as strongly metamorphosed chondrules (Stępniewski et al. 2000; Manecki and Łodziński 2001). Consequently, the meteorite may be classified as an enstatite chondrite EL7 (Stępniewski et al. 2000; Manecki and Łodziński 2001). However, alternatively, the observed

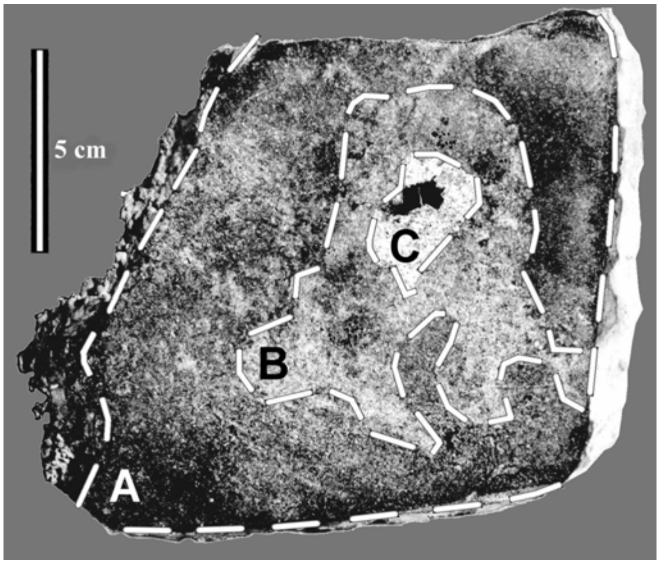

Fig. 1. A polished section of the Zakłodzie meteorite showing three concentric zones (marked as A, B, C) based on variation of macroscopic features (mainly different colors).

textures can be interpreted as the result of cumulate crystallization and, in such case, Zakłodzie might be considered an achondrite, with very high contents of metal and plagioclase (Stępniewski et al. 2000; Karwowski et al. 2001). Finally, Burbine et al. (2000) noted the abundant polysynthethic (multiple) twinning of the enstatite crystals and zoned feldspars, which suggests rapid cooling of presumably impact-related melt. These various interpretations have inspired us to perform further detailed investigations aimed at clarifying its origin and systematic position.

Patzer et al. (2001) found that the contents of heavy noble gases in Zakłodzie are different from those in enstatite chondrites except the unequilibrated ones. The calculated cosmic-ray exposure age for the Zakłodzie meteorite is 55.3 ± 5.5 Ma and is similar to those typical of enstatite achondrites (Patzer et al. 2002). The formation age of the meteorite, calculated as the time of concentration of ^{4}He, which is a product of radioactive decay of uranium and thorium, equals 2.1 Ga. However, its K-Ar retention age is estimated at 4.4 Ga. This means that the parent rock of the Zakłodzie meteorite went through its final metamorphic event or through another magmatic stage at ~2.1 Ga (Patzer et al. 2002). On the other hand, the oxygen isotope composition is similar to that of the enstatite meteorites, such as the Itqiy meteorite (Stępniewski et al. 2000; Patzer et al. 2002).

Further studies reported the presence of kamacite + schreibersite aggregates (up to 3 cm in diameter) and kamacite + graphite intergrowths (up to 5 cm across), both occurring in the most internal part of the meteorite (Karwowski et al. 2001). Graphite was found also as inclusions in kamacite and troilite, along with similar inclusions of sinoite (Karwowski et al. 2001).

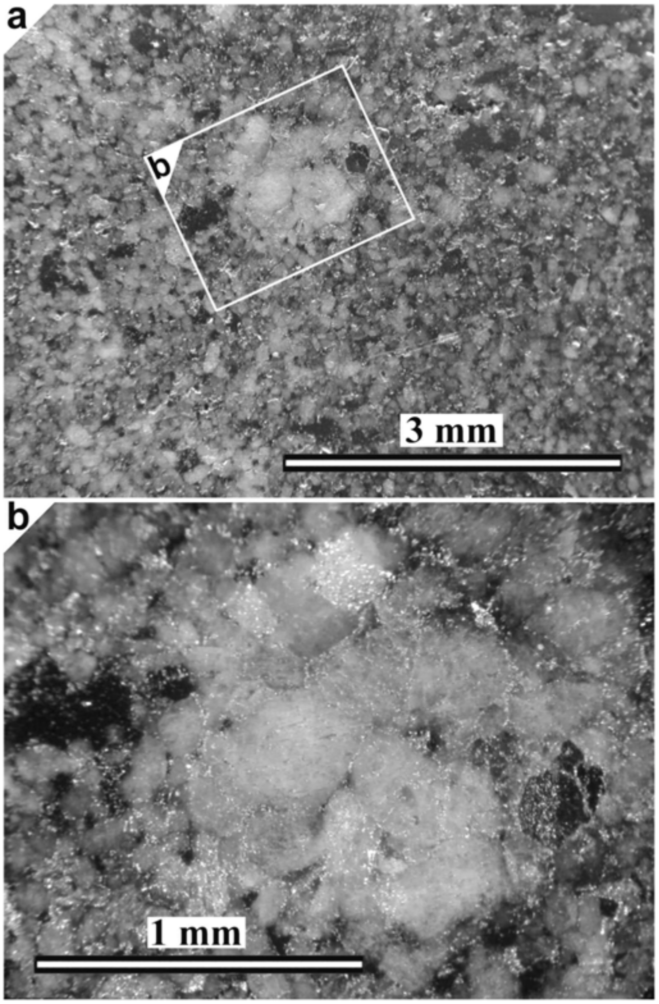

Fig. 2. Oval outline of relict chondrule and the groundmass of the Zakłodzie meteorite at two different magnifications.

THE STUDY MATERIAL AND METHODS

The Zakłodzie meteorite has a fusion crust 0.1–1.0 mm thick (average 0.3 mm); this crust is strongly weathered and contains iron oxides and hydroxides, evidence of prolonged terrestrial weathering. With a naked eye, three concentric zones varying in color can be distinguished in the stone (Fig. 1). The outer zone A is the darkest, being dark grey with a rusty tint; the intermediate zone B is rusty-grey in color and the inner zone C is pale grey, locally nearly white. In the inner zone, opaque minerals make up ~10–15 vol% and are irregularly distributed. In the other two zones, opaques reach ~20 vol%. Within the relatively homogeneous texture of the meteorite, oval aggregates are locally present. They consist of several to tens of enstatite crystals and minor other minerals including metal and troilite (Fig. 2). These forms were interpreted by some authors (Stępniewski et al. 2000; Manecki and Łodziński 2001) as "relics of chondrules."

In our studies, we had used the following three sections made from the Zakłodzie meteorite: a) a large and rather thick

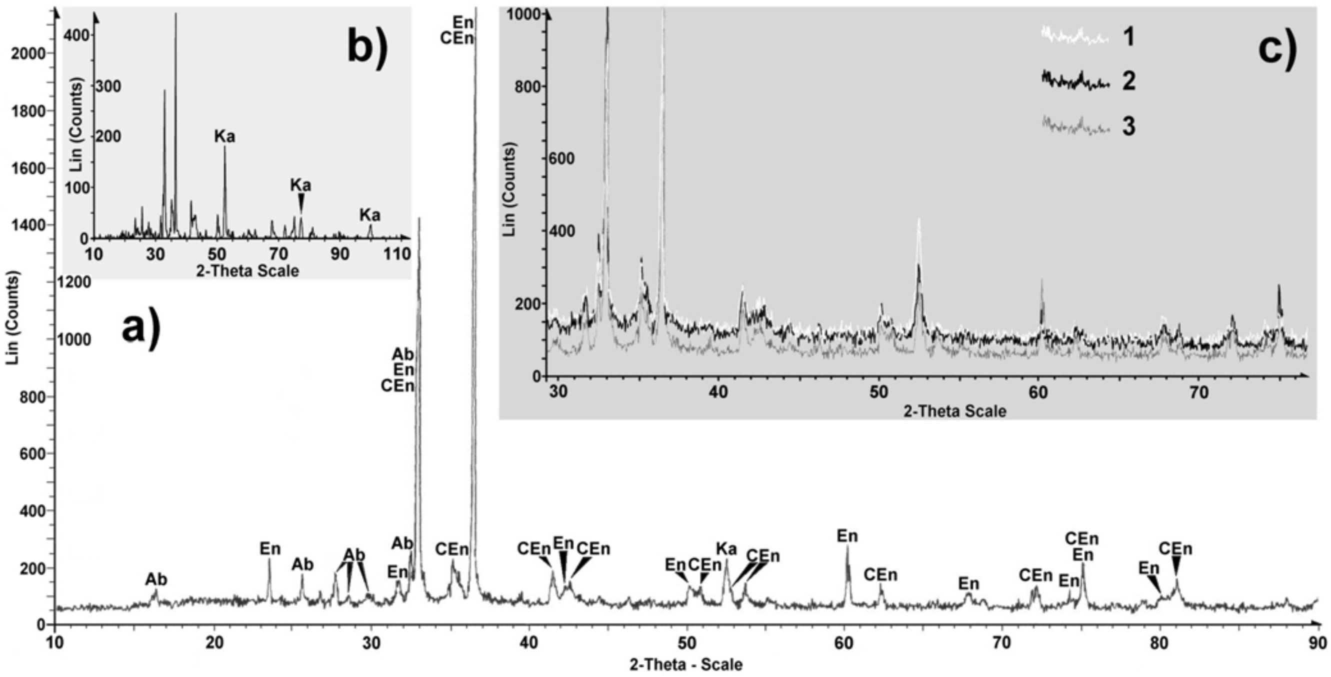

Fig. 3. XRD diffraction spectra of the Zakłodzie meteorite: a) main components of the meteorite: enstatite (En), clinoenstatite (CEn) (Ab = albite); b) characteristic peaks of kamacite (Ka); c) comparison of diffractograms of three different zones (a, b, and c on Fig. 1) of the meteorite (indicated as 1, 2, and 3).

section covering all three zones of the stone, used for reflected light and for microprobe + cathodoluminescence analyses; b) a normally-sized polished thin section of the outer zone of the stone for studies both in transmitted and reflected light and for microprobe + cathodoluminescence investigations; c) a standard glass-covered thin section of the outer and intermediate zones for conventional polarizing microscope studies. The thin sections are deposited in the Institute of Mining, Wrocław University of Technology, and can be requested from the first two authors (T. A .P. and P. P. Z.). Powdered materials from all three zones (together ~0.5 g) were used for X-ray diffraction analyses. In the studies, we omitted the most external fusion crust rich in secondary minerals resulting from weathering and from reactions between the meteorite and the loess (iron oxides and hydroxides, siderite, etc.).

We made optical investigations using a standard binocular and a Nikon Optiphot 2-POL polarizing microscope, the latter providing both transmitted and reflected light modes. The microprobe analyses (over 300 analyses on two sections) were performed on a Cambridge Microscan M9 with two wavelenght-dispersive spectrometers, WDS (analytical conditions: beam current 50 nA, accelerating voltage 15 kV, a set of natural mineral and synthetic standards, ZAF correction procedure). X-ray diffraction structural data were obtained on a Siemens D5005 instrument by the applying powder (DSH) method. Our measurements were carried out on the samples of ~0.1 g in the 2-Theta angle range between 10° and 110°. The cathodoluminescence observations were made using a Nikon Eclipse E400POL microscope with a Cambridge Image Technology Ltd. (CLmk3a cathode; current 500 mA, voltage 12–15 kV). All the instrumental analyses were preformed using the facilities at the Institute of Geological Sciences, Wrocław University.

MINERALOGY AND PETROGRAPHY

Silicates dominate the composition of the Zakłodzie meteorite, forming ~80 vol% of the rock. The remaining 20% of it comprises mainly opaques. The silicates are represented, predominantly by pyroxenes, which form auto- to hipautomorphic crystals 0.1–0.7 mm in diameter (average ~0.2 mm). X-ray diffraction data confirm the presence of both enstatite and clinoenstatite (Fig. 3). The two varieties of pyroxenes show multiple lamellar twinning parallel to (100) (Figs. 4 and 5) and are rather difficult to distinguish in routine microscopic observations. The clinoenstatite shows rather low extinction angles, from 8 to 11°, compared to those cited in handbooks (~22°); similar optical features were reported for clinoenstatite in the Happy Canyon meteorite (Olsen et al. 1977). The chemical composition of the pyroxenes in the Zakłodzie meteorite is fairly constant (Table 1). Only a slight decrease in Mg and Ca being observed from cores to rims of the grains (Fig. 6). This trend is typical for normal fractional crystallization of pyroxenes.

Table 1. Representative chemical analyses of silicates and SiO_2 polymorph (in wt%). Extreme analyses, indicated as “min.” and “max.” and displaying minimum and maximum contents of the main oxides/elements/ions (or and-members) in measured minerals, and mean values of chemical composition are presented.

	Pyroxene (enstatite)			Pyroxene (clinoenstatite)			Olivine (forsterite)			Plagioclase (feldspar I)			Alkali feldspar (feldspar II)			SiO_2 phase (crystobalite?)		
	Min.	Max.	Mean (of 11)	Min.	Max.	Mean (of 11)	Min.	Max.	Mean (of 4)	Min.	Max.	Mean (of 20)	Min.	Max.	Mean (of 5)	Min.	Max.	Mean (of 3)
SiO_2	59.16	61.14	60.53	59.17	60.94	59.97	41.15	43.65	42.57	58.87	66.20	62.22	66.08	70.33	68.55	96.56	98.90	97.89
TiO_2	0.00	0.02	0.00	0.00	0.04	0.01	0.00	0.04	0.02							0.02	0.04	0.03
Al_2O_3	0.19	0.72	0.35	0.21	0.74	0.34	0.71	2.53	1.23	18.92	26.24	23.53	16.53	19.21	18.11	0.78	1.17	1.01
Cr_2O_3	0.00	0.02	0.01	0.00	0.06	0.02	0.00	0.02	0.01							0.00	0.02	0.01
FeO/ Fe_2O_3*	0.07	0.48	0.21	0.09	0.88	0.39	0.15	0.19	0.18	0.10	2.09	0.58	1.02	2.93	1.62	0.00	1.28	0.69
MnO	0.00	0.05	0.02	0.00	0.05	0.02	0.00	0.02	0.01	0.00	0.02	0.01	0.00	0.02	0.00	0.00	0.003	0.02
NiO	0.00	0.03	0.01	0.00	0.03	0.01	0.00	0.05	0.03							0.06	2.77	1.00
MgO	37.22	38.48	37.90	36.94	38.43	37.81	53.27	54.90	54.39	0.00	0.10	0.02	0.00	0.00	0.00	0.02	0.03	0.02
CaO	0.22	0.63	0.50	0.23	0.54	0.44	0.04	0.07	0.06	2.90	8.31	6.07	0.38	1.04	0.59	0.00	0.15	0.05
Na_2O	0.04	0.28	0.17	0.03	0.45	0.24	0.00	0.28	0.11	7.00	10.37	8.36	9.88	10.89	10.54	0.00	0.37	0.13
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.17	0.66	0.34	1.32	1.90	1.63			
ZnO							0.00	0.11	0.05									
SO_2																0.00	0.38	0.15
Total	98.34	101.01	99.71	98.22	100.36	99.24	97.59	99.72	98.65	99.20	101.85	101.13	100.15	102.10	101.05	100.95	101.04	101.00
Si^{+4}	2.013	2.035	2.028	1.998	2.034	2.022	0.990	1.022	1.008	2.625	2.903	2.741	2.921	3.050	2.999	0.9742	0.9867	0.9813
Al^{+3}	0.000	0.000	0.000	0.000	0.002	0.000	0.020	0.070	0.034	0.990	1.359	1.222	0.859	1.001	0.934	0.0092	0.0138	0.0119
Position T	2.013	2.035	2.028	2.000	2.034	2.022												
Al^{+6}	0.007	0.029	0.014	0.008	0.028	0.013												
Ti^{+4}	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000							0.0002	0.0003	0.0002
Cr^{+3}	0.000	0.001	0.000	0.000	0.002	0.000	0.000	0.000	0.000							0.0000	0.0002	0.0001
Fe^{+2}/ Fe^{+3}*	0.002	0.014	0.006	0.003	0.025	0.011	0.003	0.004	0.003	0.003	0.070	0.019	0.033	0.098	0.053	0.0000	0.0107	0.0058
Mn^{+2}	0.000	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.0000	0.0003	0.0001
Ni^{+2}	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000							0.0005	0.0225	0.0081
Mg^{+2}	1.878	1.905	1.893	1.871	1.925	1.900	1.863	1.969	1.922	0.000	0.007	0.001	0.000	0.000	0.000	0.0003	0.0005	0.0003
Ca^{+2}	0.008	0.023	0.018	0.008	0.020	0.016	0.001	0.002	0.001	0.138	0.391	0.287	0.018	0.049	0.028	0.0000	0.0016	0.0006
Na^{+}	0.003	0.022	0.011	0.002	0.030	0.016	0.000	0.013	0.005	0.596	0.893	0.714	0.847	0.931	0.894	0.0000	0.0072	0.0026
K^{+}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.037	0.019	0.074	0.106	0.091			
Zn^{+2}							0.000	0.002	0.001									
S^{-2}																0.0000	0.0036	0.0014
M1, M2	1.928	1.969	1.943	1.929	1.997	1.957												
Total	3.963	3.982	3.971	3.963	3.997	3.979	2.952	3.004	2.976	4.983	5.032	5.005	4.986	5.034	5.000	1.0103	1.0155	1.0124
$O{-}2$	6.000	6.000	6.000	6.000	6.000	6.000	4.000	4.000	4.000	8.000	8.000	8.000	8.000	8.000	8.000	2.0000	2.0000	2.0000
Ca + Mg + Fe	1.903	1.930	1.916			1.926												

Table 1. *Continued.* Representative chemical analyses of silicates and SiO_2 polymorph (in wt%). Extreme analyses, indicated as “min.” and “max.” and displaying minimum and maximum contents of the main oxides/elements/ions (or and-members) in measured minerals, and mean values of chemical composition are presented.

	Pyroxene (enstatite)			Pyroxene (clinoenstatite)			Olivine (forsterite)			Plagioclase (feldspar I)			Alkali feldspar (feldspar II)			SiO_2 phase (crystobalite?)		
	Min.	Max.	Mean (of 11)	Min.	Max.	Mean (of 11)	Min.	Max.	Mean (of 4)	Min.	Max.	Mean (of 20)	Min.	Max.	Mean (of 5)	Min.	Max.	Mean (of 3)
Mg + Fe + Mn							1.867	1.972	1.925									
K + Na + Ca										0.997	1.068	1.020	0.970	1.059	1.013			
Wo	0.004	0.012	0.009	0.004	0.010	0.008												
En	0.985	0.0.992	0.988	0.979	0.992	0.986												
Fs	0.001	0.007	0.003	0.001	0.013	0.006												
Fo							0.998	0.998	0.998									
Fa							0.002	0.002	0.002									
Te							0.000	0.000	0.000									
Or										0.010	0.035	0.019	0.076	0.100	0.090			
Ab										0.598	0.836	0.700	0.873	0.903	0.883			
An										0.129	0.392	0.282	0.017	0.051	0.028			

*Fe_2O_3 and Fe^{3+} in feldspar.

Table 2. Representative chemical analyses of opaque minerals (in wt%). Extreme analyses, indicated as min. and max. and displaying minimum and maximum contents of the main elements/ions (or and-members) in measured minerals, and mean values of chemical composition are presented.

	Troilite			Schreibersite			(Mg, Mn, Fe)S—Keilite (?)			Kamacite			Taenite		
	Min.	Max.	Mean (of 14)	Min.	Max.	Mean (of 5)	Min.	Max.	Mean (of 5)	Min.	Max.	Mean (of 11)	Min.	Max.	Mean (of 4)
Si	0.03	0.12	0.05	0.11	0.17	0.14	0.05	0.51	0.18	1.45	1.68	1.50	1.40	1.50	1.46
Ti	0.62	0.81	0.72	0.00	0.02	0.01	0.00	0.02	0.01	0.00	0.02	0.01	0.00	0.01	0.00
Al	0.02	0.13	0.04	0.05	0.09	0.07	0.06	0.21	0.12	0.02	0.13	0.06	0.03	0.09	0.07
Cr	4.00	4.71	4.39	0.00	0.01	0.01	0.78	0.94	0.83	0.00	0.02	0.00	0.02	0.03	0.03
Fe	56.20	58.00	57.01	73.19	74.90	74.13	31.23	33.55	32.40	91.48	93.48	92.60	83.69	84.60	84.03
Mg	0.06	0.16	0.10	0.04	0.12	0.06	4.79	5.10	4.98	0.01	0.06	0.03	0.03	0.04	0.03
Mn	1.05	1.78	1.35	0.00	0.02	0.01	22.75	23.29	23.01	0.00	0.07	0.03	0.01	0.04	0.02
Ni	0.08	0.26	0.16	11.09	11.96	11.47	0.00	0.00	0.00	4.98	5.43	5.19	14.36	14.46	14.42
Co	0.07	0.27	0.18	0.17	0.33	0.24	0.00	0.07	0.04	0.47	0.66	0.56	0.34	0.38	0.37
Ca				0.00	0.04	0.01	0.85	0.89	0.86						
Zn	0.00	0.22	0.08				0.20	0.20	0.20						
Na	0.03	0.12	0.09	0.00	0.18	0.07	0.00	0.39	0.12						
P				12.65	13.30	13.00	0.00	0.01	0.00	0.19	0.20	0.20	0.11	0.13	0.12
S	35.62	36.28	36.07	0.06	0.10	0.08	36.74	38.33	37.74	0.00	0.02	0.01	0.00	0.01	0.00
Total	99.40	100.96	100.24	98.46	99.58	99.29	98.27	101.68	100.49	99.27	100.21	100.18	100.31	100.98	100.54
Si^{+4}	0.0009	0.0037	0.0016	0.0080	0.0123	0.0102	0.0015	0.0149	0.0054						
Ti^{+4}	0.0113	0.0148	0.0131	0.0000	0.0009	0.0003	0.0000	0.0003	0.0001						

Table 2. *Continued.* Representative chemical analyses of opaque minerals (in wt%). Extreme analyses, indicated as min. and max. and displaying minimum and maximum contents of the main elements/ions (or and-members) in measured minerals, and mean values of chemical composition are presented.

	Troilite			Schreibersite			(Mg, Mn, Fe)S—Keilite (?)			Kamacite			Taenite		
	Min.	Max.	Mean (of 14)	Min.	Max.	Mean (of 5)	Min.	Max.	Mean (of 5)	Min.	Max.	Mean (of 11)	Min.	Max.	Mean (of 4)
Al^{+3}	0.0006	0.0042	0.0012	0.0038	0.0068	0.0051	0.0018	0.0065	0.0036						
Cr^{+3}	0.0674	0.0789	0.0737	0.0000	0.0004	0.0002	0.0123	0.0148	0.0131						
Fe^{+2}	0.8810	0.9023	0.8923	2.6708	2.7291	2.7052	0.4669	0.4912	0.4758						
Mg^{+2}	0.0022	0.0058	0.0036	0.0033	0.0100	0.0054	0.1612	0.1720	0.1680						
Mn^{+2}	0.0167	0.0282	0.0214	0.0000	0.0007	0.0003	0.3364	0.3493	0.3435						
Ni^{+2}	0.0012	0.0039	0.0024	0.3838	0.4168	0.3982	0.0000	0.0000	0.0000						
Co^{+2}	0.0010	0.0040	0.0027	0.0059	0.0114	0.0083	0.0000	0.0010	0.0005						
Ca^{+2}				0.0000	0.0020	0.0007	0.0172	0.0182	0.0176						
Zn^{+2}	0.0001	0.0029	0.0011				0.0025	0.0025	0.0025						
Na^{+}	0.0011	0.0046	0.0034	0.0018	0.0159	0.0059	0.0000	0.0137	0.0042						
P^{+5}				0.8311	0.8722	0.8553	0.0000	0.0003	0.0001						
S^{-2}	0.9802	0.9895	0.9834	0.0038	0.0063	0.0050	0.9598	0.9720	0.9655						
Total	2.0000	2.0000	2.0000	4.0000	4.0000	4.0000	2.0000	2.0000	2.0000						
Charge	0.1468	0.1877	0.1675	10.4827	10.6233	10.5665									
FeS							46.0	48.0	46.7						
MnS							33.1	34.3	33.8						
(Mg,Ca,Cr)S							18.9	19.9	19.5						
Total							100.0	100.0	100.0						

Complex structural relationships in the pyroxene crystals of the Zakłodzie meteorite were discerned in cathodoluminescence images. Most crystals are magenta in color corresponding to the predominant orthoenstatite (Zhang et al. 1996). Some of the pyroxene crystals have yellowish cores and others show bluish lamellae, the latter most probably representing exsolved clinoenstatite. Similarly, we interpret blue margins of pyroxene grains as clinoenstatite rims (Fig. 7). Together with the slight but systematic difference in chemical composition between cores and rims (Fig. 6), the variation may correspond to different structural states of the pyroxene crystals.

Two pyroxene grains in the outer zone of Zakłodzie have a particularly intense yellow color under cathodoluminescence (Fig. 7). They occur within a cluster (relict chondrule) of several pyroxene grains within a paler part of the meteorite, poor in opaque minerals and containing no Fe-Ni and graphite (cf. Fig. 2). The two pyroxene crystals enclose relict olivine (forsterite) in their cores (Fig. 8). Similar pyroxene crystals with yellow cores under cathodoluminescence were observed also in other zones of the meteorite (Fig. 7). Selected microprobe analyses of the olivines are given in Table 1.

Feldspars crystallized also from the silicate part of the melt. There are two distinct generations of these minerals: a) older plagioclases, $An_{13–39}$, $Or_{\leq\sim3}$, and b) younger alkali feldspars, $An_{2–7}$, $Or_{7–10}$, containing significant amounts of Fe (Table 1, Fig. 9). In plane polarized light, multiple lamellar twining is easily visible in the older plagioclase grains. Identical optical orientations of the lamellae in apparently separate plagioclase grains indicate that they form part of a larger (~1 mm in diameter) skeletal crystal enclosing several enstatite grains (Fig. 4). The second generation alkali feldspars form rather small grains associated with Fe-Ni alloy and are found intersticially between larger pyroxene crystals.

A silica phase (SiO_2, probably cristobalite, but not proven yet due to its small size) is found as rare oval inclusions (~20 × 30 μm) and finger-like intergrowths (~35 × 150 μm) in troilite, kamacite, and schreibersite (Table 1).

Four different opaque phases were distinguished in reflected light and confirmed using the microprobe and XRD (Fig. 3) analyses. The most abundant are Fe-Ni alloys, most common is kamacite and less frequent is taenite (Table 2). The alloys form xenomorphic grains, usually 0.1–1.2 mm in diameter (max. up to 2.5 mm; Fig. 4). The alloys often enclose enstatite crystals and other opaques. Apart from the Fe-Ni alloys, the opaque minerals are represented by troilite, FeS (Table 2), schreibersite (Fe, Co, Ni)3P (Table 2), and graphite (Fig. 4). The latter forms separate aggregates and is found as inclusions in kamacite and troilite.

Several analyses of one opaque grain indicate the presence of an unusual phase: (Mg, Mn, Fe)S. Its chemical composition (Table 2, Fig. 11) suggests that this phase represents a variety of a recently discovered mineral, keilite (Shimizu et al. 2002). In comparison to the chemical composition of keilite described by Shimizu et al. (2002) from the Abee meteorite, the (Mg, Mn, Fe)S sulfide from the Zakłodzie meteorite is characterized by a higher content of MnS and a smaller amount of MgS and FeS end members. The chemical composition of this sulfide indicates strongly reducing conditions during crystallization, allowing for the substitution of a strongly lithophile element, Mg, within a sulfide. Both schreibersite and keilite are characteristic accessory minerals of enstatite chondrites (Mason 1966; Keil 1968, 1989; Lin and Kimura 1998; Shimizu et al. 2002). So far we have been unable to separate enough material for X-ray structural studies to confirm the structure of this Mg-rich sulfide present in the Zakłodzie meteorite.

Considerable amounts of graphite, schreibersite, and troilite form concentrates along relatively narrow (~1 mm) and long (~3–4 cm) dark stripes within the outer zone of the Zakłodzie meteorite (Fig. 5).

No qualitative differences in mineral composition were found between the three zones of the meteorite (see Fig. 3). The observed color differences result from higher concentrations of very fine, disseminated graphite inclusions in the two outer zones and the locally rusty color is due to weathering. In the lighter internal zone, graphite forms fairly large aggregates.

The texture of the meteorite is generally fine-grained and inequigranular. The crystal size encompasses a wide range of 0.06 to 5.5 mm. Locally, an intergranular texture is observed: small pyroxene crystals are enclosed within larger skeletal crystals of plagioclase (Fig. 4). The texture is generally massive, though locally clusters of pyroxene grains displaying similar crystallographic orientations were observed (e.g. clear dominance of sections perpendicular to the C axis), which suggests an oriented texture (Fig. 5). A similar texture was described in the Happy Canyon meteorite (Olsen et al. 1977); among terrestrial rocks such a texture is typical of cumulates. Taking into account the clearly automorphic shape and habit of the pyroxene crystals that are generally isometric, their occurrence (locally) as nearly monomineralic aggregates, the texture can be interpreted as that of cumulate type. These textural features and the silicate mineral assemblage in Zakłodzie resemble those of terrestrial pyroxenites (more specifically plagioclase-bearing websterite).

INTERPRETATION

Our observations and results suggest that the crystallization of the silicate portion of the melt may have started at ~1600 °C, with segregation of an extremely Mg-rich olivine (forsterite; Fig. 10: reference to experimental system $MgO-SiO_2$ of Bowen and Anderson 1914). At that stage, normal magmatic fractional crystallization took place (point 2 on Fig. 10). Subsequently (at T = 1557 °C according to the

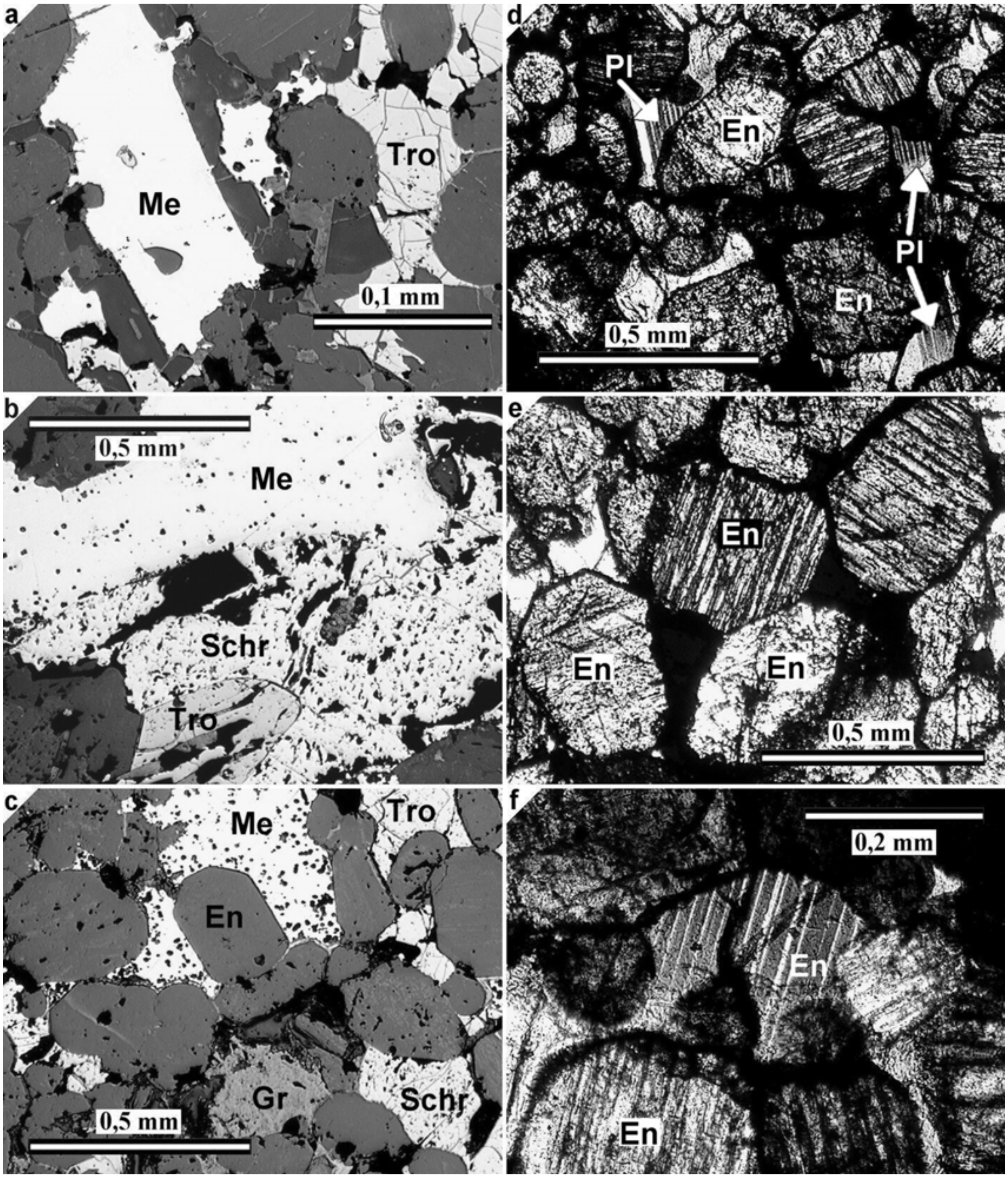

Fig. 4. Photomicrographs of the Zakłodzie meteorite in thin sections: a) crystals of metal (Me) and troilite (Tro) associated with pyroxenes (reflected light); b) crystals of metal (Me), schreibersite (Schr) and troilite (Tro) (reflected light); c) crystals of metal (Me), schreibersite (Schr) and troilite (Tro) interstitially intergrown with enstatite crystals; En = automorphic enstatite crystal, Gr = graphite (reflected light); d) intersertal texture: skeletal crystal of first generation plagioclase (Pl) “encloses” enstatite (En) crystals (transmitted light, crossed polaroids); e) hypautomorphic crystals of enstatite (En), mostly in sections perpendicular to the C axis (transmitted light, crossed polaroids); f) lamellar twining in enstatite (En) crystals (transmitted light, crossed polaroids).

data in Fig. 10b), the olivine crystals reacted with the melt and were nearly completely replaced by protoenstatite, leaving a small, “excess” amount of SiO_2 in the melt R. The relict olivines preserved in the cores of some pyroxene crystals indicate their possible isolation from the melt and incomplete replacement of the forsterite by the pyroxene. There is no doubt that the melt crossed the boundary of silica saturation and went from the Fo-En-Ab-(Di) space to the En-Ab-Qtz-(Di) space of the “basalt tetrahedron” (see arrow in Fig. 10d). Afterwards, enstatite continued its crystallization from the remaining melt and finally (point E in Fig. 10b) it was joined by an SiO_2 phase (cristobalite? according to the data in Fig. 10a), together with feldspars not shown on the diagram in Fig. 10b.

The pyroxene, which initially crystallized at high temperature in orthorhombic symmetry, was subsequently, at

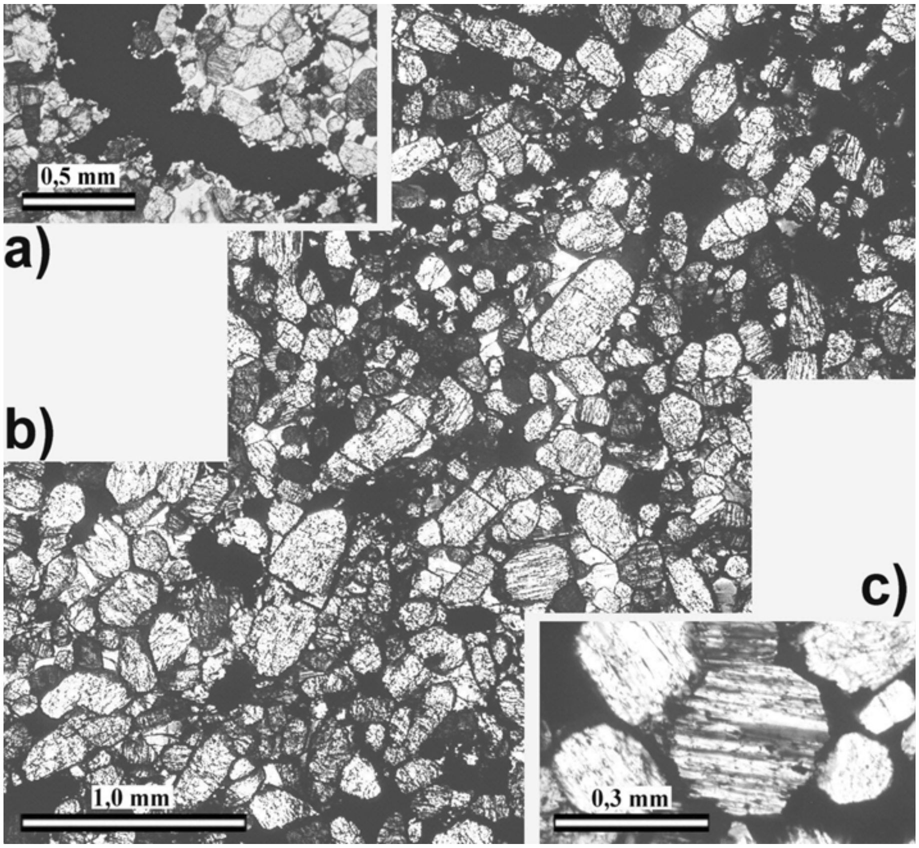

Fig. 5. Photomicrographs of the Zakłodzie meteorite in thin sections: a) “dark zone” (“vein”) filled with opaque minerals (transmitted light, crossed polaroids); b) cumulate texture with preferential orientation of pyroxene crystals (transmitted light, crossed polaroids); c) lamellar twining in enstatite (En) crystal in section perpendicular to the C axis (transmitted light, crossed polaroids).

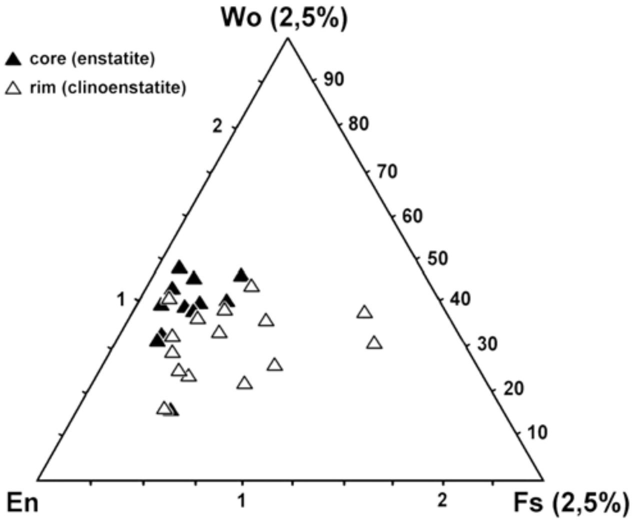

Fig. 6. Chemical composition of pyroxenes of the Zakłodzie meteorite.

decreasing temperature, partially replaced by monoclinic clinoenstatite. This process of changing the symmetry of pyroxene crystals was apparently broken, probably due to a rapid change in T-P conditions (rapid cooling?). An accelerated process of crystallization is further suggested by the way, in which the remaining silicates crystallized, as indicated by multiple-twinned pyroxenes and skeletal crystals of plagioclase interstitially enclosing the pyroxenes (Fig. 4 and 5). The wide range of anorthite contents in the plagioclase further indicates the lack of equilibrium between different parts of the rock and rapid crystallization at lower temperatures.

The final stage of the formation of parent rock of the Zakłodzie meteorite was the crystallization of metal, sulfides, and schreibersite, often in the form of interstitial aggregates and veinlets between the earlier silicates. Using the thermometer based on the FeS, MnS and MgS contents in a phase coexisting with troilite, described by Skinner and Luce (1971) (in our case keilite), the temperature of the crystallization of sulfides is estimated at ~580–600 °C (Fig. 12c).

After this first stage of rock formation, a process of partial re-melting took place, in which the most fusible components became liquid (Ab- and Or-rich feldspars, metal, and sulfides). This process resulted in a new generation of alkali feldspars (see Table 1 and Fig. 9), which often seals neighbouring grains of metal confirming their roughly contemporaneous crystallization. This was probably a brief

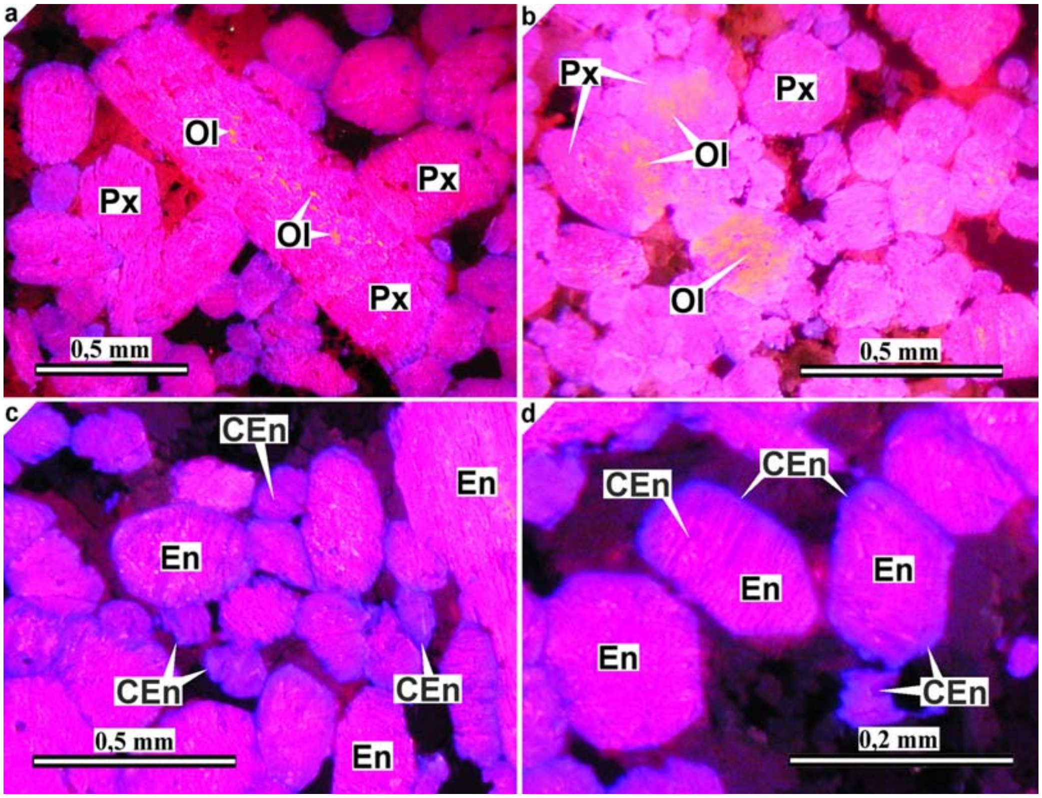

Fig. 7. Photomicrographs of Zakłodzie in cathodoluminescence: a) enstatite crystal (Px; magenta) with relict olivine in the core (Ol; yellow); b) enstatite crystals (Px) in marginal part of relict chondrule (see Fig. 2); in crystal cores, large relics of olivine are visible (Ol; yellow); c) and (d) orthoenstatite crystals (En; magenta) with clinoenstatite rims (CEn; blue).

process and the temperatures were not high enough to completely melt the feldspars or to destroy the relict chondrules.

DISCUSSION: THE GENESIS AND SYSTEMATIC POSITION OF THE ZAKŁODZIE METEORITE

The authors are inclined to interpret the origin of the Zakłodzie meteorite in terms of indigenous melting process and initially slow fractional crystallization (cumulate) and later on as a rapid cooling of ascending magma. An alternative explanation of this meteorite as an impact-melt rock (Burbine et al. 2000), similarly as in the case of the Ilafegh 009 and Happy Canyon meteorites (McCoy et al. 1995), is doubtful and makes the classification of Zakłodzie impossible within the existing groups and subgroups of meteorites.

Arguments for indigenous melting and against the impact-melt rock include:

1. The cumulate texture, with large crystals of enstatite which show a normal fractional crystallization trend (decreasing contents of Mg from core to rim), and the presence of Fe-enriched clinoenstatite rims, typical of Mg-rich pyroxenes in eruptive rocks, as described e.g. in shergottites (Lentz and McSween 2000).
2. The relics of chondrules with no evidence of impact shock, such as cracking, crushing and partial melting; the preservation of these relics are easier to explain in slow selective (fractional) melting of the protolith than in rapid and intense impact-related melting. The relics of chondrules in the Zakłodzie meteorite are depleted in most fusible components: metal and feldspars, which is also in favor of an indigenous melting process rather than a rapid impact event.
3. In an impact-melt rock, the high cooling rate is characteristic of a wide temperature range, whereas in the Zakłodzie meteorite we are dealing with an early stage of slow (long-lasting) growth of orthoenstatite crystals and subsequent accelerated crystallization of unmixed lamellar twinned ortho- and clinoentatite together with skeletal crystals of plagioclase and clinoenstatite rims on the earlier orthoenstatite grains. This suggests a rapid cooling event following the early quiet crystallization process.
4. The lamellar twinning of pyroxene crystals can be explained either as an effect of crystallization of impact-induced melt or as a product of cooling of flowing magma. However, the possible impact-related origin of the lamellar twinning in pyroxenes should be confirmed by other independent arguments (Buseck and Iijima

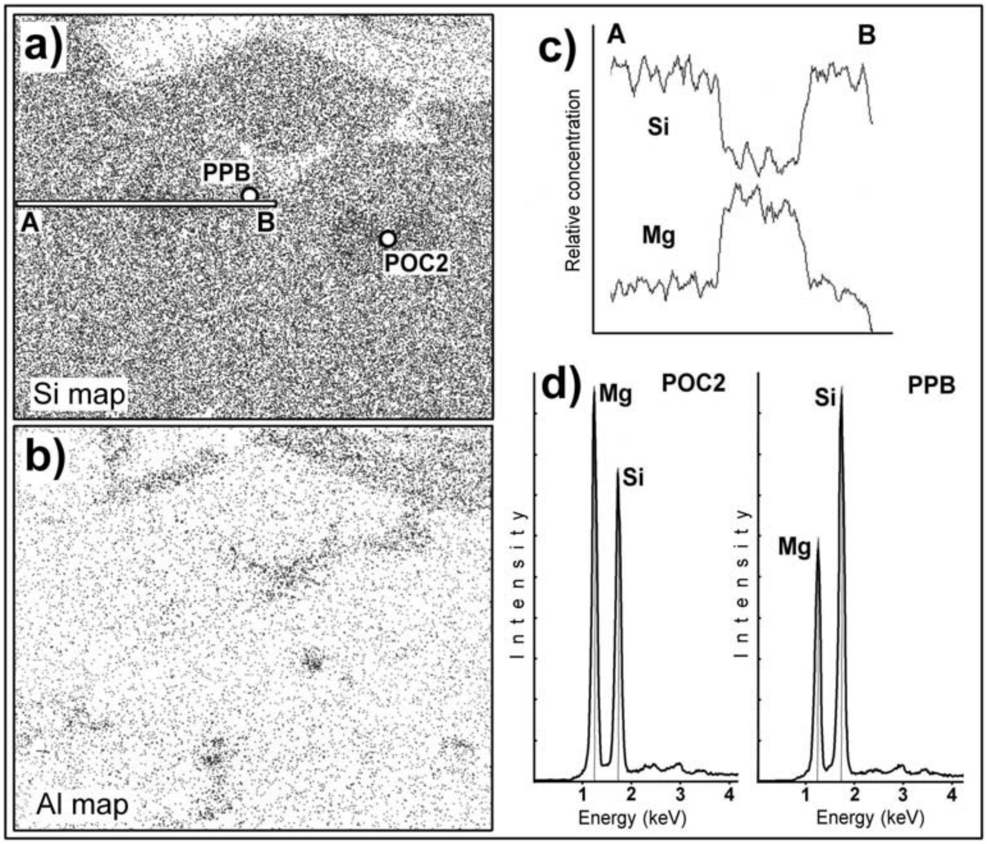

Fig. 8. Energy dispersive analysis in marginal part of a relict chondrule in the Zakłodzie meteorite (see Fig. 2): a) Si distribution map; profile line A-B shown in (c) and WDS analytical spots of olivine POC2 and pyroxene PPB are shown; b) Al distribution map; c) Si and Mg EDS profiles along A-B of figure (a); d) EDS spectra of olivine (spot POC2) and enstatite (spot PPB of figure (a)).

1975; vide Prewitt 1980) that are lacking in the case of Zakłodzie.

5. Zakłodzie is considered to be "plagioclase-enriched," igneous, enstatite meteorite (Burbine et al. 2000). However, its relative enrichment in plagioclase seems to contradict the impact-melt hypothesis. We would have to assume that the protolith, i.e., a rock of enstatite chondrite composition, was originally plagioclase-enriched, which is not supported by any evidence. On the other hand, the early cumulate crystallization of indigenous melt would evidently produce a plagioclase-enriched evolved melt, from which the parent rock of the Zakłodzie meteorite was formed. Furthermore, the latter model well explains the presence of an SiO_2 phase in the rock.

Based on the arguments and discussion above, we prefer the hypothesis of crystallization of indigenous melt as more likely and better explaining the origin of the Zakłodzie meteorite, and this model is further discussed in detail.

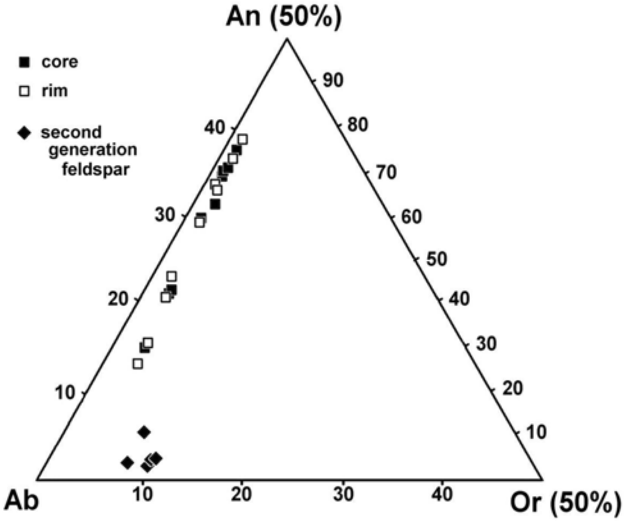

Fig. 9. Chemical composition of feldspars of the Zakłodzie meteorite; core and rim analyses of the first plagioclase generation, and the second feldspar generation are indicated.

All original features of the protolith were seemingly destroyed prior to or during the first stage of the crystallization of cumulates from the silicate magma. However, the presence of sulfides, schreibersite, and metal is evidence that the silicate magma did not separate during the melting of the protolith, suggesting that the time between the melting and crystallization processes was relatively short. Consequently, the bulk composition of the meteorite may, approximately, reflect the composition of the protolith. Thus,

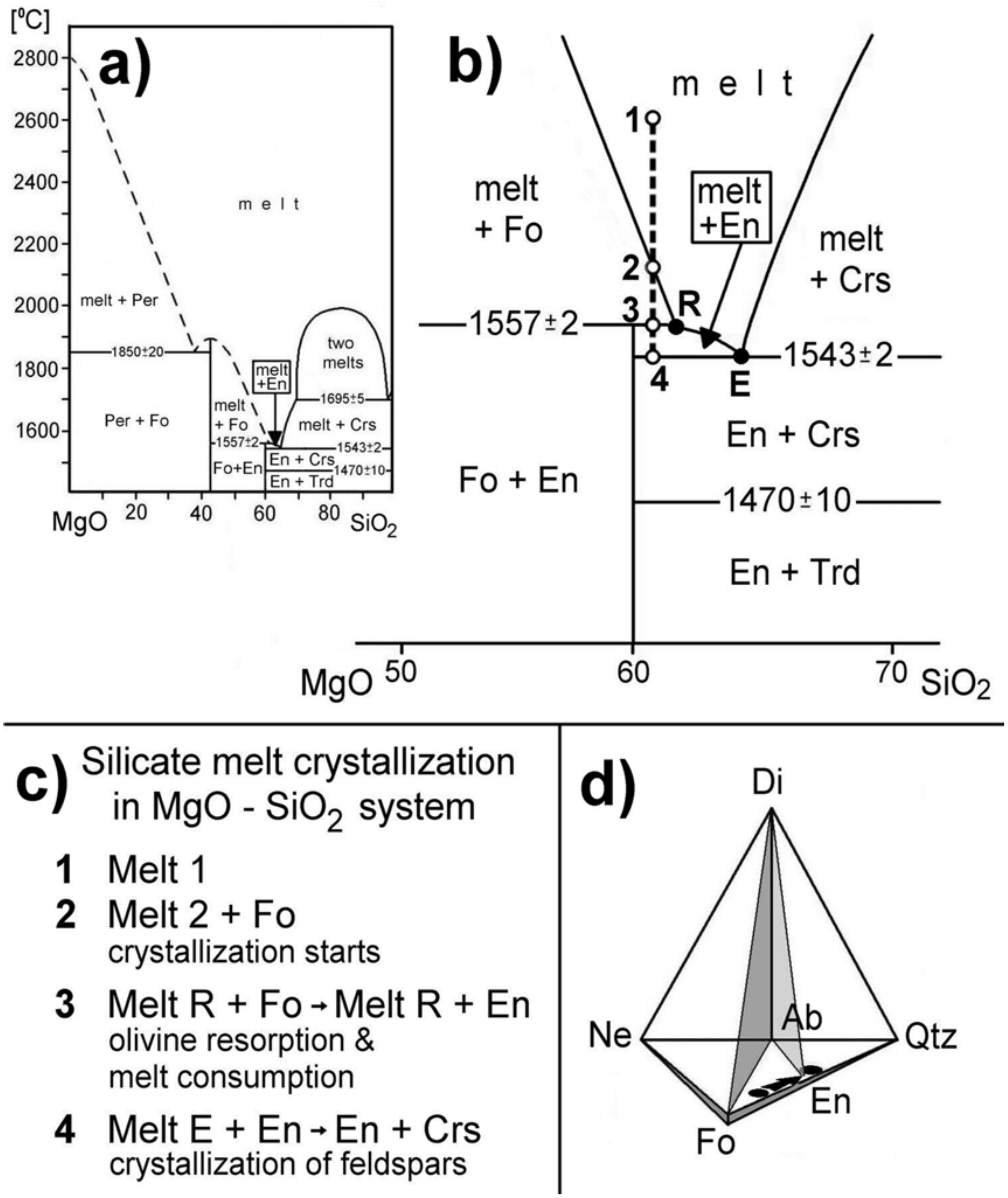

Fig. 10. Schematic crystallization path of silicates present in the Zakłodzie meteorite shown in the experimental system MgO-SiO$_2$ (a) and (b) (after Bowen and Anderson [1914]) and in the "basalt tetrahedron" (d) (after Yoder and Tilley [1962]); see text for further explanation.

the original material may have been a body of enstatite chondrite composition (EH rather than EL). Further arguments for such a protolith are: the high ratio of Ni in the schreibersite to that in the kamacite and the Ti/Cr ratio of the troilite (Fig. 12b and d). On the other hand, the Si/Ni ratio of the kamacite does not equivocally indicate whether the protolith was of EH or EL type (Fig. 12a). The problem is even more difficult when we take into account the composition of the (Mg, Mn, Fe)S sulfide, which suggests that the protolith of the Zakłodzie meteorite belonged to the enstatite chondrites EL (Fig. 12c). Summing up, the available chemical and mineralogical data do not allow us to decide whether the parent body of the Zakłodzie meteorite had the original composition of EH- or EL-type enstatite chondrites. The reason may be a high degree of melting of the parent body, while Zhang's et al. (1995) diagrams (Fig. 12) were constructed for rocks being progressively metamorphosed, but only up to the melting temperature. In any event, the question of the mineralogical type of the protolith of the Zakłodzie meteorite remains unresolved: the rock is classified

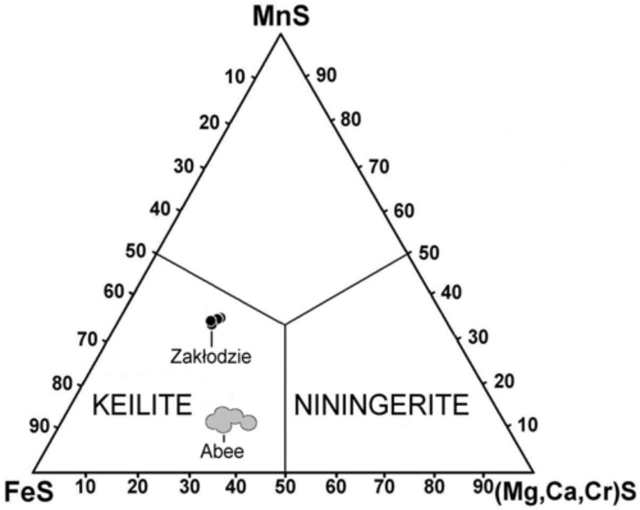

Fig. 11. Chemical composition of sulfide (Mg, Mn, Fe)S, keilite?, in a diagram by Shimizu et al. (2002). Shaded area represent chemical composition of keilite from the Abee meteorite (after Shimizu et al. 2002), while black area represent chemical composition of keilite ((Mg, Mn, Fe)S sulfide) from the Zakłodzie meteorite.

variously from β, through γ, to δ on the diagrams by Zhang et al. (1995), while as a meteorite of magmatic origin, it best fits the δ type. Such a protolith is suggested only by the chemical composition of the troilite (Fig. 12d).

The observed relics of chondrules suggest that the material of the protolith was not completely melted. It is likely that the relict chondrules are restite fragments preserved in the melt or xenoliths transported by magma on its way to external parts of the parent body. The magma movement could have caused rapid crystallization due to more effective cooling in the outer zone of the planetesimal, which prevented the complete assimilation of chondrules by melting.

We suggest that the Zakłodzie meteorite formed due to the heating and melting of a protolith of enstatite chondrite composition, possibly at a shallow depth below the surface of a planetesimal. The source of heat may have been from impact or may have been derived for instance from the decay of the ^{26}Al nuclide, abundantly present in the early stages of the evolution of the solar system; the latter mechanism is becoming widely accepted (e.g. Sanders 1996; Wood 2003).

The cumulate texture may indicate relatively slow early crystallization, inside a body large enough to maintain a sufficiently high temperature and slow cooling rate. Such a process could have happened only at an early age stage of the formation of the solar system, taking into account the relatively low decay constant of the ^{26}Al nuclide: $T_{1/2} \approx 720,000$ years. This hypotheses is supported by the ^{40}K-^{40}Ar age of the meteorite (Patzer et al. 2002).

The early stage of crystallization of the melt involved fractionation of olivine (forsterite), followed by its reaction with the melt to produce protoenstatite crystals. With decreasing temperature, this pyroxene was transformed into orthoenstatite and subsequently into clinoenstatite. At a certain moment, the crystallization process must have become accelerated as indicated by the not complete structural transformation of orthoenstatite into clinoenstatite, as well as by the formation of clinoenstatite rims on orthoenstatite crystals and skeletal crystals of plagioclase. The acceleration of crystallization may been caused by faster cooling as the melt rose to shallower depths of the planetesimal. At that time, the xenoliths taken by magma from deeper levels of the planetesimal became partly assimilated but they preserved relict chondrules. The crystallization ended with the solidification of the metal and sulfide portion of the melt.

The later thermal (magmatic) event resulted in the partial re-melting of selected components: Na and K feldspar components, metal and sulfides; it was completed with the crystallization of the second generation of feldspars (Ab- and Or-rich) and associated Fe-Ni alloys and sulfides. This event may have happened at ~2.1 Ga, the age obtained by measuring the accumulation of ^{4}He from the radioactive decay of uranium and thorium isotopes (Patzer et al. 2002). The heating and partial re-melting caused partial loss of radiogenic ^{4}He, which is more weakly bound in minerals than ^{40}Ar, what is the result of its different radiogenic origin. This may be the reason why the ages obtained by the two methods (^{40}K-^{40}Ar and ^{4}He) are different and correspond likely to two thermal events in the evolution of the parent rock of the Zakłodzie meteorite. The second thermal event was likely connected with impact and the partial melting of the parent planetesimal of the Zakłodzie meteorite. However, the limited thermal effects observed suggest that the impact took place far from the location where the Zakłodzie parent rock was formed.

This scenario assumes that the Zakłodzie meteorite represents a fragment of igneous rock, which formed from "primitive" (undifferentiated) magma, roughly corresponding in composition to the protolith. The magma reacted with the country rock (producing xenoliths) probably at shallow levels within the planetesimal. The chemical and mineral compositions of the meteorite indicate that the protolith could have been of enstatite chondrites type. Consequently, the Zakłodzie should be classified as an achondrite. Although the achondrites are considered as differentiated meteorites, there exists a group of primitive achondrites represented by acapulcoites and lodranites (which are considered to be undifferentiated melts derived from ordinary chondrites) and also winonaites (the latter having no equivalent in known chondrites). Some of these meteorites have also relics of chondrules and were formed by melting of protolith, which contained chondrule material. Subsequently, and probably in rather a short period of time not allowing for complete melting of the protolith and for significant magma differentiation, the melt migrated upwards to the surface of

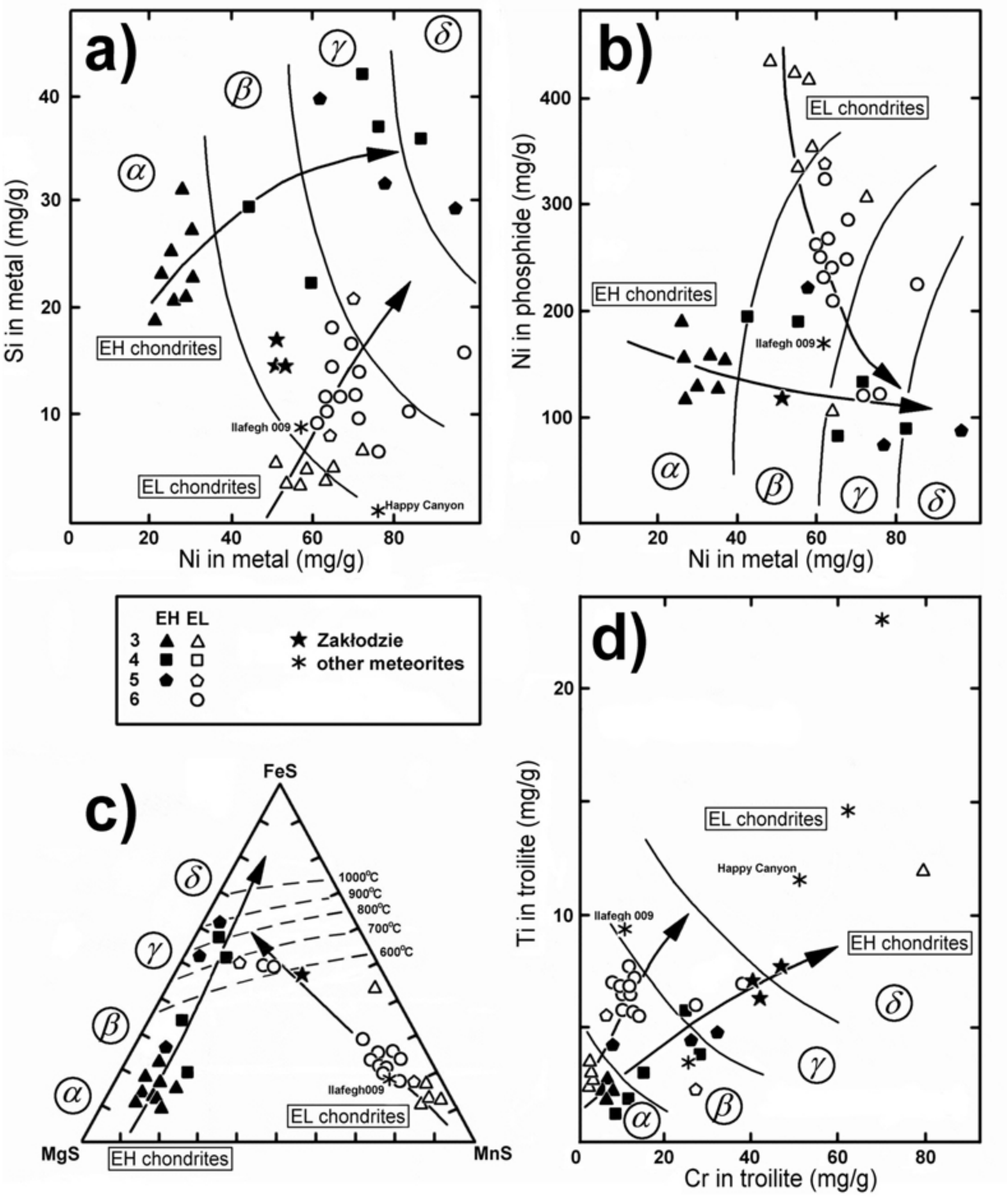

Fig. 12. Selected chemical components in the metal, troilite, schreibersite and (Mg, Mn, Fe)S sulfide of the Zakłodzie meteorite on classification diagrams for the enstatite chondrites (Zhang et al. 1995). Arrows indicate increasing metamorphism; symbols α, β, γ and δ refer to "mineralogical types" according to Van Schmus and Wood 1967 (Zhang et al. 1995): a) Si-Ni in kamacite; b) Ni in phosphide (schreibersite) and in metal (kamacite); c) chemical composition of sulfide (Mg, Mn, Fe)S, keilite?, with temperatures of crystallization of alabandite-niningerite solid solution (after Skinner and Luce 1971); d) Ti-Cr in troilite.

the parent body (Mittlefehldt et al. 1996; McCoy et al. 1997; Benedix et al. 1998; Bischoff 2001). By analogy, Zakłodzie crystallized from a melt derived from enstatite chondrite and still retains its primordial composition. Because of its old crystallization age, it should be considered a primitive enstatite achondrite.

The proposed new classification of the Zakłodzie meteorite is substantiated even if the impact-melt origin is preferred (not our preference). The reasons for protolith melting are not as important for classification as the following: re-melting of chondrite material, rather insignificant unmixture of magma and preservation of protolith relics, the crystallization age of the rock that is close to the age of the solar system. A similar interpretation was presented by Folco et al. (2004) for the impact-melt breccia from the H-chondrite parent body represented by the Dar al Gani 896 meteorite classified by those authors as a primitive achondrite.

In our discussion of the systematic position of the Zakłodzie meteorite, we should consider its relationship to the aubrites. This meteorite cannot be classified as belonging to that group because it contains too large amount of metal and sulfides as well as plagioclase components. However, its composition indicate that Zakłodzie could have crystallized from a magma left after fractional crystallization of aubrites in a magma chamber close to the surface of the parent body. This would explain enrichment in plagioclase relative to aubrites. This statement needs further detailed examination of Zakłodzie and other plagioclase-enriched, igneous, enstatite meteorites.

At least one more question remains open: the incompletely resorbed olivines within the enstatite crystals in the outer parts of relict chondrules could be witnesses to even earlier processes of transformation of olivine into pyroxene and, connected with the removal of excess water (Hutson and Ruzicka 2000) during the formation of the enstatite chondrites or the chondrules themselves, before 4.4 Ga, i.e., at the very early stage of the solar system formation. This question may be very difficult to answer.

CONCLUSIONS

Our new mineralogical, petrological, and chemical data suggest that the Zakłodzie meteorite is a fragment of igneous rock with a cumulate texture. The magma from which the rock crystallized did not exist long enough to allow efficient differentiation. The crystallization of the magma was probably accelerated as the magma ascended to shallow depths within the planetesimal. The rapid solidification prevented or limited complete assimilation of the xenoliths in the magma. This magmatic event happened, most likely, at ~4.4 Ga. Subsequently, the parent rock of the meteorite went through a second thermal event, probably caused by an impact at ~2.1 Ga. The impact, however, only moderately influenced the parent rock (with limited partial melting), which suggests that it happened far from the location of the Zakłodzie parent rock. The xenolithic fragments of the protolith containing relict chondrules and the mineral composition of Zakłodzie suggest that the protolith of the meteorite was, most likely, of the enstatite chondrite composition. We propose classifying the Zakłodzie meteorite as a primitive enstatite achondrite.

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Editorial Handling—Dr. Randy Korotev

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