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**GEOCHEMISTRY**

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## Thermobarometry of Ordinary Chondrites

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Ordinary chondrites are the most abundant type of meteorites. However, their genetic interpretation, accepted in modern literature and based on independent investigations of the formation of droplike silicate chondrules and the kamacite matrix, is obviously inconsistent with results of their petrographic and experimental studies [1], indicating the joint formation of the chondrules and chondrite matrix as a result of the development of iron–silicate immiscibility, which defined their compositional relationships according to Prior's rules. The chondrites exhibit typical magmatic textures with a normal crystallization sequence of silicates (Ol → Px → Cpx), which is similar to that of magmatic rocks in planets of the earth group with their characteristic subdivision into volcanic (I, with distinct zoning of mineral grains) and glass-bearing subvolcanic (II, with homogeneous grains), and completely crystallized plutonic (III, with homogeneous mineral grains) facies. Unlike carbonaceous chondrites, most of the ordinary chondrites are generally characterized by a relatively fresh appearance and insignificant superposition of late hydrothermal processes. Therefore, they are distinctly subdivided into the aforementioned magmatic facies (I, II, III): group H includes Yamato(Y)-82133 I (3), Raguli II (3.8), and Okhansk II (4); group L includes Y-74417 I (3), Saratov II (4), Fuchbin III (6), and Berdyansk III (6); and group LL includes Y-74160 III (7).

These concepts disagree with the generally accepted ones, according to which the diversity of petrological types of ordinary chondrites is related to the so-called thermal metamorphism. The issue of the origin of ordinary chondrites may be elucidated by the application of modern geothermometers and geobarometers for the evaluation of *PT* parameters of the formation of their different types. In this paper, conditions of the formation of aforementioned chondrites are estimated from pyroxene equilibria data presented in Table 1.

Pyroxene thermometry has already been applied for constraining the formation temperature of LL chondrites. The crystallization temperature of the chondrites of facies III is 900–1150°C based on clinopyroxene compositions and 100–200°C lower based on orthopyroxene compositions [9]. The differences are even more significant for the chondrites of facies I and II. In our work [11], the crystallization temperature of ordinary chondrites of all chemical groups was determined using several geothermometers [2, 6, 13, 14] based on the distribution of Ca, Mg, and Fe between ortho- and clinopyroxenes (Fig. 1). The crystallization temperature of chondrules was determined from compositions of ortho- and clinopyroxenes, which are the most abundant minerals (in addition to olivine) of ordinary chondrites. The representative analyses of coexisting pyroxenes are shown in Table 1. Relationships of the iron index in pyroxenes are shown in Fig. 2. All the data used for the chondrites are well consistent with compositional variations in coexisting natural (terrestrial) pyroxenes.

The applied models showed a good agreement with experimental data ( $\pm 50^\circ\text{C}$ ) and Ol–Cpx geothermometer [8] data obtained for natural assemblages ( $\pm 15^\circ\text{C}$ ). Scatter of values determined for the same meteorite assemblages by different models is within  $\pm 48^\circ\text{C}$ . The crystallization temperatures of chondrules of the ordinary chondrite of facies III determined by two-pyroxene geothermometer [2, 6, 13, 14] vary insignificantly ( $\pm 48^\circ\text{C}$ ), and the temperatures calculated by each of these thermometers (for example, [13], Table 3) are nearly constant (Berdyansk  $\pm 7^\circ\text{C}$ , Fuchbin  $\pm 19^\circ\text{C}$ , and Y-74160  $\pm 52^\circ\text{C}$ ). By contrast, the chondrules of ordinary chondrites of facies I and II crystallized within a wide temperature range (Table 2, 938–1466°C for facies I and 890–1479°C for facies II). The crystallization temperature of type III is well consistent with the crystallization temperature of equilibrium chondrites of the chemical group LL estimated from the clinopyroxene composition [9], whereas the upper temperature limit of chondrites of facies I and II is 150–200°C higher than that in [9].

The obtained crystallization temperatures of different consolidation facies of ordinary chondrites are well

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**Table 1.** Compositions of coexisting pyroxenes (Cpx and Opx) in the ordinary chondrites of different facies types (I–III)

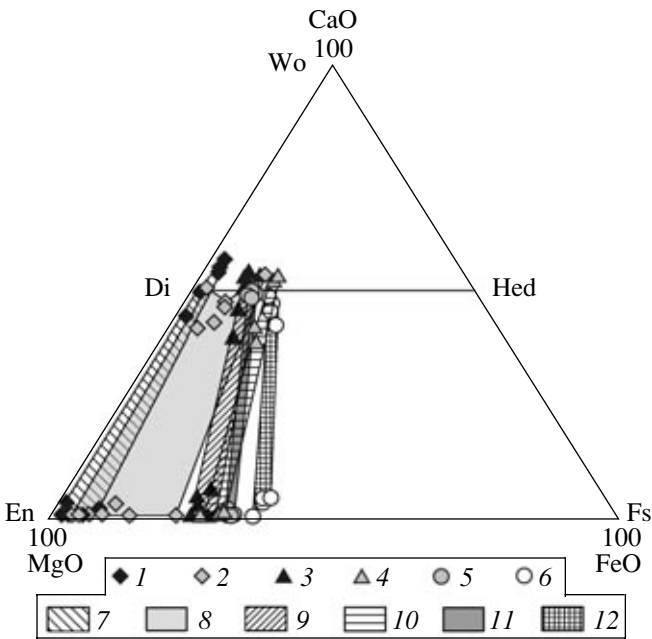
Component	Y-82133 H (I)		Y-74417 L (I)		Raguli H (II)		Saratov L (II)		Fucbin L (III)		Y-74160 LL (III)	
	Cpx	Opx	Cpx	Opx	Cpx	Opx	Cpx	Opx	Cpx	Opx	Cpx	Opx
SiO <sub>2</sub>	49.17	58.27	52.56	58.97	53.51	55.60	53.85	52.44	54.42	55.64	53.38	53.59
TiO <sub>2</sub>	1.20	0.20	0.53	–	0.60	0.16	0.83	–	0.47	0.07	0.41	0.22
Al <sub>2</sub> O <sub>3</sub>	8.64	1.08	4.04	0.35	0.80	–	4.05	–	0.71	0.27	0.89	0.36
Cr <sub>2</sub> O <sub>3</sub>	2.46	1.09	2.24	0.51	0.99	0.18	–	–	1.12	0.37	1.26	0.53
FeO	0.82	2.16	0.50	2.53	3.62	10.72	5.64	14.64	4.52	13.78	6.55	16.43
MnO	0.32	0.00	2.06	–	0.22	0.47	0.45	0.31	0.18	0.38	0.38	0.50
MgO	15.97	36.71	18.59	36.53	17.42	29.86	17.07	31.92	17.01	28.91	16.04	26.14
CaO	20.97	0.49	19.04	0.50	22.39	2.99	16.86	0.14	20.89	0.58	20.38	2.20
Na <sub>2</sub> O	0.66	–	0.43	0.43	0.45	–	1.24	0.54	0.69	–	0.71	0.03

Note: (–) Contents below the detection limit.

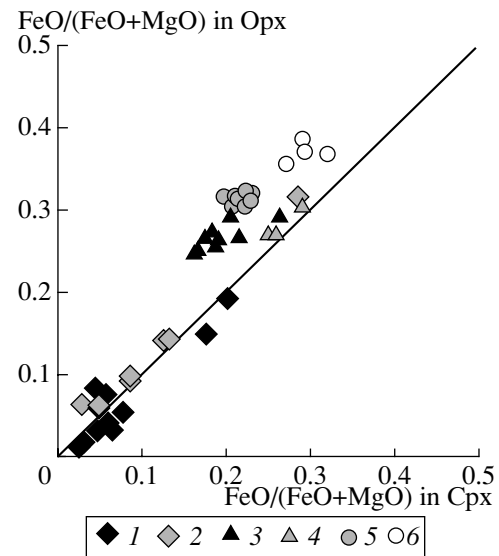
correlated with crystallization temperatures of terrestrial volcanic and plutonic rocks. The glass-bearing chondrites (I and II), which crystallized under higher and wider-range temperatures, have a more contrasting polyfacies composition relative to the chondrites of the plutonic facies III, which formed at a lower and relatively persistent temperature (Table 2, Fig. 3).

Attempts to evaluate the pressure and elucidate *PT* conditions of the formation of ordinary chondrites of

group LL based on the incorporation of Al and Ca in clinopyroxene and orthopyroxene, respectively, in [9] were unsuccessful owing to low contents of these elements. In the present paper, the crystallization pressures of magmatic assemblages of each facies of H, L, and LL chondrites were determined from the clinopyroxene geobarometer [10]. The pressure calculation using model [10] is based on the pressure dependence of the unit-cell parameters (volumes of the unit cell and M1 polyhedron) of crystallizing clinopyroxenes. This model depends less on the melt composition and mineral assemblages than the previous models. The applicability of this model for estimating crystallization pressure of clinopyroxene in chondrites is discussed in detail in [11], which showed that the convergence with



**Fig. 1.** Compositional variations in ortho- and clinopyroxenes of various consolidation facies of H (1, 3), L (2, 4, 5), and LL (6) chondrites: (1, 2) volcanic, (3, 4) subvolcanic, (5, 6) plutonic; (7–12) fields of tie lines connecting coexisting ortho- and clinopyroxenes from Y-82133 H, Y-74417 L, Raguli H, Saratov L, Fucbin L + Berdyansk L, and Y-74160 LL + Uden LL chondrites, respectively.



**Fig. 2.** Variations of FeO/(FeO + MgO) in equilibrium ortho- and clinopyroxenes of different magmatic facies of H, L, and LL chondrites (symbols correspond to 1–6 in Fig. 1).

**Table 2.** Results of thermobarometric study of ordinary chondrites of different facies types (I–III)

Facies	Chondrite	N	T, °C		P, kbar	
			interval	average	interval	average
I	Y-82133 H	12	938–1466	1190	0–15.9	8.4
	Y-74417 L	11	1106–1307	1207	3.6–12.2	7.7
II	Raguli H	11	890–1479	1193	0–13.7	6.0
	Raguli H, Ur-Jd Cpx	4		1000	63.7–81.6	70.1
	Saratov L	5	900–1203	1129	0–14.6	5.9
III	Berdyansk L	6	985–1000	993	3.8–5.1	4.5
	Berdyansk L, Ur-Jd Cpx	8		1000	66.9–72.8	69.6
	Fuchin L	7	992–1030	1011	3.6–8.3	5.7
	Y-74160 LL	2	1000–1105	1053	3.1–5.0	4.0

Note: (N) Number of analyzed grains. Temperature was calculated with the two-pyroxene geothermometer [13]; pressure, with clinopyroxene geobarometer [10]. Compositions of pyroxene pairs for chondrite Y-74160 LL(III) were taken from [12].

experimental data is  $\pm 1.13$  kbar (maximum deviation 3.86 kbar) for a pressure range of 0–18 kbar; i.e., the calculated pressures ( $>5$  kbar) can be taken as significant values.

The average pressure values (Table 2) yielded by the clinopyroxene geobarometer [10] for ordinary chondrites of different facies (I–III) and groups (H, L, and LL) vary from 4 to 8.4 kbar, while the crystallization pressure of clinopyroxenes in equilibrated chondrites of facies III varies within a narrower range (3.1–8.3 kbar) than those of unequilibrated chondrites of facies I and II (0–10.6 kbar). In addition, the chondrites of facies I and II contain single clinopyroxene grains that crystallized under higher pressures (up to 16 kbar). This reflects the polyfacies composition of glass-bearing chondrites, which were formed from deeper sources than real plutonic rocks

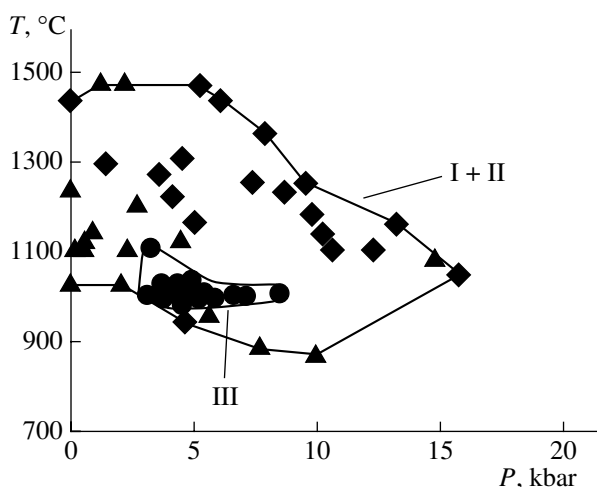
represented in the diagram (Fig. 3) by chondrites Fuchin L(III), Berdyansk L(III), and Y-74160 LL(III).

Thus, the obtained data unambiguously indicate that clinopyroxenes from ordinary chondrites crystallized at pressures and temperatures (900–1500°C) typical of magmatic rocks. The most typical pressure range is 0–10.6 kbar (occasionally, up to 16 kbar).

In addition to our data, the presence of protopyroxenes in chondrites of facies I–III constrains the crystallization pressure to 8 kbar [5]. The scarce presence of protopyroxenes in plutonic chondrites suggests that the pressure during their formation could exceed 8 kbar.

Ordinary chondrites of all three facies contain relict grains with exsolution lamellae [1, 15], which crystallized prior to silicates predominating in the chondrites. Based on the clinopyroxene barometer [10], relict jadeite–ureyite clinopyroxene grains crystallized at a pressure of 82 kbar (Table 2). The second variety of relict grains—silica–clinopyroxene solid solutions first found in ordinary chondrites [15]—are comparable with terrestrial high-pressure solid solutions [7]. These solid solutions were synthesized at pressures of 35–150 kbar [3, 4]. The findings of relict grains of high-pressure minerals indicate that the stage of chondrite melt crystallization recorded in chondrite structures was preceded by high-pressure crystallization ( $>60$  kbar).

Thus, results of the thermobarometric study of ordinary chondrites support the model of two-stage formation of the chondrites scrutinized in [1]. The thermobarometric investigations recorded both conditions of high-pressure ( $>60$  kbar) crystallization at the protoplanetary to planetary transition stage and *PT* crystallization conditions at the planetary stage, which preceded the breakup of chondrite planets into asteroids.



**Fig. 3.** General diagram for determination of *PT* parameters of the crystallization of ordinary chondrites: (I) volcanic, (II) subvolcanic, and (III) plutonic.

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