EVALUATION OF THE CRYSTALLIZATION TEMPERATURES AND PRESSURES FOR CLINOPYROXENE IN THE PARENTAL BODIES OF ORDINARY CHONDRITES

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Thermo- and barometry of clinopyroxene in ordinary chondrites indicates that, regardless of the chemical groups and petrological types of chondrites, they crystallized from chondritic melts at pressures of >0 kbar.

McSween & Patcheon [5] applied pyroxene thermometry to constrain the formation temperatures of LL chondrites and evaluated these temperatures at 900–1150ºC for meteorites of different petrological types: LL3 and LL7. The pressures under which meteorites were produced were evaluated in [5] by the Al concentrations in clino- and orthopyroxene. In this paper, the crystallization temperatures of chondrites were evaluated using a number of geothermometers, and the pressures were estimated by the clinopyroxene geobarometer [6] for the crystallization of the magmatic mineral assemblages in meteorites of each type.

All two-pyroxene thermometers are underlain by the utilization of the Ca, Mg, and Fe distribution between ortho- and clinopyroxene. We used a selection of experimental data to test different published variants of the two-pyroxene geothermometer and have obtained the best agreement with experimental data (±50°C) for the thermometer models [10, 9, 1A, 7]. These models of the thermometer were then tested using natural (terrestrial) assemblages for agreement with the olivine–clinopyroxene geothermometer [2]. The differences between the temperatures yielded by this olivine–clinopyroxene geothermometer and the aforementioned variants of the two-pyroxene geothermometers lie within ±15°C. The values determined by the models [10, 9, 1A, 7] for the same assemblages from meteorites are scattered within ±48°C. Hence, the accuracy of the geothermometers utilized in our research can be assumed as ±50°C.

Pressure evaluations by the model [6] are based on the baric dependences of some unit-cell parameters of crystallizing clinopyroxene (the volume of its unit cell and the M1 polyhedron) and are dependent not so crucially on the melt composition and the mineral assemblage. Nevertheless, these are a number of calibrations of this geobarometers proposed for melts having different compositions and existing under different conditions. The calibration most suitable for meteorites (of planetary proper stage) is that developed for terrestrial tholeiitic basalts and characterized by practically anhydrous (<0.1 wt.% H_2O) reduced conditions. The experimental data utilized in this model cover a pressure range of 0–18 kbar, and the differences between the values yielded by this model and experimental data are ±1.13 kbar at the maximum deviation of 3.86 kbar. Thus, it can be safely presumed that calculated pressures of >5 kbar are significant. The differences between tholeiitic basalts and meteorites and temperature uncertainties can introduce additional uncertainties into the pressure estimates. As was demonstrated above, the temperatures are determined by two-pyroxene thermometers accurate to ±50°C. An increase in the temperature inputted into the model by 100°C results in a decrease in the pressure estimate by 2.5–3 kbar for pressures of <25 kbar and by 1–1.5 kbar for pressures of >25 kbar. The temperatures determined by the two-pyroxene thermometers correspond to the temperatures of the latest equilibrium between the clino- and orthopyroxene and can be somewhat underestimated with respect to the actual values if the clino- and orthopyroxene could continue exchanging components after crystallization. Thus, the uncertainties in the temperature estimates can lead to pressure overestimates by 2.5–3 kbar. At the same time, some of the calculated pressure values can lie far outside the range of the experimental data against which the model [6] was calibrated. At $P \geq$ 20 kbar, the calculated pressure is systematically lower than the experimental values [6], so that the values thus obtained can be underestimated. The effect of other factors (such as high alkalinity or high water contents) that can significantly shift the pressure estimates are negligibly small for meteorites.

Ordinary chondrites	T, ºC*	P, kbar**
Yamato-74417 LI(3) av.##	1106-1306 (10)# 1210	3.6-12.2 (10) 7,4
Yamato-82133 HI(3) av.	938-1476 (10) 1218	0-14.1 (10) 8.4
Saratov LII(4) av.	1032-1204 (3) 1122	0.1-4.4 (3) 2.4
Raguli HII(3.8) av.	890-1464 (12) 1104	0-13.7 (12) 5,3
Raguli HII(3.8) Ur-Jd CPx av.	1000	63.7-81.6 (4) 70.1
Berdyansk LIII(6) av.	985-1000 (6) 993	3.8-5.1 (6) 4,5
Berdyansk LIII(6) Ur-Jd CPx av.	1000	66.9-72.8 (8) 69,6
Fucbin LIII(6) av.	992-1030 (7) 1011	3.6-8.3 (7) 5,7
Yamato-74160 LLIII(7)### av.	1000-1005 (2) 1053	3.1-5.0 (2) 4,0

* — temperatures calculated by the two-pyroxene geo thermometer [9]
** — pressures calculated by the clinopyroxene geobarometer [6]
# — amount of analyzed grains
— average temperature, pressure
— composition of pyroxene pairs from the Yamato-74160 LLIII(7) chondrite were borrowed from [8]

The table lists the temperatures and pressures of clinopyroxene crystallization in ordinary chondrites of different chemical groups and petrological types: low—I(3.0–3.7), intermediate—II(3.8–4), and high—III(5–7), as exemplified by Yamato-82133 I(3), Raguli II(3.8), and Okhansk II(4) (group H); Yamato-74417 I(3), Saratov II(4), Fucbin III(6), and Berdyansk III(6), (group L). The table also presents the analogous values for clinopyroxene from other ordinary chondrites [8].

Our data definitely indicate that clinopyroxene in all of the ordinary chondrites crystallized under pressures of >0 kbar (whatever the chemical group or the petrological type of the meteorite). The most typical pressure range is 0–10 kbar. Some early chondrules that bear pyroxene and olivine grains with compound zoning (normal zoning giving way to reversed one and reflecting two stages of meteorite formation [3]) yield pressures of up to 14.5 kbar. Some ordinary chondrites contain relict clinopyroxene grains of jadeite–ureyite composition [4, 11-13], for which the crystallization pressure was evaluated (by the clinopyroxene barometer [6]) at 63–71 kbar.

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