Compositional traits and thermobarometry of the Chelyabinsk meteorite.

L.I. Glazovskaya, N.G. Zinovieva, P.Yu. Plechov, Department of Petrology, Faculty of Geology, Moscow State University, Vorob'evy Gory, Moscow 119991, Russia (glazov@geol.msu.ru).

Introduction: The Chelyabinsk meteorite fell in the vicinity of the town of Chelyabinsk, Russia, on February 15, 2013, and this event was witnessed by thousands of persons. At a height of 30-50 km [11], the meteorite exploded with a flare and broke up into numerous fragments. Its largest fragment (570 kg) was lifted from Chebarkul Lake. We examined a fragment (2 by 1.4 cm) of this meteorite, which had an outermost black fused rind varying from a few fractions of a millimeter to 1 mm in thickness. The meteorite is classed with ordinary chondrites of the LL5/S4-WO class [1]. One-third of the found fragments of this meteorite show evidence of shock-induced transformations.

New observations:

The fragment we studied exhibits no traces of shock metamorphism (such as fractures filled with impact melt and/or planar elements). Chondrules and their fragments make up a little less than half of the meteorite by volume and are clearly pronounced round objects of barred, radiating, beam, porphyritic, or granular texture. The chondrules consist mostly of olivine ($\boldsymbol{Fa}_{29\text{-}30}$) and orthopyroxene ($\boldsymbol{En}_{75}$ $\boldsymbol{Fs}_{24\text{-}25}$) and contain clinopyroxene ($\boldsymbol{En}_{44\text{-}46}$, $\boldsymbol{Wo}_{43\text{-}45}$, $\boldsymbol{Fs}_{7,5\text{-}9}$), and plagioclase ($\boldsymbol{An}_{10\text{-}15}$, $\boldsymbol{An}_{17\text{-}22}$). The orthopyroxene contains minor Ca and Al admixtures, and the clinopyroxene contains some Na, Ti, and Cr. The matrix also consists of a coarse-grained aggregates of olivine, orthopyroxene, clinopyroxene, and plagioclase of the same composition as in the chondrules.

Similar to the matrix, the metallic phase of the chondrules consists of kamacite and taenite, which bear inclusions of troilite, ilmenite, and chromite. Apatite was found near boundaries between chondrules and groundmass. The olivine and orthopyroxene are not zonal, and their relations suggest their equilibrium crystallization, as can be clearly seen in the granulated chondrule in shown Fig. 1 and the matrix in Fig. 2. The chemical composition of the minerals was analyzed at the Laboratory of Analytical techniques of High Spatial Resolution at the Geological Faculty, Moscow State University, using a Jeol JSM-6480LV scanning microscope equipped with an INCA-ENERGY-350 EDS analytical setup, at an accelerating voltage of 20 kV and current of 2 nA.

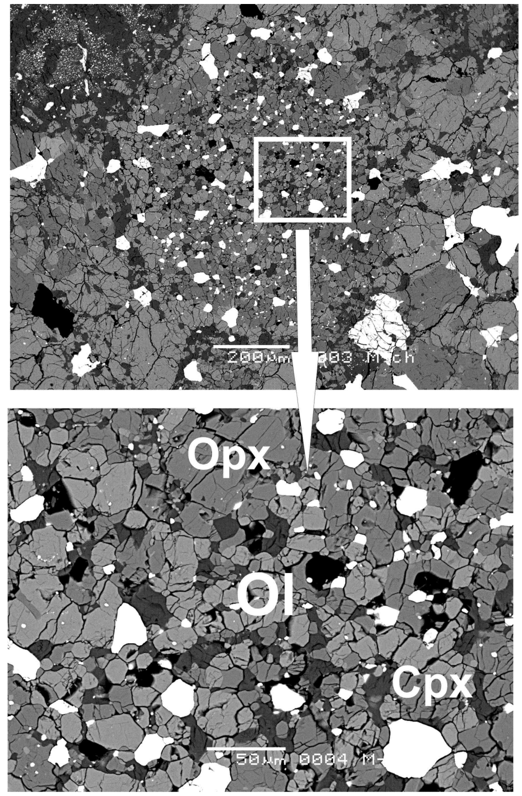

Fig1. Chondrule showing evidence of normal magmatic crystallization sequence of minerals: *Ol → OPx → CPx*.

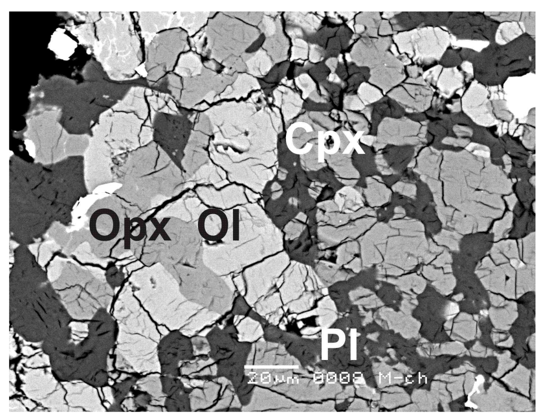

Fig. 2. Coarse-grained matrix of the Chelyabinsk meteorite.

Results and discussion: The temperatures and pressures were evaluated using the olivine-clinopyroxene-orthopyroxene assemblage by the method described in [5, 9]. The temperature was also estimated by the two-pyroxene geothermometer in versions [4, 6, 7], which yielded closely similar temperature values constrained within the range of 890-915^{0}C, measured accurate to 52^{0}C. The crystallization temperatures of the chondrules was calculated by the olivine-clinopyroxene equilibrium [2] and was somewhat higher: 933^{0}C. This difference likely stems from the errors of the thermometers, which were calibrated for terrestrial rocks but were now applied to meteorites. The pressure was evaluated by assuming that the temperature was within the range of 900-930^{0}C.

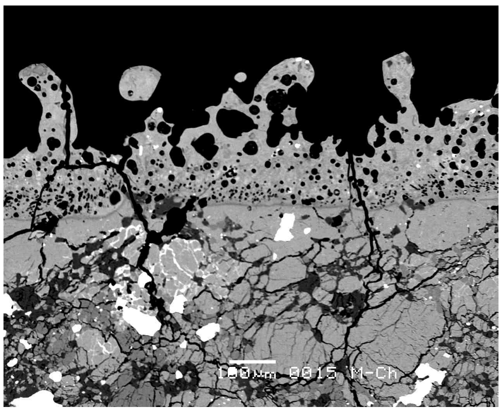

Fig 3. Rim of glass around fragment of meteorite Chelyabinsk. Ablation traces are visible.

The crystallization pressure of the chondrites evaluated by model [3] is underlain by a pressure dependence of the unit-cell parameters of clinopyroxene. The applicability of this model to evaluating the crystallization pressure of clinopyroxene in ordinary chondrites is discussed in [5]. The pressure estimates lie within the range of 6.1-6.8 kbar. The effect of a temperature underestimate on pressure calculation by this technique is insignificant at pressures <20 kbar. According to data in [10], the crystallization temperature of clinopyroxene in ordinary chondrites of various chemical groups and petrological types varies from 900 to 1500^{0}C (these temperatures correspond to the temperatures of magmatic processes), and the pressure varies from 0 to 10.6 kbar (occasional clinopyroxene grains crystallized under pressures as high as 14.5 kbar).

Fused rinds. Fragments of the Chelyabinsk chondrite were produced by an explosion of the main meteorite body above the Earth's surface. Upon the explosion, the fragments falling onto the Earth's surface were partly fused in the atmosphere and now have outermost glassy rinds of variable porosity (Fig. 3). The marginal part of the rinds shows traces of ablation. The composition of the fused rinds corresponds to a mix of olivine and orthopyroxene with minor amounts of plagioclase, clinopyroxene, metallic constituents (kamacite and taenite), and troilite. The bulk composition of the rinds was evaluated by scanning an area of 400 µm^2 by an electron beam and is as follows: Na_2O 0.1-0.9, MgO 27-35, Al_2O_3 0-2.4, SiO_2 36-42, K_2O 0.1, CaO 0-1.6, MnO 0.3-0.5, FeO 25-25.6, NiO 0-0.5. During the rapid melting of the meteorite and cooling of the melt, the melt had not enough time to homogenize. The opaque glassy rind contains skeleton magnetite crystals ranging from a few fractions to 2 µm, which also crystallized at the rapid cooling of the melt in an oxidizing environment. The temperature of the melt whose quenching resulted in the glassy rind should have been higher than 1300 - 1557^{0}C (the solidus temperature) according to melting diagrams for the *Fa-An* and *Fo-En*-SiO_2 systems [8].

Conclusions: Our data on the chondrule and matrix minerals allowed us to evaluate the temperature and pressure by the olivine-clinopyroxene-orthopyroxene assemblage. The textural traits of the chondrules and matrix with a normal magmatic crystallization succession of minerals and the narrow ranges of temperature (890-950^{0}C) and pressure (6.1-6.8 kbar) suggest that the minerals crystallized in equilibrium from a chondritic melt at a certain depth in the parent body. Our pressure estimates for clinopyroxene crystallization in the parent body make it possible, according to data in [9], to evaluate the radius of the parent body during the planetary episode of its evolution at 600 - 700 km.

Acknowledgments: The authors thank the Committee on Meteorites of the Russian Academy of Sciences for providing us with the sample.

References:[1] Galimov (2013) Geochemistry №7,580-598.[2];Loucks(1996)Contr.Min. And Petrol. V. 125. 140-150; [3] Nimis (1999) *Contr. Min. Petr.* **135**, 62-74; [4] Perchuk (1977) Doklady AN USSR **233**, N 3, 456-459; [5] Plechov et al. (2005)In *LPS XXXVIII*, 1041#; [6] Wells (1977) *Contr. Min. Petr.* **62**, 129-139; [7] Wood &Banno S. (1973) *Contr. Min. Petr.* 1973. 42, 109-124; [8] Zharikov (2005) Основы физической геохимии. Moscow, 653; [9] Zinovieva et al.,(2005)In *LPS XXXVIII*; [10] Zinovieva *et al.* (2006) Thermobarometry of Ordinary Chondrites *Doklady Earth Sciences, , 409, No 5,758-761;* [11]http://www.ras./news/shownews.aspx?id=1da2959b-902f-46b2-9f1f-0cb2d19740t8#content.