Experimental Modeling of the Formation of the Metallic Core of the Moon by the Method of High-Temperature Centrifuges

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Abstract: At early stages of the formation of planetary bodies, silicate, metallic, and sulfide phases, which have been formed in the course of the partial or complete fusion of the initial planetary substance, were subject to a gravitational differentiation. The latter is related to the separation of the crystalline and molten phases in density and composition. Althose in recent years a number of papers deal with the experimental and theoretical determination of the processes of the percalation of metallic melts through the crystalline silicate matrix and the physical properties of the metallic and sulfide melts. For the Moon, the problem of the existence of the metallic or sulfide core still remains unsolved. There is stil the nessity of further investigation in this direction. The possible origin of the Moon's metallic core at the precipitation of iron-sulfide phases during the partial melting of ultramafic material under various redox conditions was experimentally modeled by partially melting the model system olivine (85 wt %)+ ferrobasalt (10 wt %)+ metallic phase $Fe_{95}S_5$ (5 wt %) in a high-temperature centrifuge at 1430-1450°C.

Keywords: Origin of the Moon, Experiment, High-Temperature Centrifugation, Partial Melting, Iron Fractionation, Metallic Core

1. Introduction

The number of the papers deal with the experimental and theoretical determination of the processes of the percolation of metallic melts through the crystalline silicate matrix and the physical properties of the metallic and sulfide melts, there is still the necessity of further investigation in this direction.

It includes the concentration, thermal and phase convection, the mechanisms of which are thought to be rather intricate A. P. Vinogradov, 1975 [1].

A possible result of these processes is the formation of cores and external silicate shells of terrestrial planets and the Moon. For the Moon, the problem of the existence of the metallic or sulfide core still remains unsolved (Its solution is crucial for understanding the mechanism of moon formation in General and its evolution [2, 3]

Although in recent years a number of papers deal with the experimental and theoretical determination of the processes of the percolation of metallic melts through the crystalline silicate matrix. There is still the necessity of further investigation. [4-6]

These are a number of papers deal with the influence of the deformation on segregation of phases [8, 9].

According to E. M. Galimov's model for the origin of the Earth-Moon system [2, 6], the Moon was formed of the material of originally chondritic composition during the fragmentation of a dust accumulation, from which both the Moon and the proto-Earth were produced.

Data obtained by experimentally modeling the segregation and accumulation of iron-sulfide melt phases in high-temperature centrifuges show that the percolation of the

metallic phases through silicate matrix in partial melting zones depends not only on the degree of partial melting (temperature) and the metal content but also on the composition of the equilibrium phases of the system [5], with these parameters notably affecting the rheology of silicate and metallic melts and their interaction with one another and the crystalline phases of the silicate matrix (wettability, viscosity, surface tension, electrical conductivity, elastic wave velocity etc).

2. Simulation Method

The segregation of the iron-sulfide metallic phase during partial melting was modeled by means of high temperature centrifugation [5, 12].
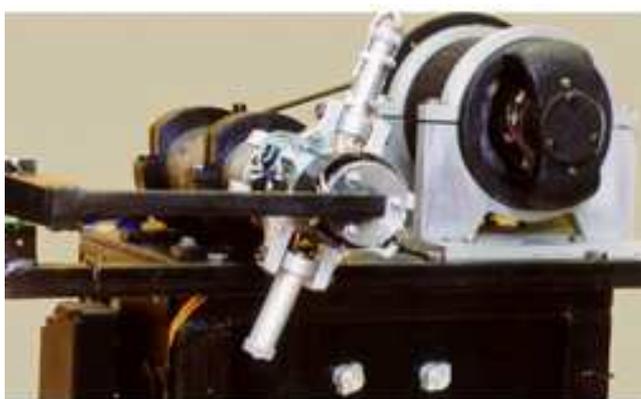

Figure 1. High-temperature centrifuge.

The experimental setup was a centrifuge (3000-6000 rpm) of original design equipped with a heater [5, 12]. The container with the sample was ~1 cm long, and the rotation radius was 11 cm. The setup is able to imitate 2000 to 4000 g gravitation, and the heater maintains an even temperature field throughout the whole sample length at experimental temperatures of 1430-1450°C. Different redox conditions during the experiments wereensured by various materials around the sample: they

contained various metals (iron-based alloys, tungsten, etc.), graphite, and other carbon-bearing materials. Oxygen fugacity $lgfO_2$ at any given temperature was evaluated from the composition of the quenched phases after the experiments, using three different methodological approaches, which will be described in more detail below.(Lebedev. Kadik, "High temperature centrifuge," RF Patent no. 2082786, Byull. Isobret. No. 18, (1997)).
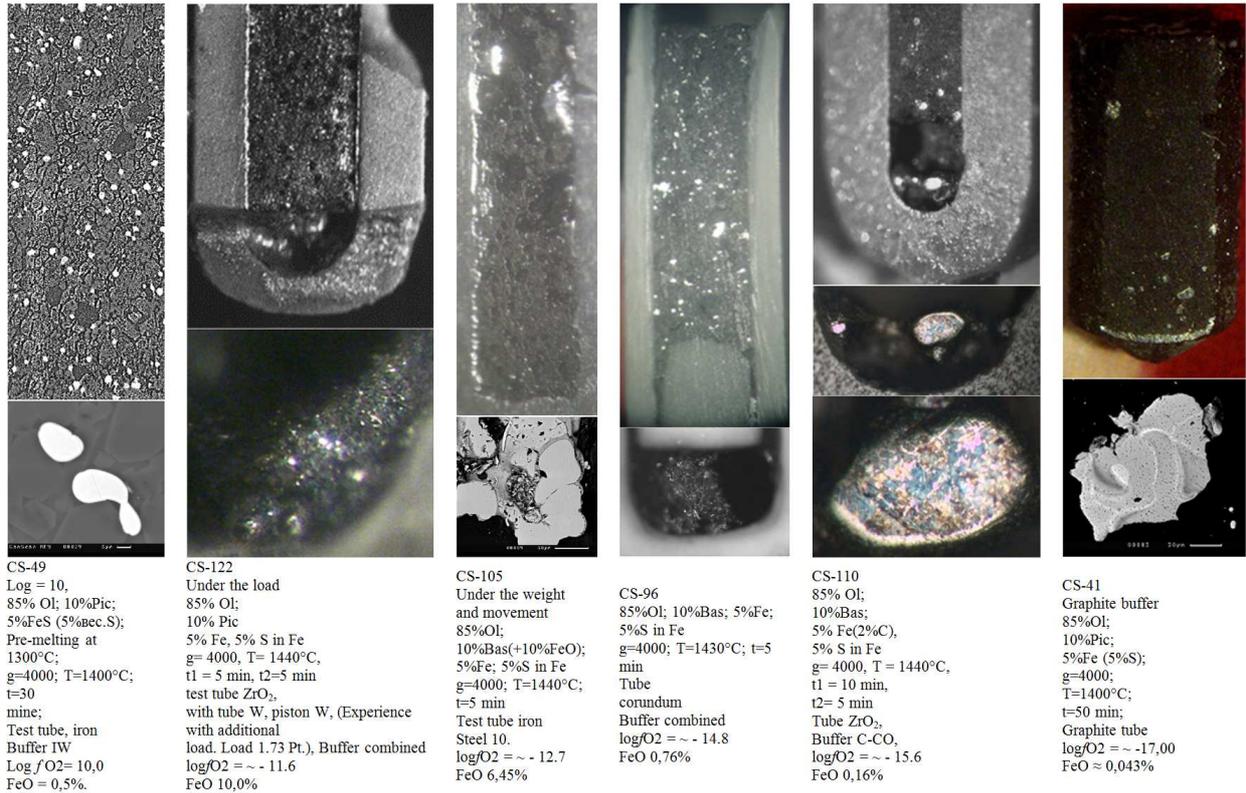
2.1. Experimental

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Oxygen fugacity fO_2 at any given temperature was evaluated from the composition of the quenched phases after the experiments, using three different methodological approaches, which will be described in more detail below.

The vertical cross sections of the samples obtained after centrifugation and quenching in the experiments of CS-49, CS-122, CS-105, CS-96, CS-110, CS-41 and the shape of the metal drop in the samples in the experiments of CS-49, CS-65, CS-96, CS-97, CS-105, CS-122 and in the experiments, in addition to the pure effect of centrifugal forces on the melts and as a result of the additional load and the movement of the melt in the lower pressure zone are shown in Figure 2, Figure 3, and the compositions of silicate melts after the experiments (wt. %) Table 1.

Table 1. The compositions of silicate melts after the experiments (wt. %).

Experiment numbers	SiO$_2$	MgO	FeO	Al$_2$O$_3$	CaO	TiO$_2$	MnO	Na$_2$O	K$_2$O	Σ
CS-122	50.96	10.97	9.60	13.46	10.65	0.65	0.00	1.49	0.34	98.12
CS-44	60.51	7.22	13.13	11.53	0.60	0.00	0.00	1.26	0.17	101.89
CS-105	58.65	6.35	6.45	15.27	9.25	0.80	0.37	2.30	0.74	100.18
CS-53	58.56	10.79	6.47	12.07	9.97	0.58	0.14	1.28	0.26	100.12
CS-45	62.21	17.99	4.32	7.85	5.28	0.31	0.00	0.91	0.14	99.02
CS-96	47.48	18.15	0.76	15.86	12.69	0.85	0.00	2.11	1.06	98.97
CS-57	60.81	10.89	0.40	14.79	13.23	0.37	0.20	0.60	0.10	101.38
CS-58	66.67	8.49	0.40	13.91	10.74	0.14	0.11	0.42	0.42	101.29
CS-110	60.24	17.29	0.17	12.20	7.68	0.40	0.00	0.82	0.34	99.14
CS-41	45.425	56.87	0.57	0.15	9.22	0.00	0.08	0.04	0.00	103.61
CS-49	60.31	5.31	9.50	11.18	9.80	0.25	0.26	0.89	0.97	98.65

CS-49	CS-122	CS-105	CS-96	CS-110	CS-41
Log = 10, 85% Ol; 10%Pic; 5%FeS (5%вес.S); Pre-melting at 1300°C; g=4000; T=1400°C; t=30 mine; Test tube, iron Buffer IW Log *f* O2= 10,0 FeO = 0,5%.	Under the load 85% Ol; 10% Pic 5% Fe, 5% S in Fe g= 4000, T= 1440°C, t1 = 5 min, t2=5 min test tube ZrO₂, with tube W, piston W, (Experience with additional load. Load 1.73 Pt.), Buffer combined log*f*O2 = ~ -11.6 FeO 10,0%	Under the weight and movement 85%Ol; 10%Bas(+10%FeO); 5%Fe; 5%S in Fe g=4000; T=1440°C; t=5 min Test tube iron Steel 10. log*f*O2 = ~ - 12.7 FeO 6,45%	85%Ol; 10%Bas; 5%Fe; 5%S in Fe g=4000; T=1430°C; t=5 min Tube corundum Buffer combined log*f*O2 = ~ - 14.8 FeO 0,76%	85% Ol; 10%Bas; 5% Fe(2%C), 5% S in Fe g= 4000, T = 1440°C, t1 = 10 min, t2= 5 min Tube ZrO₂, Buffer C-CO, log*f*O2 = ~ -15.6 FeO 0,16%	Graphite buffer 85%Ol; 10%Pic; 5%Fe (5%S); g=4000; T=1400°C; t=50 min; Graphite tube log*f*O2 = ~ -17,00 FeO ≈ 0,043%

Experience CS-122 with an additional load of 1.73 g placed on a tungsten piston, which exerted additional pressure on the sample in a tungsten shell.

Figure 2. *Distribution of phases after centrifugation in runs CS-49, CS-122, CS-105, CS-96, CS-110, CS-41.*

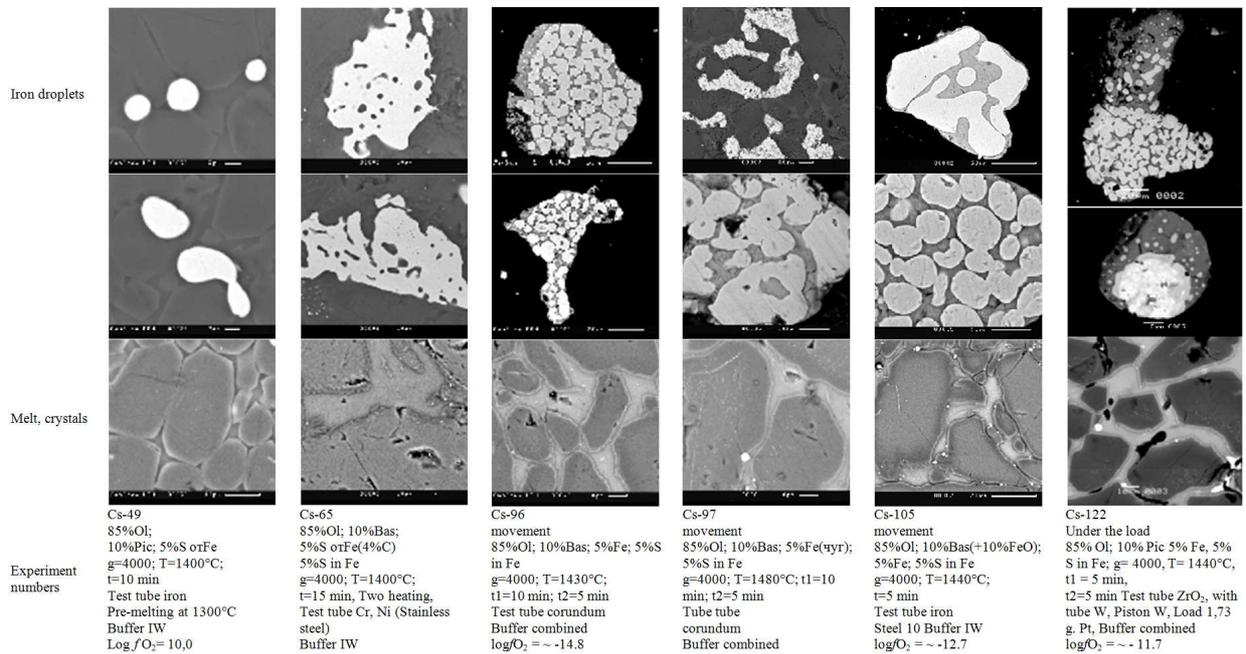|	Cs-49	Cs-65	Cs-96	Cs-97	Cs-105	Cs-122
Iron droplets						
Melt, crystals						
Experiment numbers	85%Ol; 10%Pic; 5%S отFe g=4000; T=1400°C; t=10 min Test tube iron Pre-melting at 1300°C Buffer IW Log *f*O₂= 10,0	85%Ol; 10%Bas; 5%S отFe(4%C) 5%S in Fe g=4000; T=1400°C; t=15 min, Two heating, Test tube Cr, Ni (Stainless steel) Buffer IW	movement 85%Ol; 10%Bas; 5%Fe; 5%S in Fe g=4000; T=1430°C; t1=10 min; t2=5 min Test tube corundum Buffer combined log*f*O₂ = ~ -14.8	movement 85%Ol; 10%Bas; 5%Fe(чуг); 5%S in Fe g=4000; T=1480°C; t1=10 min; t2=5 min Tube corundum Buffer combined	movement 85%Ol; 10%Bas(+10%FeO); 5%Fe; 5%S in Fe g=4000; T=1440°C; t=5 min Test tube iron Steel 10 Buffer IW log*f*O₂ = ~ -12.7	Under the load 85% Ol; 10% Pic 5% Fe, 5% S in Fe; g= 4000, T= 1440°C, t1 = 5 min, t2=5 min Test tube ZrO₂, with tube W, Piston W, Load 1,73 g. Pt, Buffer combined log*f*O₂ = ~ - 11.7

Figure 3. *Phase distribution (iron droplets) after centrifugation, works in CS-49, CS-65, CS-96, CS-97, CS-105, CS-122.*

3. Redox Conditions

The oxygen fugacity in the system whose iron-sulfide melt was in equilibrium with a metal phase can be calculated using the reaction

$$(FeO)_L = (Fe)_{Met.} + .O_2$$
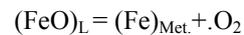
The oxygen fugacity fO_2 was determined from the composition of the quenched experimental silicate melts (glasses). A decrease in fO_2 is proved to be favorable for the segregation of iron-sulfide melt from the silicate matrix. The

metallic phase is most effectively segregated in the form of melt droplets, and these droplets are accumulated in the lower portions of the samples under strongly reduced conditions, at $fO_2 \sim$ -5.5 (CS-110) orders of magnitude lower than the iron-wustite buffer [10].

4. Discussion

Calculations show that the observed distribution of siderophilic elements on the Moon can be achieved if the iron is separated from the initial material of the chondrite composition under the condition of its partial melting. It is believed that a lower degree of partial melting prevents the metal from seeping into the core.

The possibility of percolation of iron-rich metal melts through the crystal matrix of ultrabasic composition, which is in a partially molten state, depends mainly on the energies of the interphase interaction of the crystalline and molten phases in the system, which determine the following physical properties of phases as wetting, surface and interphase tension of coexisting melts and crystals. The criterion of melt seepage through the crystal matrix is the value of the dihedral wetting angle (Θ)[10].

At low degrees of melting and small amounts of iron and sulfur in the deformation of the silicate frame and flow in the lower pressure zone gives sufficient justification to one of the possible mechanisms of formation of theMoon core - percolation model (seepage and deposition) in contrast to the mega-impact (shock) model orformation and evolution of a lunar core from ilmenite-rich magma ocean cumulates using a thermo-chemical convection model [11].

5. Conclusions

1. The method of high-temperature centrifugation was used for experimental modeling of iron segregation under partial melting of a model ultrabasic substance under certain redox conditions.
2. The oxygen fugacity in the experiments was estimated by the composition of the silicate melt in the quenching samples after the experiments using three thermodynamic methods.
3. In experiments lg$fO2$ varied from~ 2 to ~5.5 log. units below the IW buffer.
4. The most complete deposition of the iron melt is observed in the experience of CS-110 to clean the centrifugal field with the fugacity of oxygen lgfO_2 = ~ - 15.6 in residual amounts in the silicate melt FeO = 0,16%.
5. The result obtained indicates the possibility of the implementation of the proposed mechanism of formation of the core of the Moon from a primary substance, similar to the composition of CI - carbonaceous chondrites.

Acknowledgements

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