Supplementary material

Apollo 15 regolith breccia provides first natural evidence for olivine incongruent melting

Niccolò Satta[1, 2, *], Masaaki Miyahara[3], Shin Ozawa[4], Hauke Marquardt[2], Masahiko Nishijima[5], Tomoko Arai[6] and Eiji Ohtani[4]

[1]Bayerisches Geoinstitut, Universität Bayreuth, Bayreuth 95440, Germany

[2]Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, United Kingdom

[3]Department of Earth and Planetary Systems Science, Graduate School of Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan

[4]Department of Earth Science, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

[5]Laboratory for Protein Crystallography and Laboratory for Electron Structural Biology Institute for Protein Research, Osaka University, Suita-shi Osaka 565-0871, Japan

[6]Planetary Exploration Research Center, Chiba Institute of Technology, Chiba 275-0016, Japan

Corresponding author: Niccolò Satta (niccolo.satta@earth.ox.ac.uk)

Text S1

In this manuscript, we assumed that the studied shock melt pocket would solidify similarly to a shock melt vein. According to Langenhorst and Poirier (2000), the solidification time (t_s) of a shocked vein can be achieved by heat conduction with the surrounding material, and the solidification time t_s can be estimated as:

$$t_s = \frac{w^2}{4k\lambda^2}$$

Where w is the half width of the shocked feature, k is the thermal diffusivity of the solidified shocked and surrounding materials, while λ is a dimensionless coefficient that can be determined using the relation:

$$\frac{L\sqrt{\pi}}{C_P(T_m - T_0)} = \frac{e^{-\lambda^2}}{\lambda(1 + erf\lambda)}$$

With L being the latent head of solidification, while C_P is the isobaric specific heat and erf is the error function (Langenhorst and Poirier, 2000).

During the shock event, the shock feature is expected to reach a melting temperature (T_m) with the host rock during shock compression having a temperature of T_0. Average diurnal surface temperatures of the Moon peak at -20 °C (Fang and Fa, 2014), accordingly we assumed $T_0 = -20$ °C. In addition, we assumed T_m = 2200 °C following the experimental results on the liquidus temperature of Mg_2SiO_4 (Presnall and Walter, 1993) at 14 GPa. Our TEM observations show the thickness of the pocket in which ferropericlase was observed is 10 µm, constraining w to 5 µm. Assuming L = 320 kJ/kg, C_P = 1.2 kJ/kg, and k = 10^{-6} m^2/s (Langenhorst and Poirier, 2000), the λ coefficient can be calculated to be 0.97, hence constraining t_s to about 6 µs.

References:

Fang, T., and Fa, W. (2014). High frequency thermal emission from the lunar surface and near surface temperature of the Moon from Chang'E-2 microwave radiometer. *Icarus*, *232*, 34–53. https://doi.org/10.1016/j.icarus.2013.12.024

Langenhorst, F., and Poirier, J.-P. (2000). Anatomy of black veins in Zagami: Clues to the formation of high-pressure phases. *Earth and Planetary Science Letters*, *184*(1), 37–55. https://doi.org/10.1016/S0012-821X(00)00317-4

Presnall, D. C., and Walter, M. J. (1993). Melting of forsterite, Mg2SiO4, from 9.7 to 16.5 GPa. *Journal of Geophysical Research: Solid Earth*, *98*(B11), 19777–19783. https://doi.org/10.1029/93JB01007

Figures

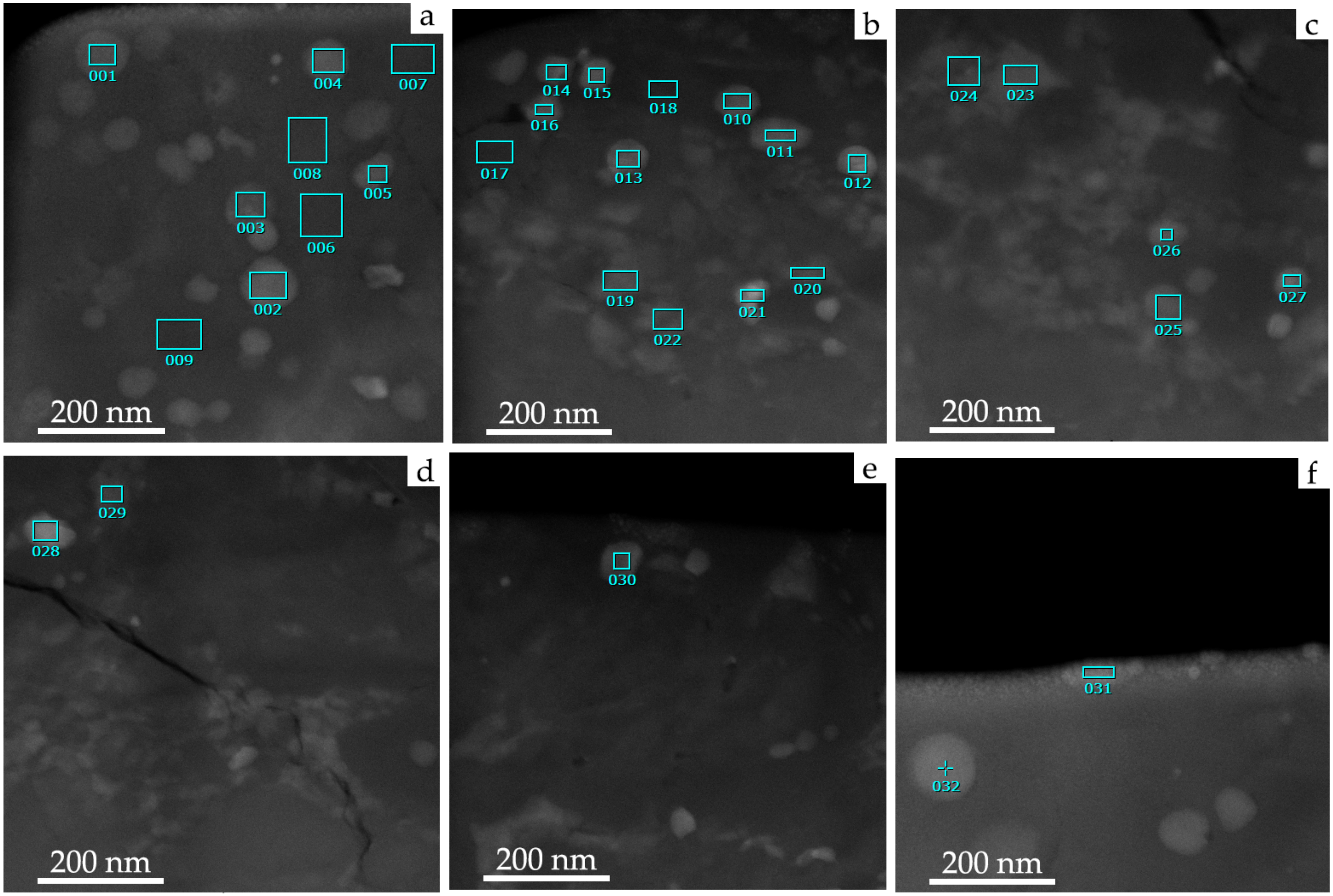

Figure S1. STEM-EDS analysis points in the outer region of the investigated shock-melt pocket.

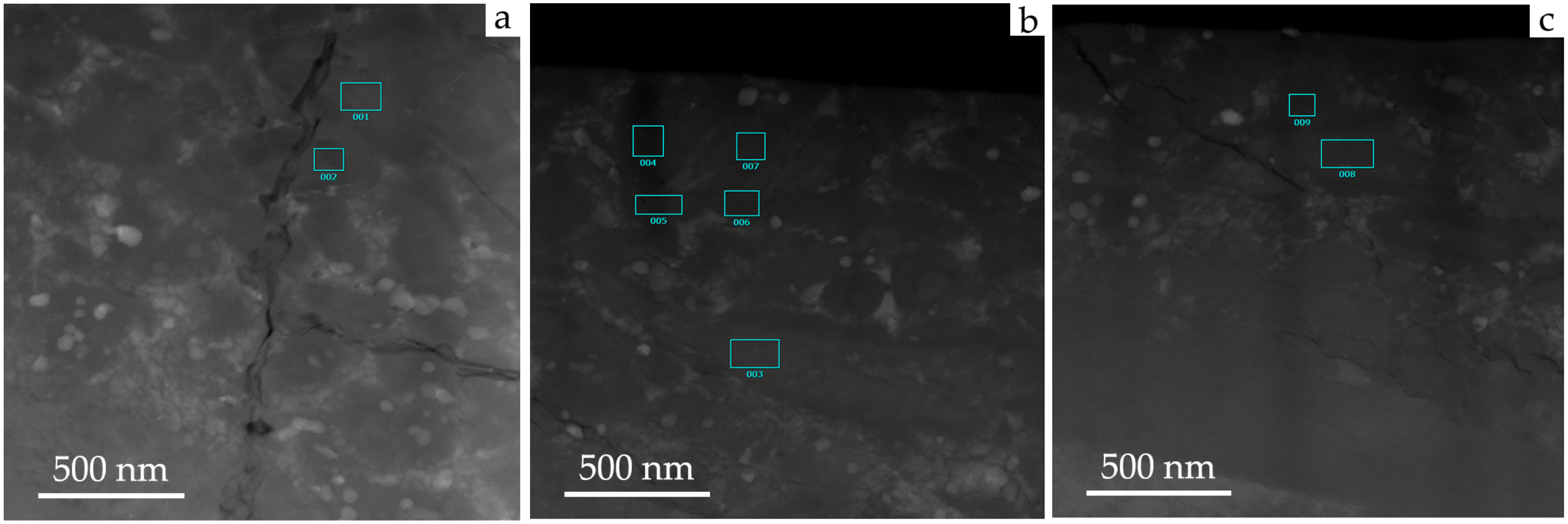

Figure S2. STEM-EDS analysis points in the inner region of the investigated shock-melt pocket..

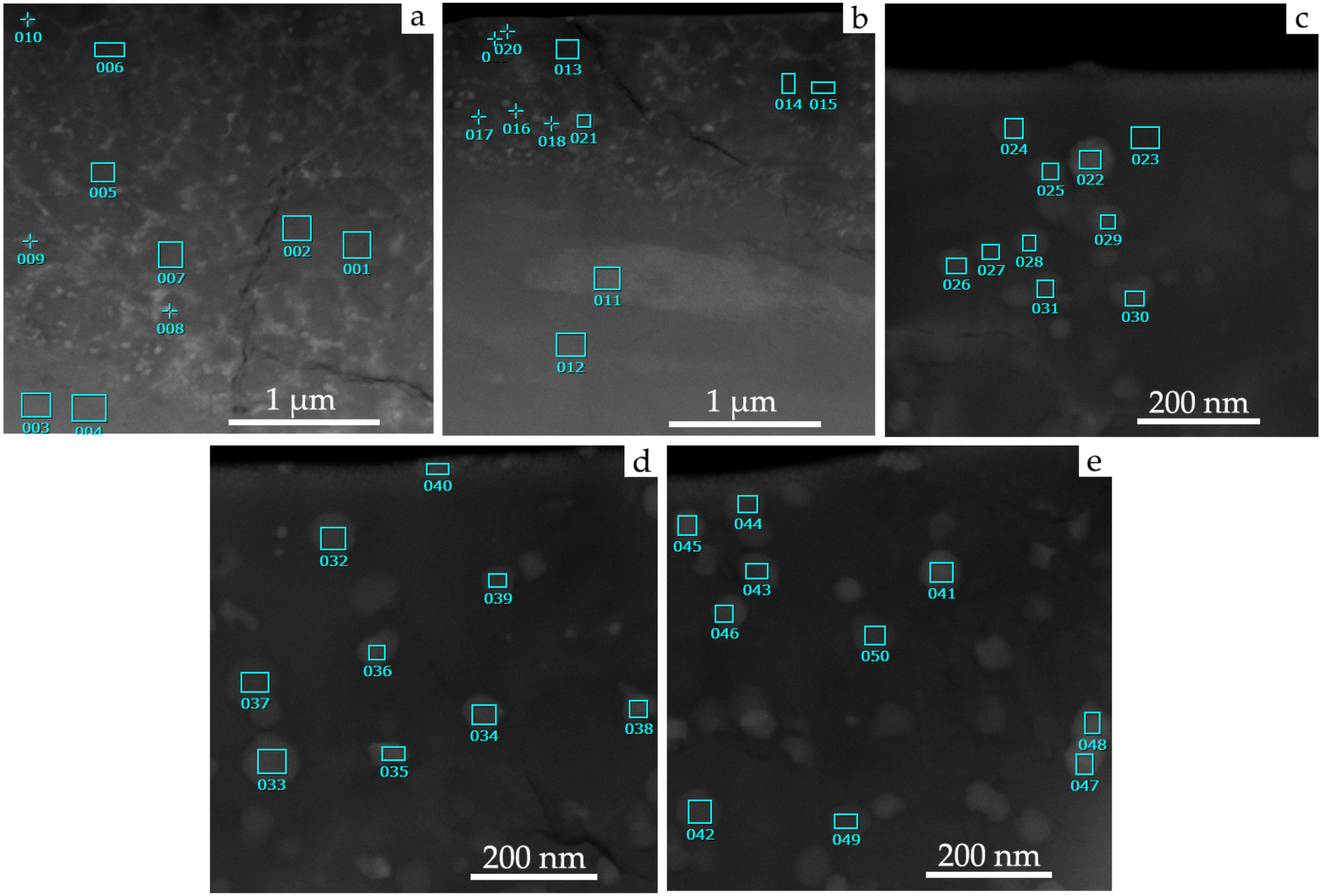

Figure S3. STEM-EDS analysis points in the inner (S3a and S3b) and outer (S3c, S3d and S3e) regions of the investigated shock-melt pocket.

Tables

Table S1. Results of the STEM-EDS analysis of the points shown in Figure S1.

N.	Target	MgO (wt%)	SiO_2 (wt%)	FeO (wt%)	MgO (mol%)	SiO_2 (mol%)	FeO (mol%)	MgPFU	SiPFU	FePFU
001	Fp	40.0	16.5	43.5	53.0	14.7	32.3	1.85	0.51	1.13
002	Fp	40.0	14.0	45.9	53.2	12.5	34.3	1.89	0.45	1.22
003	Fp	40.3	24.6	35.1	52.7	21.5	25.8	1.74	0.71	0.85
004	Fp	32.7	20.1	47.2	45.0	18.5	36.4	1.52	0.63	1.23
005	Fp	35.5	28.5	36.0	47.4	25.5	27.0	1.51	0.81	0.86
006	Outer Ol	35.6	40.7	23.7	46.7	35.9	17.4	1.38	1.06	0.51
007	Si-rich	24.2	48.0	27.7	33.7	44.7	21.6	0.93	1.24	0.60
008	Outer Ol	34.2	40.0	25.9	45.3	35.5	19.2	1.34	1.05	0.57
009	Outer Ol	43.6	37.3	19.1	54.9	31.6	13.5	1.67	0.96	0.41
010	Fp	29.1	19.2	51.7	41.0	18.1	40.9	1.39	0.61	1.39
011	Fp	25.2	21.0	53.8	36.2	20.3	43.5	1.21	0.67	1.45
012	Fp	21.3	16.2	62.5	31.7	16.1	52.2	1.09	0.56	1.80
013	Fp	29.1	21.0	49.9	40.9	19.8	39.3	1.37	0.66	1.31
014	Fp	28.5	22.8	48.7	40.0	21.5	38.4	1.32	0.71	1.27
015	Fp	23.4	18.0	58.6	34.3	17.6	48.1	1.17	0.60	1.64
016	Fp	26.2	20.7	53.2	37.5	19.8	42.7	1.25	0.66	1.43
017	Outer Ol	41.3	37.1	21.7	52.7	31.8	15.5	1.60	0.96	0.47
018	Outer Ol	44.1	38.0	17.9	55.4	32.0	12.6	1.68	0.97	0.38

Continuing next page

019	Outer Ol	25.1	35.9	39.1	35.3	33.9	30.8	1.06	1.01	0.92
020	Outer Ol	20.7	41.0	38.2	29.8	39.5	30.8	0.86	1.14	0.89
021	Fp	30.9	28.5	40.6	42.4	26.3	31.3	1.35	0.83	0.99
022	Outer Ol	32.1	38.0	29.9	43.2	34.3	22.5	1.29	1.02	0.67
023	Outer Ol	21.1	34.9	44.0	30.5	33.9	35.7	0.91	1.01	1.07
024	Outer Ol	30.0	36.6	33.4	41.0	33.5	25.5	1.23	1.01	0.77
025	Fp	35.7	28.0	36.3	47.7	25.1	27.2	1.53	0.80	0.87
026	Fp	30.2	28.2	41.6	41.7	26.1	32.2	1.32	0.83	1.02
027	Fp	31.6	29.9	38.6	43.1	27.4	29.6	1.35	0.86	0.93
028	Fp	15.3	13.0	71.7	23.8	13.5	62.6	0.84	0.48	2.21
029	Outer Ol	25.5	35.3	39.2	35.8	33.2	30.9	1.08	1.00	0.93
030	Fp	21.9	17.3	60.9	32.4	17.1	50.5	1.11	0.59	1.73
031	Fp	34.6	16.2	49.2	47.3	14.9	37.8	1.65	0.52	1.32
032	Fp	25.3	21.4	53.2	36.4	20.7	42.9	1.21	0.69	1.42

All Fe is assumed ferrous. wt% and mol% are normalized to 100%. Atoms per formula units (APFU) are based on 4 oxygens per formula. Fp = ferropericlase, Ol = olivine.

Table S2. Results of the STEM-EDS analysis of the points shown in Figure S2.

N.	Target	MgO (wt%)	SiO_2 (wt%)	FeO (wt%)	MgO (mol%)	SiO_2 (mol%)	FeO (mol%)	MgPFU	SiPFU	FePFU
001	Inner Ol	34.2	37.9	27.9	45.4	33.8	20.8	1.36	1.01	0.62
002	Inner Ol	38.8	39.9	21.3	50.1	34.5	15.4	1.49	1.03	0.46
003	Inner Ol	33.9	38.9	27.1	45.1	34.7	20.2	1.34	1.03	0.6
004	Inner Ol	38	39.5	22.5	49.3	34.4	16.4	1.47	1.02	0.49
005	Inner Ol	37.9	39.4	22.7	49.2	34.3	16.5	1.47	1.02	0.49
006	Inner Ol	39.6	39.1	21.3	50.9	33.7	15.4	1.52	1.01	0.46
007	Inner Ol	34.9	38.3	26.8	46.1	34.0	19.9	1.38	1.01	0.59
008	Inner Ol	33.6	39.3	27.1	44.7	35.1	20.2	1.32	1.04	0.6
009	Inner Ol	39.6	39.4	21	50.9	34.0	15.1	1.52	1.01	0.45

All Fe is assumed ferrous. wt% and mol% are normalized to 100%. Atoms per formula units (APFU) are based on 4 oxygens per formula. Ol = olivine.

Table S3. Results of the STEM-EDS analysis of the points shown in Figure S3.

N.	Target	MgO (wt%)	SiO_2 (wt%)	FeO (wt%)	MgO (mol%)	SiO_2 (mol%)	FeO (mol%)	MgPFU	SiPFU	FePFU
001	Inner Ol	40.3	37.2	22.5	51.7	32.1	16.2	1.57	0.97	0.49
002	Inner Ol	35.9	37.1	27.0	47.2	32.8	20.0	1.42	0.99	0.60
003	Host Ol	33.6	37.7	28.7	44.8	33.7	21.5	1.34	1.01	0.64
004	Host Ol	34.2	36.7	29.0	45.5	32.8	21.7	1.37	0.99	0.65
005	Inner Ol	40.5	38.8	20.7	51.9	33.3	14.8	1.56	1.00	0.45
006	Inner Ol	37.3	38.3	24.4	48.6	33.5	17.9	1.46	1.01	0.54
007	Inner Ol	40.0	38.3	21.7	51.4	33.0	15.6	1.54	0.99	0.47
008	Fp	28.3	25.4	46.2	39.7	23.9	36.3	1.28	0.77	1.17
009	Fp	32.7	30.6	36.7	44.3	27.8	27.9	1.39	0.87	0.87
010	Fp	22.0	23.7	54.4	32.2	23.2	44.6	1.05	0.75	1.45
011	Inner Ol	35.1	35.1	29.8	46.6	31.2	22.2	1.42	0.95	0.68
012	Host Ol	35.8	37.1	27.0	47.2	32.8	20.0	1.42	0.99	0.60
013	Inner Ol	39.0	39.2	21.8	50.3	33.9	15.8	1.50	1.01	0.47
014	Inner Ol	43.6	37.7	18.7	55.0	31.8	13.2	1.67	0.97	0.40
015	Inner Ol	43.5	37.4	19.1	54.8	31.7	13.5	1.67	0.96	0.41
016	Fp	26.0	22.4	51.6	37.2	21.4	41.4	1.22	0.71	1.36
017	Fp	31.4	27.2	41.3	43.1	25.1	31.8	1.38	0.80	1.02
018	Fp	24.2	25.2	50.6	34.8	24.3	40.9	1.12	0.78	1.32
019	Inner Ol	26.5	35.5	38.0	37.0	33.2	29.7	1.11	1.00	0.89
020	Inner Ol	25.6	38.6	35.8	35.7	36.2	28.1	1.05	1.06	0.83

021	Inner Ol	26.4	36.4	37.2	36.8	34.1	29.1	1.10	1.02	0.87
022	Fp	47.3	7.7	45.1	60.9	6.6	32.5	2.28	0.25	1.22
023	Outer Ol	34.8	40.3	25.0	45.9	35.6	18.5	1.35	1.05	0.55
024	Fp	41.7	18.6	39.7	54.5	16.3	29.2	1.87	0.56	1.00
025	Fp	45.0	11.9	43.1	58.3	10.3	31.4	2.11	0.37	1.14

Continuing next page

026	Fp	46.0	20.3	33.8	58.6	17.3	24.1	2.00	0.59	0.82
027	Fp	42.0	28.9	29.1	54.1	24.9	21.0	1.73	0.80	0.67
028	Fp	43.6	20.1	36.3	56.3	17.4	26.3	1.92	0.59	0.90
029	Fp	42.1	17.9	40.0	55.0	15.7	29.3	1.90	0.54	1.01
030	Fp	40.8	20.6	38.6	53.5	18.1	28.4	1.81	0.61	0.96
031	Fp	35.6	25.3	39.1	47.8	22.7	29.5	1.56	0.74	0.96
032	Fp	31.7	15.7	52.6	44.2	14.7	41.1	1.54	0.51	1.43
033	Fp	41.8	13.3	44.9	55.1	11.7	33.2	1.97	0.42	1.19
034	Fp	33.0	19.4	47.5	45.4	17.9	36.7	1.54	0.61	1.24
035	Fp	29.3	23.2	47.5	41.0	21.7	37.3	1.35	0.71	1.23
036	Fp	33.1	20.3	46.6	45.4	18.7	35.9	1.53	0.63	1.21
037	Fp	40.5	24.3	35.1	53.0	21.3	25.7	1.75	0.70	0.85
038	Fp	31.4	17.2	51.4	43.8	16.0	40.2	1.51	0.55	1.39
039	Fp	34.0	23.4	42.6	46.2	21.3	32.5	1.52	0.70	1.07
040	Fp	32.1	18.5	49.4	44.5	17.2	38.4	1.52	0.59	1.31
041	Fp	22.1	13.3	64.6	32.8	13.3	53.9	1.16	0.47	1.90
042	Fp	38.6	20.6	40.8	51.3	18.3	30.4	1.73	0.62	1.03
043	Fp	32.7	23.1	44.2	44.8	21.2	34.0	1.48	0.70	1.12
044	Fp	43.4	13.9	42.7	56.6	12.1	31.3	2.02	0.43	1.12
045	Fp	24.3	15.7	60.1	35.5	15.3	49.2	1.23	0.53	1.71
046	Fp	25.1	21.3	53.6	36.2	20.5	43.3	1.20	0.68	1.44
047	Fp	25.9	22.8	51.4	37.0	21.8	41.2	1.21	0.72	1.35
048	Fp	29.4	20.5	50.1	41.2	19.3	39.4	1.38	0.65	1.32
049	Fp	44.9	17.3	37.8	57.8	14.9	27.3	2.01	0.52	0.95
050	Fp	35.1	24.9	40.0	47.3	22.5	30.2	1.55	0.73	0.99

All Fe is assumed ferrous. wt% and mol% are normalized to 100%. Atoms per formula units (APFU) are based on 4 oxigens per formula. Fp = ferropericlase, Ol = olivine.