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# Comment on: *Melting behavior of SiO<sub>2</sub> up to 120 GPa [Andrault et al., 2020]*

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## I. ABSTRACT

The additional work we have done using our new laser-heating in the diamond anvil cell system since the publication of [Andrault et al., 2020] leads us to the conclusion that there was a systematic bias in the determination of temperature. First, the temperature of the W-lamp used for the calibration of the optical system was overestimated by  $\sim 22$  K at 2273 K. Then, we made the assumption that hot SiO<sub>2</sub> was a grey-body (constant emissivity  $\epsilon(\lambda)$ ), while the available measurements suggest instead that  $\epsilon(\lambda)$  of SiO<sub>2</sub> is similar to that of tungsten. Applying these two corrections lowers the SiO<sub>2</sub> melting temperatures significantly. In LMV, we performed a new experimental determination of the SiO<sub>2</sub> melting temperature, at 5000(200) K and  $\sim 70(4)$  GPa, which is well compatible with the amplitude of the correction proposed. The reevaluation of the melting temperature profile does not affect largely the interpretations or the main conclusions presented in [Andrault et al., 2020]. Within the stability field of stishovite, the melting curve still presents a relatively sharp change of slope at P-T recalculated as  $\sim 40$  GPa and  $\sim 4800$  K. It is related to a change of the melt structure. At higher pressures, the melting curve is almost flat up to the subsolidus transition from stishovite to the CaCl<sub>2</sub>-form around 85 GPa, where the slope of the melting curve increases again up to  $\sim 120$  GPa. We present corrected Figures and Tables of the original publication.

## II. CALIBRATION OF THE OPTICAL SYSTEMS

On the course of the development of our new system for laser heating in the diamond anvil cell (LH-DAC) at the *Laboratoire Magma et Volcans* (LMV), we dedicated special efforts to the temperature calibration. Our new LH-DAC system is very similar to that of the ID27 beamline (ESRF), which we used to determine the melting properties of SiO<sub>2</sub> [Andrault et al., 2020]. Both system adopt the basic principles established by us several years ago [Schultz et al., 2005], in particular the Schwarzschild reflective objectives that present no chromatic aberrations [Giampaoli et al., 2018]. The LMV system is optimized for simultaneous temperature measurements on both sides of the sample using the TRax software [Holtgrewe et al., 2019].

Calibration of the optical response of the LH-DAC system is essential for the accuracy of the temperature measurements. At ID27, the same tungsten lamp is used for many years. It presents a flat part on its filament, which achieves a constant temperature (e.g. 2273 K) at a given electric power. The lamp was initially calibrated on a black body reference. The relationship between applied electrical current and W-lamp temperature is checked regularly based on the thermal expansion of W measured using X-ray diffraction [Miiller and Cezairliyan, 1990]. With a resolution on the W cell parameter  $\Delta d/d$  of  $\sim 1.5 \cdot 10^{-4}$  [Mezouar et al., 2005], the temperature uncertainty is calculated to be  $\sim 30$ -40 K at 2273 K [Dubrovinsky and Saxena, 1997; Miiller and Cezairliyan, 1990]. Still, there could be other experimental uncertainties than thermal expansion itself.

In LMV, we calibrate the optical response using two techniques: (i) a Pt heating wire is calibrated at 1664 K and 1817 K based melting point of diopside and wollastonite, respectively [Richet et al., 1993]. The onset of melting is indicated by the formation of a thin film of melt at the surface of the wire. Reproducing the measurement several times yields to an uncertainty of  $< 10$  K. (ii) We acquired a new lamp from Pyrometer-LLC (USA), which thermal emission intensity for photons between 0.6 and 0.7  $\mu\text{m}$  was calibrated on a NIST black body standard at different temperatures between 1973 K and

56 2573 K. Our two methods of calibration, with Pt-wire and W-lamp, agree with each other within 10-15  
 57 K. As a result, we adopted the certified W-lamp at 2273 K to calibrate the optical response of the LMV  
 58 system. We note that performing the calibration using of a W-lamp implies correcting for the emissivity  
 59 function ( $\epsilon(\lambda, T)$ ) of the W-lamp. This is not a negligible effect; a W-lamp at 2273 K presents a thermal  
 60 emission spectrum similar to a grey-body (constant  $\epsilon(\lambda)$ ) at 2358 K ( $\Delta T = -85$  K) [Devos, 1954].

61 We then performed a cross-check of the temperature calibration between the LMV and ID27  
 62 systems using a secondary W-lamp that was alternately installed on both systems. Its thermal emission  
 63 spectrum was measured at temperatures between 2244 K and 2566 K using the different optical paths  
 64 available on both systems. The procedure was repeated after several months. The result is a temperature  
 65 significantly smaller at LMV compared to ID27, for a same electrical current applied to the W-lamp.  
 66 The average temperature difference is  $\sim 22(14)$  K in the range of temperature investigated, which is  
 67 within the uncertainty of the W-lamp temperature based on X-ray diffraction (30-40 K). Such  
 68 systematic difference does not have major implication for experimental temperatures up to 2500-3000  
 69 K, considering that other sources of uncertainties yield to a final temperature uncertainty of  $\pm 100$  K (see  
 70 details in [Andrault *et al.*, 2020]). However, it becomes more significant for the study on the melting of  
 71  $\text{SiO}_2$  that implies temperatures higher than 5000 K.

### 72 73 74 **III. SELECTING A PROPER EMISSIVITY FUNCTION FOR $\text{SiO}_2$**

75  
76 In order to measure the sample temperature properly, one should take into account its  $\epsilon(\lambda, T)$  at high  
 77 temperature. Unfortunately  $\epsilon(\lambda, T)$  is poorly constrained for  $\text{SiO}_2$ , which implies making assumptions. In  
 78 [Andrault *et al.*, 2020], we considered a constant emissivity within the 600-900 nm range of wavelength  
 79 used for the temperature determination and applied the Wien law to estimate the  $\text{SiO}_2$  temperatures.  
 80 However, an important observation in [Andrault *et al.*, 2020] is a good coupling between the laser  
 81 radiation at  $\sim 1\mu\text{m}$  and the  $\text{SiO}_2$  sample, which is accompanied by a sample darkening in the optical  
 82 range at 300 K. It makes it unlikely that  $\text{SiO}_2$  presents a perfectly flat absorption spectrum of  $\text{SiO}_2$   
 83 within 600-900 nm at very high temperature. The same property should also apply for the  $\text{SiO}_2$   
 84 emissivity function, according to the Kirchhoff law correlating to each other these two functions.

85 Absorption spectra have been reported in the literature for several silicates including  $\text{SiO}_2$  [Trukhin  
 86 *et al.*, 2011] and Fe-bearing bridgmanite (e.g. [Keppler *et al.*, 2008]), even though this range of  
 87 wavelength is generally not the main region of interest for this type of studies. It is very interesting to  
 88 note that the absorption spectra present slopes comparable to the emissivity function of tungsten  
 89 [Devos, 1954] within the 600-900 nm range (New Fig. 9). This effect could be due to a stronger  
 90 interaction between light and electrons with increasing the light energy. This trend favors an alternative  
 91 assumption to the grey-body (constant  $\epsilon(\lambda)$ ); namely a sample  $\epsilon(\lambda, T)$  similar to that of the W-lamp at  
 92 the calibration temperature of  $\sim 2273$  K. This hypothesis was largely used in the past in the Mineral  
 93 Physics community. This implies a significant correction to the  $\text{SiO}_2$ -sample temperature; e.g. -85 K for  
 94 a refined grey-body temperature of 2358 K.

### 95 96 97 **IV. CORRECTED RESULTS**

98  
99 We reinvestigate the sample temperatures reported in [Andrault *et al.*, 2020] applying the correction  
 100 of 22 K to the tungsten lamp and the same  $\epsilon(\lambda, T)$  for  $\text{SiO}_2$  and the W-lamp. We are conscious that the  
 101 latter has consequences; A temperature correction may be applied in the future, when  $\epsilon(\lambda, T)$  of  $\text{SiO}_2$   
 102 will be better constrained. To calculate the updated sample temperatures ( $T_{\text{updat}}$ ), we consider that the  
 103 optical response of the ID27 LH-DAC system had not been evaluated properly, considering a W-lamp  
 104 at 2295 K instead of 2273 K. For a dozen of temperatures between 1500K and 7000K (published  
 105 temperatures;  $T_{\text{pub}}$ ), we calculate: (i) The grey-body function of the sample at  $T_{\text{pub}}$ :  $\text{GB}(T_{\text{pub}})$ . (ii) The  
 106 grey-body functions of the W-lamp at 2295 K and 2273 K:  $\text{GB}(T_{\text{lamp-old}})$  and  $\text{GB}(T_{\text{lamp-new}})$ ,  
 107 respectively. (iii) The sample thermal emission:  $\text{TE} = \text{GB}(T_{\text{pub}}) * \text{GB}(T_{\text{lamp-new}}) / \text{GB}(T_{\text{lamp-old}})$ . (iv) Then,  
 108 we refine  $T_{\text{updat}}$  based on TE assuming  $\epsilon(\lambda, T)$  of  $\text{SiO}_2$  similar to that of W. The use of Wien or Planck  
 109 laws is indifferent. It yields a polynomial relation between  $T_{\text{pub}}$  and  $T_{\text{updat}}$ :  $T_{\text{updat}} = -26 + 1.017 T_{\text{pub}} -$   
 110  $2.316 \cdot 10^{-5} T_{\text{pub}}^2$ .

111 The uncertainty of 14K on the temperature correction of 22(14) K at 2273 K induces uncertainties of  
112 25 or 113 K on the  $T_{\text{updat}}$  sample temperature at 2816 or 6163 K, respectively. This is significantly  
113 smaller than the accuracy of the melting curve temperature determination, which is the temperature  
114 difference between data points at which the sample was found solid or liquid (blue and red dots in [Fig.](#)  
115 [3-corr](#), respectively).

116 We reevaluated the sample pressures as well, because we had considered a pressure increase due to  
117 some isochoric heating (see [[Andrault et al., 2020](#)]). The correction yields significant changes in the  
118 melting curve of  $\text{SiO}_2$  ([Table 1-corr](#); [Fig. 3-corr](#)). For example, the maximum (P,T) investigated are  
119 recalculated to be  $\sim 117$  GPa and  $\sim 6200$  K, instead of  $\sim 120$  GPa and  $\sim 7000$  K in [[Andrault et al., 2020](#)].  
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## 121 122 V. NEW EXPERIMENTAL MEASUREMENT

123  
124 To check the robustness of the proposed temperature correction, we performed a new determination  
125 of the  $\text{SiO}_2$  melting temperature using the LH-DAC system of LMV. The sample consisted of two thin  
126 pellets of  $\text{SiO}_2$  between which we deposited a little bit of Si-powder to facilitate absorption of the  $\sim 1$   
127  $\mu\text{m}$  laser radiation at low temperature. This is similar as the second series of experiments in [[Andrault et](#)  
128 [al., 2020](#)]. Melting criteria were based on (i) analysis of the relation between the sample temperature  
129 and the laser power and (ii) optical observation of the recovered sample ([New Fig. 10](#)). For a nominal  
130 pressure of 49 GPa (at 300K), temperature increased progressively with laser power until a flattening of  
131 this relationship. Above 140 W of laser power, we observed temperature fluctuations because the  $\text{SiO}_2$   
132 melt, which was produced sporadically, did not absorb enough laser radiation to maintain the  
133 temperature in its stability field. The highest temperature that we could reach up to 180 W is 4950(200)  
134 K, which we associate to the highest possible temperature for solid  $\text{SiO}_2$  at this pressure. Steady state  
135 production of liquid- $\text{SiO}_2$  in this sample (as performed in [[Andrault et al., 2020](#)]) would require even  
136 more laser power. The sample pressure at  $\sim 4950$  K is estimated to 70(4) GPa after correction for the  
137 thermal pressure. The recovered sample presents circular figures of absorption that are typical of  
138 melting corona observed on several types of sample ([New Fig. 10](#)).  
139

## 140 141 VI. DISCUSSIONS

142  
143 Global trends and main conclusions of [[Andrault et al., 2020](#)] are not significantly affected by the  
144 temperature correction. We detail below the changes that apply:

145 - The steep  $\text{SiO}_2$  melting curve extends to  $\sim 40$  GPa and the Clapeyron slope between stishovite and  
146 the low-density melt (LDM) is  $\sim 76$  K/GPa ([Table 2-corr](#), [New Table 3](#)). This corresponds to similar  
147 temperatures than reported in some theoretical calculations [[Belonoshko and Dubrovinsky, 1995](#); [Usui](#)  
148 [and Tsuchiya, 2010](#)]. On this segment, our data plot more linearly than any other melting studies,  
149 including the experimental work [[Shen and Lazor, 1995](#)]. As mentioned in [[Andrault et al., 2020](#)], this  
150 observation is compatible with minor changes in the LDM structure up to  $\sim 40$  GPa.

151 - The triple point between stishovite, LDM and high-density melt (HDM) is found at  $\sim 40$  GPa and  
152  $\sim 4800$  K. We refine a LDM-HDM volume change of  $-4.21(20)$  instead of  $-4.02(20)$   $\text{cm}^3/\text{mol}$  in  
153 [[Andrault et al., 2020](#)].

154 - A relatively flat melting curve extends from 40 to 85 GPa and 4800 to 5200 K with a Clapeyron  
155 slope of 9 GPa/K. The associated stishovite-HDM volume of fusion is  $0.56(13)$   $\text{cm}^3/\text{mol}$ , which  
156 corresponds to 4.0(0.9)% of the stishovite volume. This is  $\sim 10$  times smaller than the stishovite-LDM  
157 volume change of  $\sim 4.77$   $\text{cm}^3/\text{mol}$ .

158 - As a result, the volume change between LDM and HDM melts is  $\sim 26\%$ .

159 - Above 85 GPa, the Clapeyron slope increases again to  $\sim 31$  GPa/K. At the highest pressure of this  
160 study,  $\sim 117$  GPa, the melting point of  $\text{SiO}_2$  in its  $\text{CaCl}_2$ -form plots at  $\sim 6200$  K, which is just in-between  
161 temperatures reported at each side of the solid-liquid transition of shocked quartz [[Akins and Ahrens,](#)  
162 [2002](#)] ([Fig. 3-corr](#)).  
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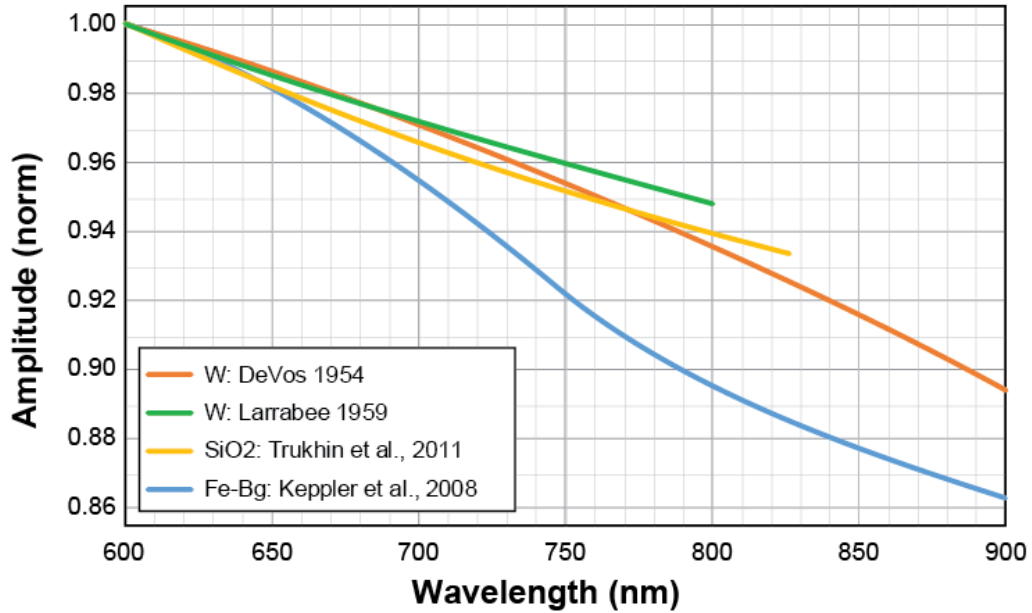
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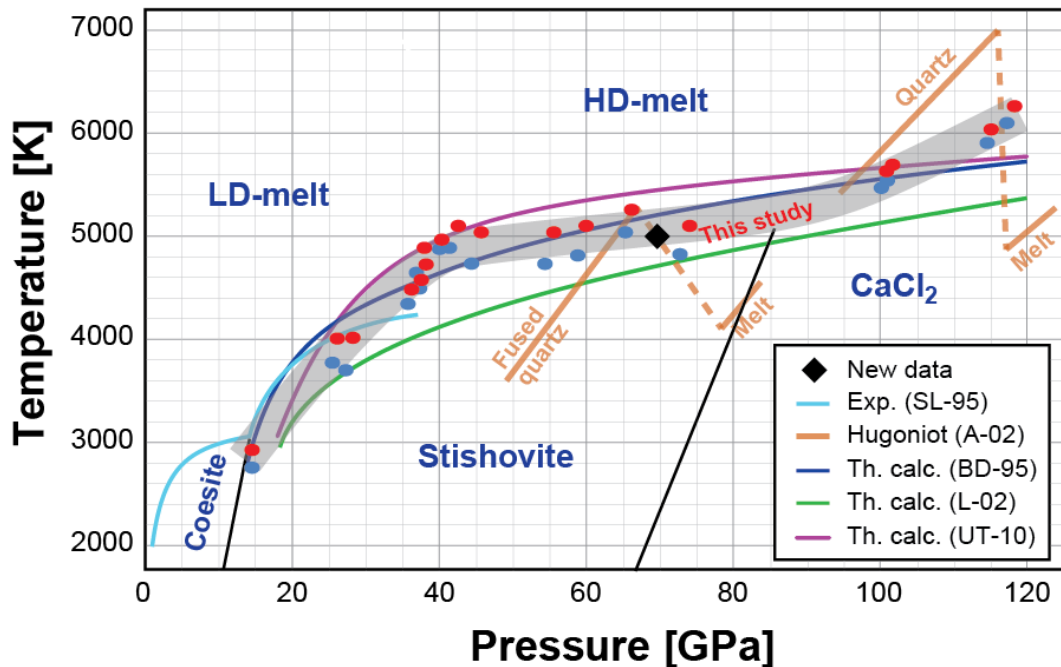
## REFERENCES

- Akins, J. A., and T. J. Ahrens (2002), Dynamic compression of SiO<sub>2</sub>: A new interpretation, *Geophys. Res. Lett.*, 29(10), 1394.
- Andraut, D., G. Morard, G. Garbarino, M. Mezouar, M. A. Bouhifd, and T. Kawamoto (2020), Melting behavior of SiO<sub>2</sub> up to 120 GPa, *Phys. Chem. Mineral.*, 47(2).
- Belonoshko, A. B., and L. S. Dubrovinsky (1995), Molecular-dynamics of stishovite melting, *Geochim. Cosmochim. Acta*, 59(9), 1883-1889.
- Devos, J. C. (1954), A new determination of the emissivity of tungsten ribbon, *Physica*, 20(9), 690-&.
- Dubrovinsky, L. S., and S. K. Saxena (1997), Thermal expansion of periclase (MgO) and tungsten (W) to melting temperatures, *Phys. Chem. Mineral.*, 24(8), 547-550.
- Giampaoli, R., I. Kantor, M. Mezouar, S. Boccato, A. D. Rosa, R. Torchio, G. Garbarino, O. Mathon, and S. Pascarelli (2018), Measurement of temperature in the laser heated diamond anvil cell: comparison between reflective and refractive optics, *High Pressure Research*, 38(3), 250-269.
- Holtgrewe, N., E. Greenberg, C. Prescher, V. B. Prakapenka, and A. F. Goncharov (2019), Advanced integrated optical spectroscopy system for diamond anvil cell studies at GSECARS, *High Pressure Research*, 39(3), 457-470.
- Keppler, H., L. S. Dubrovinsky, O. Narygina, and I. Y. Kantor (2008), Optical Absorption and Radiative Thermal Conductivity of Silicate Perovskite to 125 Gigapascals, *Science*, 322(5907), 1529-1532.
- Larrabee, R. D. (1959), Spectral emissivity of tungsten, *Journal of the Optical Society of America*, 49(6), 619-625.
- Mezouar, M., et al. (2005), Development of a new state-of-the-art beamline optimized for monochromatic single-crystal and powder X-ray diffraction under extreme conditions at the ESRF, *J. Synchr. Rad.*, 12, 559-664.
- Miiller, A. P., and A. Cezairliyan (1990), Thermal-expansion of tungsten in the range 1500-3600-K by a transient interferometric-technique, *International Journal of Thermophysics*, 11(4), 619-628.
- Richet, P., P. Gillet, A. Pierre, M. A. Bouhifd, I. Daniel, and G. Fiquet (1993), Raman spectroscopy, x-ray diffraction, and phase relationship determinations with a versatile heating cell for measurements up to 3600-K (or 2700-K in air), *Journal of Applied Physics*, 74(9), 5451-5456.
- Schultz, E., et al. (2005), Double-sided laser heating system for in situ high pressure-high temperature monochromatic x-ray diffraction at the ESRF, *High Pressure Research*, 25(1), 71-83.
- Shen, G., and P. Lazor (1995), Measurement of melting temperatures of some minerals under lower mantle conditions, *J. Geophys. Res.*, 100(B9), 17699-17713.
- Trukhin, A. N., K. Smits, A. Sharakosky, G. Chikvaidze, T. I. Dyuzheva, and L. M. Lityagina (2011), Luminescence of dense, octahedral structured crystalline silicon dioxide (stishovite), *Journal of Luminescence*, 131(11), 2273-2278.
- Usui, Y., and T. Tsuchiya (2010), Ab Initio Two-Phase Molecular Dynamics on the Melting Curve of SiO<sub>2</sub>, *J. Earth Sci.*, 21(5), 801-810.

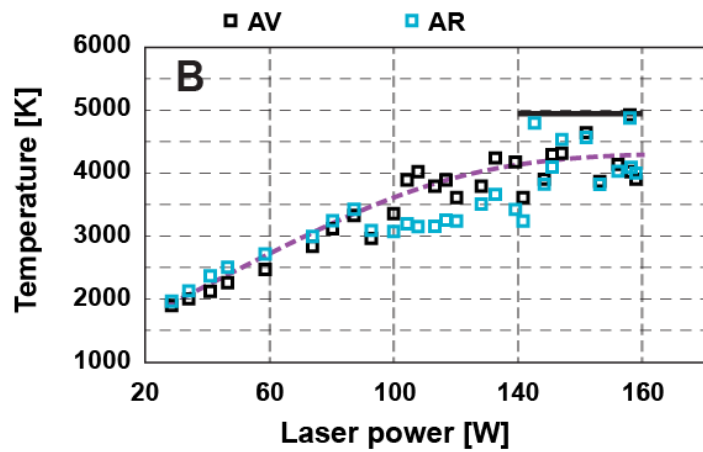
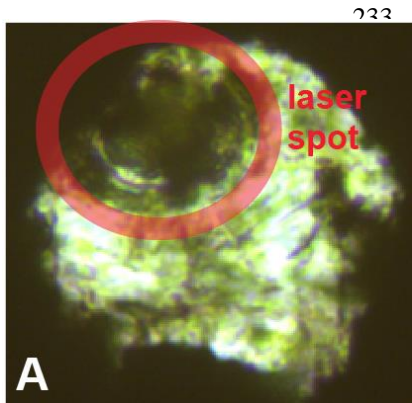
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 213 **New Figure 9: Normalized absorption and emissivity functions.** Emissivity functions of a tungsten  
 214 wire [Devos, 1954; Larrabee, 1959] are plotted together with absorption spectra of SiO<sub>2</sub> [Trukhin et al.,  
 215 2011] and Fe-bearing bridgmanite [Keppler et al., 2008], within the range of wavelength (600-900 nm)  
 216 used for pyrometric determination of temperature in our LH-DAC experiments.  
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 219 **Figure 3 corrected:**  
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 224 **New Figure 10:** (A) **Optical microphotograph** showing circular figures around the melted zone of the  
 225 recovered sample. The external diameter is  $\sim 60 \mu\text{m}$ . (B) **Relationship between sample temperature**  
 226 **and laser power:** A maximum temperature of 4950(200) K was reached on both sample sides for a  
 227 laser power up to 180 W, even though higher temperatures are predicted from the linear relationship  
 228 between laser power and temperature up to  $\sim 120$  W (dashed line). Between 140 and 180 W,  
 229 temperature fluctuations occurred because the melt, which is produced sporadically at temperatures  
 230 higher than  $\sim 4950$  K, does not absorb enough the laser radiation to maintain the sample temperature in  
 231 its stability field (AV for front side and AR for rear side of the sample).  
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**Table 1 corrected:**

P(300K)	Temp.	P(high-T)	Temp	Temp
GPa	K	GPa	solid	Melt
12	2816	14	2728	2904
16	3877	25	3754	4000
19	3836	28	3671	4000
19	4751	37	4636	4866
19.5	4713	37	4519	4713
20	4866	40	4866	4942
21	4942	42	4866	5093
21.5	4558	38	4479	4713
21.5	4401	36	4321	4479
26	4866	46	4713	5018
36	4866	55	4713	5018
39	5018	60	4790	5093
45	5093	66	5018	5241
54	5018	74	4790	5093
76	5605	102	5533	5676
76	5533	101	5461	5605
85	6163	117	6095	6231
85	5957	114	5888	6026

**Table 2 corrected:**

Transition considered	Press. GPa	Temp. K	dT/dP K/GPa	$\Delta S$ mol/K	$\Delta V$ cm <sup>3</sup> /mol	Vstish cm <sup>3</sup> /mol	Vcoes cm <sup>3</sup> /mol	VLDM cm <sup>3</sup> /mol	VHDM cm <sup>3</sup> /mol	$\Delta V/V$
C => S	15	2900	312 a	-15.3 a	-4.77 b	14.69 g	19.46 h			-28% k
C => LDM	15	2900		74.9 d	0.00 e		19.46 h			
S => LDM	15	2900	76 *	62.7 b	4.77 g	14.69 g		19.5 i		28% k
S => HDM	40	4800	9 *	77.7 d	0.69 b	13.63 g			14.3 j	4.9% k
LDM => HDM	40	4800		-15.0 c	-4.08 f			18.4 i	14.3 j	-25% k
S => HDM	40	4800	9 *	62.7 d	0.56 b	13.63 g			14.2 j	4.0% k
LDM => HDM	40	4800		0.0 c	-4.21 f			18.4 i	14.2 j	-26% k
S => HDM	40	4800	9 *	47.7 d	0.42 b	13.63 g			14.1 j	3.1% k
LDM => HDM	40	4800		15.0 c	-4.34 f			18.4 i	14.1 j	-27% k

C, S, LDM and HDM stand for Coesite, Stishovite, low-density and high-density SiO<sub>2</sub> melts

\*, this study

a, from Akaogi et al. (2011)

b, calculated based on the Clapeyron relation  $dT/dP = \Delta V / \Delta S$

c, value assumed to be -15, 0 or 15 J/molK (see text)

d, derived from Clapeyron relations around the (C, S, LDM) or (C, LDM, HDM) triple points

e, derived from the flat melting curve of coesite between 9 and 14 GPa (Zhang et al., 1993)

f, calculated using  $\Delta V = VHDM - VLDM$

g, calculated at the considered P-T conditions using the EoS of Wang et al. (2012)

h, calculated using  $V_{coes} = V_{sti} + \Delta V(C-S)$

i, calculated using  $VLDM = V_{sti} + \Delta V(LDM-S)$

j, calculated using  $VHDM = V_{sti} + \Delta V(HDM-S)$

k,  $\Delta V$  of the transition normalized to the mean value between the two phases considered

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**New Table 3:** Conditions (P-T) of the triple points and maximum conditions performed in this study. We also report the Clapeyron slopes between these points taken 2 by 2.

	Pressure GPa	Temperature K	Slope K/GPa
Triple (C,S,LDM)	15	2900	
Triple (S,LDM,HDM)	40	4800	76
Triple (S,CaCl <sub>2</sub> ,HDM)	85	5200	9
P-T max	117	6200	31