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Comment on: *Melting behavior of SiO₂ 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 ~ 22 K at 2273 K. Then, we made the assumption that hot SiO₂ was a grey-body (constant emissivity $\epsilon(\lambda)$), while the available measurements suggest instead that $\epsilon(\lambda)$ of SiO₂ is similar to that of tungsten. Applying these two corrections lowers the SiO₂ melting temperatures significantly. In LMV, we performed a new experimental determination of the SiO₂ 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 ~ 40 GPa and ~ 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 CaCl₂-form around 85 GPa, where the slope of the melting curve increases again up to ~ 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 SiO₂ [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 ~ 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 μm 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 ± 100 K (see
70 details in [Andrault *et al.*, 2020]). However, it becomes more significant for the study on the melting of
71 SiO_2 that implies temperatures higher than 5000 K.

72 73 74 III. SELECTING A PROPER EMISSIVITY FUNCTION FOR 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 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 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 SiO_2 sample, which is accompanied by a sample darkening in the optical
82 range at 300 K. It makes it unlikely that SiO_2 presents a perfectly flat absorption spectrum of SiO_2
83 within 600-900 nm at very high temperature. The same property should also apply for the 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 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 ~ 2273 K. This hypothesis was largely used in the past in the Mineral
93 Physics community. This implies a significant correction to the 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 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 SiO_2
102 will be better constrained. To calculate the updated sample temperatures (T_{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_{pub}), we calculate: (i) The grey-body function of the sample at T_{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_{updat} based on TE assuming $\epsilon(\lambda, T)$ of SiO_2 similar to that of W. The use of Wien or Planck
109 laws is indifferent. It yields a polynomial relation between T_{pub} and T_{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_{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 SiO₂ (**Table 1-corr**; **Fig. 3-corr**). For example, the maximum (P,T) investigated are
119 recalculated to be ~117 GPa and ~6200 K, instead of ~120 GPa and ~7000 K in [Andrault *et al.*, 2020].
120

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 SiO₂ melting temperature using the LH-DAC system of LMV. The sample consisted of two thin
126 pellets of SiO₂ between which we deposited a little bit of Si-powder to facilitate absorption of the ~1
127 μm 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 SiO₂
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 SiO₂ at this pressure. Steady state
135 production of liquid-SiO₂ in this sample (as performed in [Andrault *et al.*, 2020]) would require even
136 more laser power. The sample pressure at ~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**).
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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 SiO₂ melting curve extends to ~40 GPa and the Clapeyron slope between stishovite and
146 the low-density melt (LDM) is ~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 ~40 GPa.

151 - The triple point between stishovite, LDM and high-density melt (HDM) is found at ~40 GPa and
152 ~4800 K. We refine a LDM-HDM volume change of -4.21(20) instead of -4.02(20) cm³/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) cm³/mol, which
156 corresponds to 4.0(0.9)% of the stishovite volume. This is ~10 times smaller than the stishovite-LDM
157 volume change of ~4.77 cm³/mol.

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

159 - Above 85 GPa, the Clapeyron slope increases again to ~31 GPa/K. At the highest pressure of this
160 study, ~117 GPa, the melting point of SiO₂ in its CaCl₂-form plots at ~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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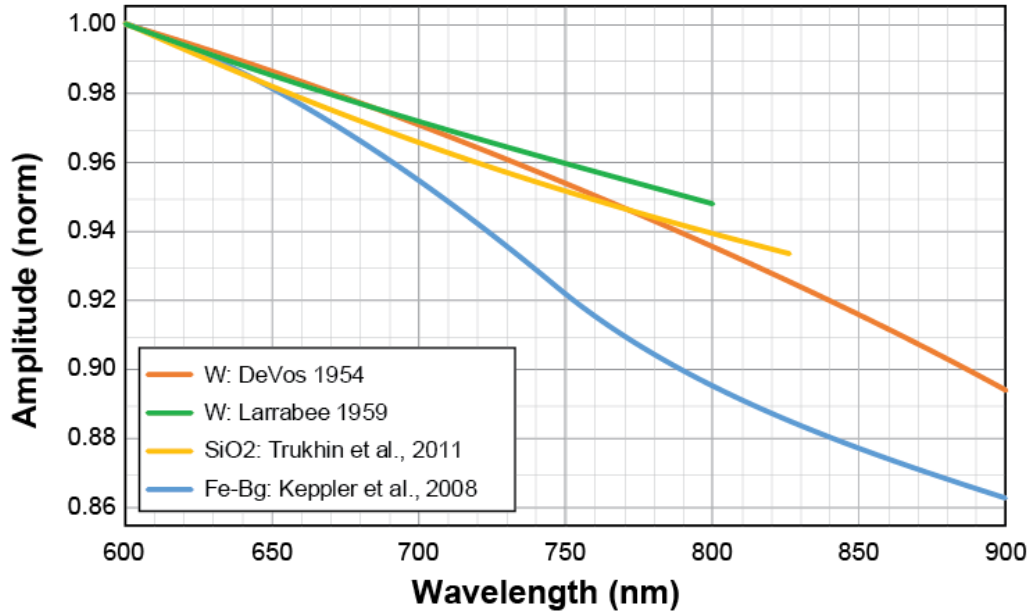
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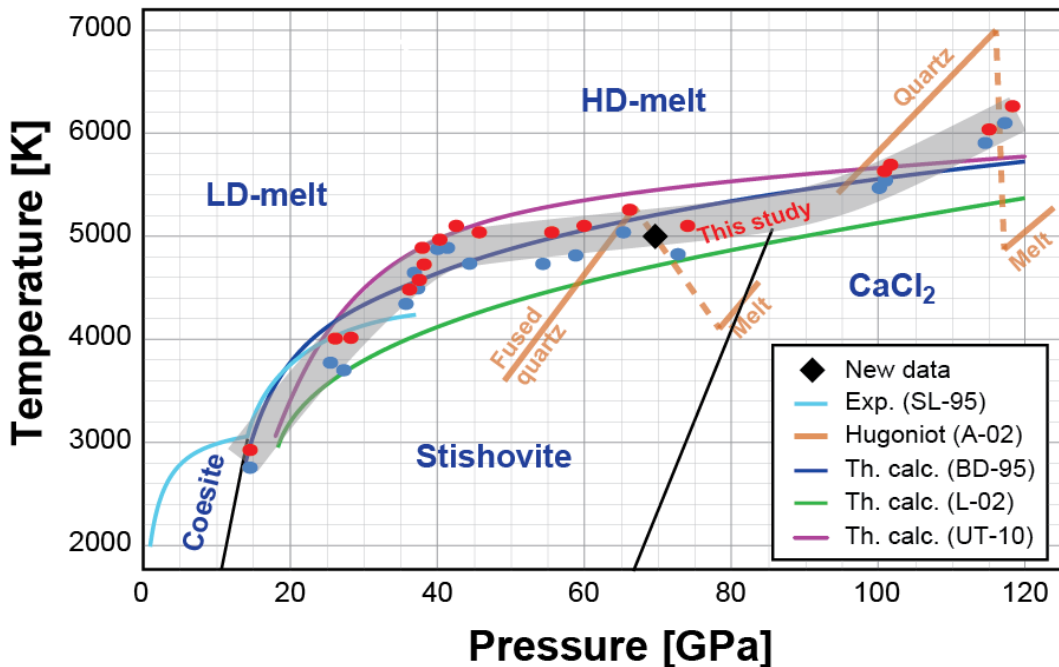
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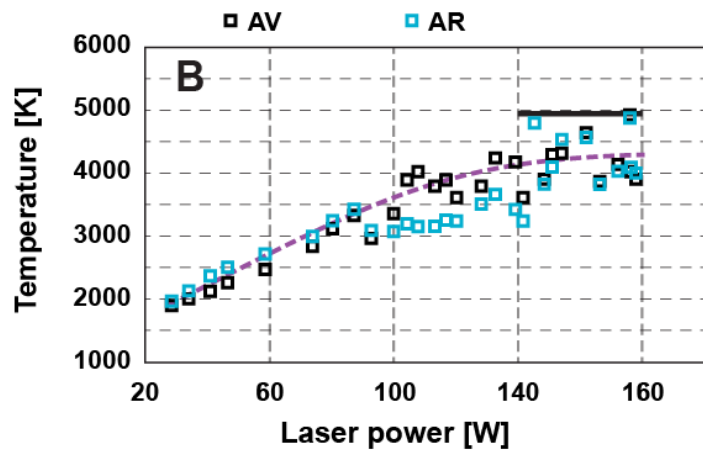
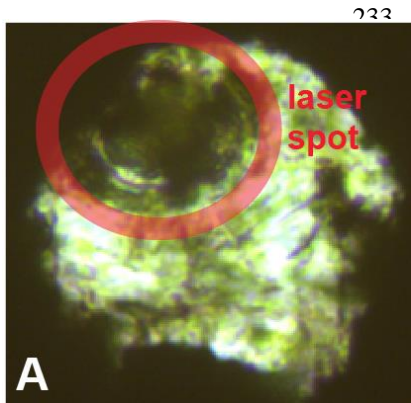
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 213 **New Figure 9: Normalized absorption and emissivity functions.** Emissivity functions of a tungsten
 214 wire [Devos, 1954; Larrabee, 1959] are plotted together with absorption spectra of SiO₂ [Trukhin et al.,
 215 2011] and Fe-bearing bridgmanite [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 ~ 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 ~ 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) GPa | Temp. K | P(high-T) GPa | Temp solid | Temp 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 | ΔS mol/K | ΔV cm ³ /mol | Vstish cm ³ /mol | Vcoes cm ³ /mol | VLDM cm ³ /mol | VHDM cm ³ /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 SiO₂ 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, ΔV 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 ₂ ,HDM) | 85 | 5200 | 9 |
| P-T max | 117 | 6200 | 31 |