Major mineral fraction and physical properties of carbonated peridotite (listvenite) from ICDP Oman Drilling Project Hole BT1B inferred from X-ray CT core images

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Abstract

We evaluated the mineral fractions of listvenite (completely carbonated peridotite) in Hole BT1B drilled by the ICDP Oman Drilling Project from 3D X-ray Computed Tomography (XCT) images. Total >250,000 XCT images from continuous ~200 m listvenite core samples were analyzed. Histograms of the intensity of X-ray attenuation (XCT number) of each XCT core-slice image were fitted assuming that the CT histogram is composed of magnesite, quartz, and dolomite peaks. These mineral peaks were confirmed by comparison of XCT numbers with chemical mapping data obtained using an XRF core scanner. In most core sections, XCT data indicate that listvenite matrix is composed of magnesite and quartz, consistent with discrete XRD and XRF data. Veins are composed mostly of dolomite. The mean abundance of dolomite in listvenite from BT1B is 11 vol.%, whereas that in core sections within 15 m of the basal thrust is >50 vol.%, suggesting that the basal thrust acted as a pathway for Ca- and CO fraction than that of Oman peridotite (39:60:1), indicating enrichment of Si during carbonation. P- and S-wave velocities and density of listvenite is close to that of peridotite while higher than that of serpentinites. These results suggest that limited material transfer during carbonation and hydration of the Oman Ophiolite, except for Si, Ca, CO₂ and H₂O, but potential as an overlooked carrier of CO₂ into the deep of Earth's interior.

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25	Key points (Max. 140 characters):

26 1. A method was developed to determine the downhole mineral fractions of drill cores

27 from continuous X-ray CT images.

Quartz-magnesite-dolomite fractions were estimated from X-ray CT images of
 listvenite cores from ICDP Oman Drilling Project Hole BT1B.

30 3. Results indicate limited material transfer during carbonation and hydration of the
31 Oman Ophiolite, except for Si, Ca, CO₂, and H₂O.

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Keywords: Ophiolite, Listvenite, X-ray CT, Carbonation, Mantle, Oceanic plate, Carbon
 storage

35

36 Abstract (247/250 words)

37 We evaluated the mineral fractions of listvenite (completely carbonated peridotite) 38 in Hole BT1B drilled by the ICDP Oman Drilling Project from 3D X-ray Computed 39 Tomography (XCT) images. Total >250,000 XCT images from continuous ~200 m 40 listvenite core samples were analyzed. Histograms of the intensity of X-ray attenuation 41 (XCT number) of each XCT core-slice image were fitted assuming that the CT histogram 42 is composed of magnesite, quartz, and dolomite peaks. These mineral peaks were 43 confirmed by comparison of XCT numbers with chemical mapping data obtained using 44 an XRF core scanner. In most core sections, XCT data indicate that listvenite matrix is 45 composed of magnesite and quartz, consistent with discrete XRD and XRF data. Veins 46 are composed mostly of dolomite. The mean abundance of dolomite in listvenite from BT1B is 11 vol.%, whereas that in core sections within 15 m of the basal thrust is >5047 vol.%, suggesting that the basal thrust acted as a pathway for Ca- and CO₂-rich fluids. 48 49 The overall SiO₂:MgO:CaO ratio in BT1B is 43:51:5, similar to that of onboard XRF data 50 (41:54:5) whereas lower SiO₂ fraction than that of Oman peridotite (39:60:1), indicating enrichment of Si during carbonation. P- and S-wave velocities and density of listvenite is 51 52 close to that of peridotite while higher than that of serpentinites. These results suggest 53 that limited material transfer during carbonation and hydration of the Oman Ophiolite, 54 except for Si, Ca, CO₂ and H₂O, but potential as an overlooked carrier of CO₂ into the 55 deep of Earth's interior.

56 **1. Introduction**

57 To understand planetary-scale fluid circulation from the surface to deep regions of Earth, it is important to constrain how fluids are captured/released by 58 59 hydration/dehydration and carbonation/decarbonation of minerals and the associated 60 volumes of these fluids. Moreover, the distribution of earthquakes and island arc volcanism can be influenced by the distribution of volatiles (cf. Abers et al. (2013); Mibe 61 62 et al. (1999); Okazaki and Hirth (2016); Omori et al. (2004)). Hydrated/carbonated 63 lithospheric mantle materials (i.e., ultramafic rocks) could be the primary carrier of 64 volatiles into deep regions of Earth, as their volumes are larger than those of subducting 65 sediments and oceanic crust (i.e., felsic and mafic rocks). Seismic observations suggest 66 the presence of fluids at the corner of the mantle wedge (Kamiya & Kobayashi, 2000; 67 Nakajima & Uchida, 2018) as well as in subducting slabs (Audet et al., 2009; Peacock et 68 al., 2011; Tsuji et al., 2008). However, as the evaluation of the alteration intensity of the 69 mantle lithosphere from the velocity structure is totally model dependent, and there has 70 been no direct drilling into the mantle, quantitative estimation of the intensity of alteration 71 of the lithospheric mantle is lacking.

72 Ophiolites, which are fossil material of paleo-oceanic plates, are obducted and 73 widely exhumed on Earth's surface (Dilek & Furnes, 2011). The Samail Ophiolite (Oman Ophiolite, hereafter), which is located in the Sultanate of Oman and the United Arab 74 75 Emirates, is the most extensive and best-exposed cross-section of oceanic lithosphere 76 from sediments and pillow lavas to mantle harzburgite (Figure S1). The basal thrust at 77 the base of the ophiolite separates the ophiolite sequence from the underlying 78 metamorphic sole consisting of greenschist- to amphibolite-facies metasediments and 79 metabasalts. The metamorphic sole is underlain by Permian to Late Cretaceous

80 formations composed mainly of marine sediments, meta-volcanic rocks, and limestone (Hacker & Mosenfelder, 1996; Ishikawa et al., 2005). Overall, peridotite in the Oman 81 Ophiolite has undergone a degree of hydration (serpentinization), probably during 82 83 obduction. In addition to the serpentinization, some parts of the peridotite close to the 84 basal thrust are carbonated. Listvenite, which is fully carbonated mantle material, was 85 originally defined as quartz-carbonate metasomatic rocks that were initially regarded in 86 terms of their relationship to gold mineralization and other ore deposits, but more recently 87 has been highlighted as a natural analog to mineral carbon storage (Beinlich et al., 2020; 88 Falk & Kelemen, 2015; Hansen et al., 2005; Kelemen et al., 2011; Streit et al., 2012). It 89 is considered that the basal thrust of the Oman Ophiolite was active as the paleo plate 90 boundary between the ophiolite body and over-thrusted oceanic plate and as a pathway 91 for fluids since the initial stage of obduction (Hacker & Mosenfelder, 1996; Ishikawa et 92 al., 2005). Since the late stage of obduction, carbonation of obducted peridotites and 93 serpentinites has been occurring continuously close to the basal thrust (Falk & Kelemen, 94 2015). The deformation structure and lithological and geochemical properties of these 95 rocks have been closely investigated by recent studies (Beinlich et al., 2020; Falk & 96 Kelemen, 2015; Menzel et al., 2020).

In the present study, we developed a method to estimate the mineral fraction of core samples from X-ray computed tomography core images with confirmation using chemical mapping data from an X-ray fluorescence (XRF) core scanner. The technique of non-destructive X-ray computed tomography is widely used, not only for medical purposes but also for industrial and material science applications requiring acquisition of internal structures of objects. Similarly, in earth sciences, this method has been applied, for example, to evaluate the grades of ore deposits, analyze samples from asteroid bodies, 104 and observe the real-time development of microstructures during deformation (Baker et 105 al., 2012; Godel, 2013; Ketcham & Carlson, 2001; Kyle & Ketcham, 2015; McBeck et 106 al., 2019; Okumura et al., 2008; Renard et al., 2016; Tsuchiyama et al., 2011). Using this 107 technique, we estimated continuous downhole-scale major mineral and element fractions 108 of listvenite in Hole BT1B drilled by the ICDP Oman Drilling Project (Kelemen et al., 109 2020b). These results were compared with physical property and geochemical data of 110 individual discrete listvenite samples from BT1B analyzed onboard D/V Chikyu in 2017 111 (Kelemen et al., 2020b, 2020c), on which basis we infer material transfer by CO₂-rich fluids during carbonation and potential as an overlooked carrier of CO₂ into the deep of 112 113 Earth's interior.

- 114
- 115 **2.** Core sample and method

116 **2.1. Listvenite core from ICDP Oman Drilling Project Hole BT1B**

117 Continuous drilling from the bottom of the ophiolite through the basal thrust to the 118 footwall metamorphic sole was conducted in Hole BT1B by the ICDP Oman Drilling 119 Project (Figure S1). Listvenite (completely carbonated former peridotite) is the main 120 lithology in Hole BT1B and is also found in other ophiolite bodies. Figure 1 presents the 121 downhole lithology of the core sample obtained from Hole BT1B. Listvenite is composed mainly of magnesite, quartz, dolomite, and Fe-hydroxide, with minor chromian spinel 122 123 and chromian mica (fuchsite; (Kelemen et al., 2020c). Two serpentinite and 124 ophicarbonate intervals also occur above the basal thrust. Below the basal thrust, metamorphic sole composed of greenschist/greenstone is the main lithology. 125





127 **2.2.** X-ray computed tomography core images taken onboard D/V Chikyu

128 All raw X-ray computed tomography (XCT) data used in this study are archived on 129 the ICDP website and have already been published in the initial report on the ICDP Oman 130 Drilling Project (Kelemen et al., 2020a, 2020b, 2020c). Therefore, in this and next 131 sections, we briefly describe the methods and procedures for XCT and XRF core scanning. 132 All core samples obtained by the Oman Drilling Project have been passed through 133 an XCT scanner, which enables the non-destructive observation of the internal structure 134 of core samples and is a routine measurement of the IODP drilling performed by D/V 135 Chikyu. The procedures for XCT scanning adopted in the present study followed those of previous IODP expeditions (e.g., IODP Expedition 322, Underwood et al. (2010); and 136 IODP Expedition 343, Expedition 343/343T Scientists (2013)), which is based on the 137

138 previous studies (GE healthcare, 2013; Mees et al., 2003; Nakano et al., 2000) . A 139 medical-use XCT scanner (Discovery CT 750HD, GE Medical Systems) was used for the 140 measurements. The excitation voltage and current for the X-ray tube (X-ray source) were 141 140 kV and 100 mA, respectively. All core sections of BT1B were scanned by the XCT 142 scanner with resolutions of 0.176 mm/pixel for the core-axis-normal (X and Y) directions 143 and 0.625 mm/pixel for the core-axis-parallel (Z) direction. Listvenite core sections have 144 similar dimensions (~63.5 mm in diameter) and thus similar volumes; therefore, the XCT 145 number provides information regarding the physical and chemical properties of the core 146 samples. More details on the XCT scanning procedure can be found in the initial report 147 on the ICDP Oman Drilling Project (Kelemen et al., 2020a, 2020b, 2020c).

Figure 2a shows an image taken using multi-sensor core logger (MSCL-I) of the archive half split core surface of core section BT1B 49Z-1, and Figure 2b shows a 2D XCT image (X–Z slice) reconstructed from X–Y slice images of this core section. Examples of the X–Z images are presented in Figure 2c–h. The color indicates the CT number of each voxel, which is defined as;

154
$$CT number = [(\mu_t - \mu_w)/\mu_w] \times 1000$$
 (1)

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where μ_t is the linear attenuation coefficient (LAC) of the target material (minerals and airs, in this study), and μ_w is the LAC for water. X-ray intensity varies as a function of Xray path length and the linear attenuation coefficient (LAC) of the target material as; $I = I_0 \times e^{-\mu L}$ (2)

161

162 where I is the transmitted X-ray intensity, I_0 is the initial X-ray intensity, and L is the

163 length of the X-ray path through the material. A reference material was used for quality 164 control (QC) and comprised three layers: air, water, and aluminum consisting of a telescope-shaped cylinder with six steps (1-6 cm in diameter). The QC material was 165 166 scanned after air calibration to check that the CT numbers were within QC ranges of 167 -1008 < CT number < -1002 for the air layer, -2 < CT number < 7 for the water layer, 168 and 2416 < CT number < 2499 for the aluminum layer. The LAC is a function of the 169 chemical composition and density of the target material (Godel, 2013), meaning that XCT 170 imaging provides information not only about density but also about chemical compositions (i.e., constituent elements) of the cores. For example, onboard lithological 171 172 observations have suggested that the matrix of listvenite is composed of magnesite (density = 3037 kg/m^3 : Yao et al. (2018) and quartz (density = 2650 kg/m^3 : Mavko et al. 173 174 (2020), whereas veins are inferred to be composed mainly of dolomite (density = 2880kg/m³: Mavko et al. (2020). However, CT numbers of the matrix in core section BT1B 175 176 49Z-1 (~3000) are lower than those of veins (~3400), which reflects the presence of calcium in dolomite, which has a higher atomic number and thus higher attenuation 177 178 coefficient than those of other elements in magnesite and quartz (i.e., Mg, Si, C, and O). 179 Figure 3 shows histograms of CT numbers for slices taken at intervals of 100 mm 180 along the Z-axis for the 100-600 mm core section of BT1B 49Z-1 and corresponding to 181 the slices shown in Figure 2c-h. For quantitative evaluation of the mineral assemblage of

182 the listvenite core, we used histograms for data taken from the center of the core cropped



Figure 2. (a) MSCL-I image along the X–Z plane and (b) X-ray CT images along (b) the X–Z plane and (c–h) X–Y planes for intervals between 100 and 600 mm along the Z-axis of core section 49Z-1 from Hole BT1B.

in a circle with a radius of 100 pixels (i.e., 17.6 mm in radius). This data screening process
removed the CT numbers of air and core tubes (CT number peaks of ~1000 and ~1300)
and the regions affected by the X-ray hardening effect, which cover mostly the boundary
between core sample and air. In Figure 3b, there are at least two peaks in each histogram,
and the position and the height of these peaks change with position on the Z-axis of the
core sample.



Figure 3. Histograms of CT number from images from Figure 2c–h for core section 49Z-1 from Hole BT1B. (a) Histograms of CT number for entire images for each X–Y slice along the Z-axis (i.e., depth). (b) Histograms of CT numbers for images cropped in a circle with a radius of 100 pixels for each X–Y slice along the Z-axis.

190 2.3. XRF mapping of the working half core surface using an XRF core scanner

191 To establish the relationship between XCT number and mineral species, we 192 directly compared CT number with the element abundance measured by an XRF core 193 scanner for the same locations. Twenty intervals of listvenite core were selected for non-194 destructive X-ray chemical analysis of the flat surface of the archive half core using the 195 mapping mode of the XRF core scanner (Table S1). Detailed measurement conditions 196 have been described in the initial report on the ICDP Oman Drilling Project (Kelemen 197 et al., 2020). The operating conditions were a voltage of 30 kV, a beam current of 0.04 198 mA, a counting time of 60 s, a spot size 7 mm, and a spacing between spots of 5 mm. 199 Figure 4 shows examples of an MSCL-I image (a), an XCT image (b), and XRF-200 scanner element maps for SiO₂ (c), MgO (d), CaO (e), and Fe^{*}O (f) of the archive half 201 core split surface at an interval of 200-550 mm along core section BT1B 49Z-1. Similar 202 XCT and XRF maps from all other intervals of listvenite cores from Hole BT1B (Table 203 S1) used in this study are presented in the Supplementary Information (Figures S2–S19). 204 These maps are useful for distinguishing relative element abundances and were used to 205 identify mineralogical and lithological variability and compositional transitions. Data 206 correction was performed to improve the raw output from the XRF scanner as described 207 in Kelemen et al. (2020b). Data correction was conducted to allow comparison of the 208 shore-based analysis at Southampton University, shipboard XRF analyses of BT1B core 209 samples, and previous work (Falk & Kelemen, 2015). We considered only the weight 210 fractions of SiO₂, MgO, CaO, and Fe^{*}O, and assumed that the sum of these four oxides 211 should be 100%. Details of the data correction procedure are described in the method 212 section in the initial report on the ICDP Oman Drilling Project (Kelemen et al., 2020a).



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Figure 4. Comparison of (a) the MSCL-I image, (b) the XCT image, and (c) SiO₂, (d) FeO, (e) MgO, and (f) CaO chemical mapping from the XRF scanner for core section BT1B 49Z-1.

216 **2.4. Comparison between CT number and XRF element composition**

217 To determine the ideal CT numbers for quartz, magnesite, and dolomite with respect to the dimensions of drill cores and settings for the XCT scanner, composition 218 219 maps (SiO₂, MgO, and CaO) from the XRF core scanner were compared with the CT 220 number of the pseudo-archive half section (X-Z plane) image generated from the XCT 221 image. To remove the CT hardening effect, which is an effect in which the CT number 222 appears artificially high at the boundary between two material with extremely different 223 CT numbers such as the boundary between air and minerals, we used those XCT and XRF 224 data from the center of the core cropped in a circle with a radius of 100 pixels (35.2 mm 225 in diameter) for comparison. A total of 865,415 data points for each element are plotted 226 in Figure 5. Using these data, we determined the relationship of CT number with 227 abundances of SiO₂, MgO, and CaO using multiple linear regression (MLR) analysis, 228 which yielded the equation:

229

230	$CT number = -5.16 \pm 0.10 \times SiO_2 [wt.\%] - 3.83 \pm 0.10 \times$	MgO [wt.%] + 1.26 ±
231	$0.10 \times CaO [wt.\%] + 3489.64 \pm 8.80$	(3).

232

These parameters obtained from MLR (Table S2) gave ideal CT numbers for quartz (SiO₂), magnesite (MgCO₃), and dolomite (CaMg(CO₃)₂) from the core of Hole BT1B of 2974.1 \pm 18.9, 3106.4 \pm 19.2, and 3415.5 \pm 19.8, respectively (Table 1). These numbers are consistent with the CT numbers of rock samples of quartz, magnesite, and dolomite measured onboard D/V *Chikyu* (Kelemen et al., 2020b), but we were able to determine the positions of the peaks more strictly by additionally considering the confidence interval for the position of each peak. It should be noted that we did not consider Fe and its related minerals in this study, because Fe can exist as Fe^{2+} and Fe^{3+} and thus in many mineral phases in listvenite (e.g., magnetite, hematite, Cr-spinel, and even siderite as an end-member of the magnesite– calcite–siderite solid solution).



Figure 5. Comparisons of CT number with XRF chemical data for listvenite core samples from Hole BT1B. (a) CT number versus SiO₂, (b) CT number versus MgO, and (c) CT number versus CaO. Black lines in figures depict the linear relationship between XCT number and element fractions, whereas actual parameters of the relationship among XCT number and element fractions used for the downhole calculation are obtained using multiple linear regression (see section 2.4).

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Table 1. Parameters used for the calculation for the downhole mineral fraction and physical properties

	Table 1.1 alameters used for the calculation for the downhole mineral fraction and physical properties.										
Mineral	Chemical formula	CT number*	Density [kg/m3]	Bulk modulus (GPa)	Shear modulus (GPa)	Vp [km/s]**	V₅ [km/s]**	λ [W/m/K]***			
Quartz	SiO ₂	2974.1 ± 18.9	2650	36.6	45.0	6.04	4.12	7.69			
Magnesite	MgCO₃	3106.4 ± 19.2	3037	117.5	69.1	8.31	4.77	5.84			
Dolomite	CaMg(CO ₃) ₂	3415.5 ± 19.8	2880	69.4	51.6	6.93	4.23	5.51			

*CT number for dolomite is calculated from the CT number of 60.7% CaO + 39.3% MgO

**Reference for velocities: Quartz; Mavko et al., (2020), Magnesite; Yao et al., (2018), Dolomite; Mavko et al., (2020).

246 **2.5. Fitting of peaks of each XCT slice image**

Using the ideal CT numbers for quartz, magnesite, and dolomite (Table 1), we conducted peak fitting for all X–Y plane XCT images of the 200-m-long core BT1B,

^{245 ***}Thermal conductivities from Clauser and Huenges (1995)

which number more than 250,000 for the listvenite sections. An important assumption 249 250 used for calculating the mineral fractions of listvenite is that the CT number of a pixel reflects the sum of the product of the volume fractions and the CT number of the different 251 252 minerals (and possibly the volume fraction of air) in the pixel. Therefore, a histogram of 253 the distribution of CT number in a CT image shows the volume fractions of minerals in 254 the core. For calculation of XCT data, we used MATLAB and its Image Processing 255 Toolbox and Curve Fitting Toolbox. The procedure for image analysis involved eight 256 steps, as follows:

257 1. X–Y plane 2D XCT data were saved as raw DICOM files and merged into a single X–
 258 Y–Z 3D XCT dataset for each core section. 3D XCT data of each core section were
 259 saved in a folder in MATLAB standard format (.mat).

260 2. A histogram of CT number for each X–Y plane image was calculated using the data
261 from the center of the core cropped in a circle with a radius of 100 pixels (e.g., Figure
262 3b).

263 3. Each histogram was fitted with three peaks (i.e., quartz, magnesite, and dolomite peaks),
264 assuming that the shape of the peaks follows a Gaussian distribution:

265

266
$$y = \sum_{i=1}^{3} a_i \exp\left[-\left(\frac{x-b_i}{c_i}\right)^2\right]$$
(4)

267

where a_i , b_i , and c_i are constants for quartz (i = 1), magnesite (i = 2), and dolomite (i = 269 3) peaks, respectively; and x is the XCT number. The position of each peak (e.g., b_i) was fitted using the ideal CT numbers for quartz, magnesite, and dolomite as described above in section 2.4. and considering the respective confidence intervals. The height and width (i.e., a_i and c_i) of each peak were assumed to range from 0 to infinity for the

fitting process.

4. Fitting results [(values of a_i , b_i , and c_i and the coefficient of determination (R^2)] were saved in the workspace.

5. Volume fractions of quartz (n_1) , magnesite (n_2) , and dolomite (n_3) from the fitting parameters of the histogram were also calculated as follows:

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279
$$n_i = a_i c_i / \sum_{i=1}^3 a_i c_i$$
 (5).

280

281 The volume fraction of each mineral was also saved in the workspace.

6. The pixels for which the CT number is lower than that of the lower side of the 99% confidence interval (2.5σ) of the quartz peak were considered for calculating porosity. Similarly, the pixels for which the CT number is higher than that of the higher side of the 99% confidence interval of the dolomite peak were considered for calculating the volume fraction of heavy minerals. A more detailed description of this procedure is given below in section 4.3.

7. Histogram peak fitting was continued for all X–Y CT images of a core section. Once
the calculation for a section was finished, data were saved as a .mat file in a folder.

8. X–Y–Z CT data for a section and saved calculation results were deleted from the
workspace, then new X–Y–Z CT data of another section were opened, with the process
continuing through steps 2 to 7 until calculations for all core sections had been completed.

3. Results

3.1. Peak fitting results and downhole volumetric mineral fractions of listvenite from
 core BT1B

Figure 6 presents an example of the results of peak fitting from core section BT1B 49Z-1. Mineral fractions as a function of distance along the Z-axis (i.e., depth) inferred from XCT images indicate that matrix-rich parts are composed mainly of a quartzmagnesite mixture, whereas vein-rich parts are composed predominantly of dolomite (Figure 6b). This result is consistent with elemental mapping obtained from the XRF core scanner (Figure 4).



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Figure 6. (a) XCT image and (b) calculated mineral fractions from XCT images of core section BT1B 49Z-1. (c–h) Examples of peak fitting results of XCT histograms at depths (core section Z-axis) of 100–600 mm.

Figure 7 shows the lithology of core BT1B, the downhole volume fractions of minerals, and the mole fraction of SiO₂, MgO, CaO, and CO₂ calculated from XCT data. Analytical results for which the R^2 value of fitting is ≥ 0.99 were used to calculate the mean mineral fractions for each core section for Figure 7b as well as the mean mole 308 fractions for each core section for Figure 7c. Results show that the mineral fractions are 309 successfully solved from the XCT images in most core sections and that most of the listvenite section is composed of quartz and magnesite, except for the depth range of 310 311 \sim 200–170 m, that is, within \sim 30 m above the basal thrust. In this deeper part of the core, 312 dolomite is the dominant mineral phase, and the presence of minor quartz is detected from 313 the XCT data. The downhole mean volume fractions of quartz, magnesite, and dolomite 314 are 0.38, 0.49, and 0.13, respectively. These values correspond to downhole mean weight 315 fractions for SiO₂, MgO, and CaO of 0.52, 0.42, and 0.06, respectively.



316



317 **3.2.** Data refinement using R^2 values to calculate downhole mineral fractions

The quality of fit of the obtained XCT data depends on the condition of core samples (e.g., the number of open fractures because fracturing increases the air-mineral contact area resulting CT hardening effects), which in turn influences the calculated downhole mineral fractions. Figure 8 shows the degree to which the peak fitting results capture the characteristics of the histograms of the XCT images. A fitting result with $R^2 = 0.90$ fails to adequately describe the histograms of the XCT images (Figure 8a). Figure 9a shows how the calculated total volume fraction of each mineral in Hole BT1B changes with respect to the adopted threshold R^2 value. Fitting results for $R^2 < 0.925$ tend to show a higher abundance of dolomite (Figure 9a) than those for $R^2 > 0.99$. The total quartz



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328

Figure 8. Examples of the changing appearance of histogram peak fitting results with different R² values. All histograms are for core section 49Z-1 of Hole BT1B.

fraction is nominally constant regardless of the threshold R^2 value, whereas the magnesite fraction increases and dolomite fraction decreases with increasing threshold R^2 value. This might reflect the fact that dolomite occurs mostly heterogeneously as veins, which tend to be located close to fractures, resulting in CT hardening. The presence of fractures or void spaces filled by air in the core sample also decreases the quality of the fitting. Alternatively, some calcite-rich veins might be present in the cores, which show higher CT numbers than that of dolomite (CT number = ~4000; Kelemen et al., 2020b), whereas onboard microstructural and geochemical observations reveal that calcite or calcite-rich carbonate vein is minor (Kelemen et al., 2020b). Even if we applied such a tight threshold $(R^2 \ge 0.99)$, more than 50% of data (>125,000 XCT images) remain available for analysis (Figure 9b). Therefore, we use only the fitting results for R^2 values of ≥ 0.99 as a basis for discussion in Section 4.



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Figure 9. Data selection using threshold R^2 values of the histogram peak fitting results with respect to downhole mineral fractions evaluated from XCT images of entire listvenite sections from Hole BT1B. (a) Calculated volume mineral fractions as a function of threshold R^2 value. (b) Number and fraction of data used for calculating downhole mineral fractions as a function of threshold R^2 value.

342 4. Discussion

343 4.1. SiO₂–MgO–CaO fractions in listvenite from BT1B

344 Figure 7c presents the downhole mole fractions of SiO₂, MgO, CaO, and CO₂ from 345 the mineral fractions estimated from XCT data for Hole BT1B. The downhole mean mole fractions of SiO₂, MgO, CaO, and CO₂ are 0.28, 0.33, 0.03, and 0.36, respectively. The 346 abundance of MgO ranges from 0.2 to 0.5, and that of CO₂ increases slightly with 347 increasing depth. The abundances of SiO2 and CaO vary with depth more than that of 348 349 MgO, and the variation in SiO_2 is larger than that in MgO, ranging between 0.1 and 0.8. 350 The abundance of dolomite (i.e., CaO, as only one Ca-bearing mineral was considered in 351 this study) shows a spiked distribution with depth, and its abundance increases downward

352 from ~40 m above the basal thrust (~160 m depth). In contrast, the abundance of quartz 353 decreases markedly downward from a depth of ~140 m, and dolomite becomes the most abundant mineral downward from a depth of 170 m. These patterns could indicate that 354 355 the relative abundance of Si decreases owing to enrichment of Ca and CO₂ and/or loss of 356 Si by dissolution into fluid near the basal thrust. In fact, high fracture and vein densities 357 have been observed close to the basal thrust (Kelemen et al., 2020c). Therefore, the 358 heterogenous distributions of Si and Ca could indicate that the basal thrust acted as a 359 pathway for Ca- and CO₂-rich fluids.

360

4.2. Comparison of CT data with geochemistry data from core samples

362 Figure 10a–d shows a comparison between SiO₂, MgO, CaO, and CO₂ abundances 363 estimated from the XCT images and geochemical measurements on individual quartercore samples conducted onboard D/V Chikyu (Kelemen et al., 2020a; Kelemen et al., 364 365 2020c). Geochemical data were calculated from the weight fractions of SiO₂, MgO, and 366 CaO estimated from XRF measurements using bead samples and the CO₂ weight fraction 367 from loss of ignition (LOI) measurements. The weight fraction of MgO from XCT is in 368 good agreement with that from geochemical measurements. The XRF data for SiO₂ and 369 CaO are less variable than the corresponding XCT data, especially for depths below 160 370 m. This could represent the effect of sample bias for the geochemical measurements, 371 given that analysis locations that were relatively intact and uniform could have been 372 chosen for XRF measurements, or a shift of CT numbers for the cores slightly toward 373 higher values because of the CT hardening effect between the quartz/magnesite matrix 374 and dolomite veins. Interestingly, mineral volume fractions from XCT data show good 375 agreement with those obtained from thin-section observations (Figure 10f and g).



Figure 10. Downhole element and mineral fractions estimated from XCT images and from geochemical measurements of individual samples for Hole BT1B. (a) Downhole volume fractions of quartz, magnesite, and dolomite. (b-e) Element fractions of SiO₂, MgO, CaO, and CO₂, showing a comparison between data from XCT images and from XRF and LOI measurements. (f and g) Comparison of mineral fractions estimated from XCT images and from thin section observations under an optical microscope.

4.3. Comparison of CT data with physical property data core samples

378 Physical properties of the listvenite core sections from Hole BT1B can also be 379 calculated from mineral fractions estimated from XCT images. We estimated porosity and 380 the volume fraction of high-density (heavy) minerals from XCT images (Figure 11b and 381 c). Porosity and the heavy mineral (HM) fraction were calculated from the fitting of XCT 382 images (see also section 2.5. above). Porosity was determined from the residual of the 383 XCT histogram after fitting the histogram with the three peaks for quartz, magnesite, and 384 dolomite considering the pixels for which CT number was lower than that of the lower 385 part of the 99% confidence interval (2.5σ) of the quartz peak. Similarly, the HM fraction 386 was also determined from the residual of the XCT histogram after fitting, considering the pixels for which CT number was higher than that of the higher part of the 99% confidence 387 388 interval of the dolomite peak. In addition to porosity, the density, thermal conductivity, 389 and seismic velocity were calculated from the XCT mineral fractions. For calculations, 390 we adopted standard values for the physical properties (density, elastic constants, and 391 thermal conductivity) of quartz, magnesite, and dolomite, as summarized in Table 1.

392 The bulk density of listvenite was determined from the density of each mineral 393 and the density of water multiplied by volume fractions, similar to the measurements for 394 bulk density made onboard D/V Chikyu using individual water-saturated samples 395 (Kelemen et al., 2020a). Seismic velocities and thermal conductivities were calculated on 396 the basis of the Voigt-Reuss-Hill averages and series-parallel models of each mineral, 397 respectively. The effects of pore spaces on seismic velocity and thermal conductivity 398 depend not only on the porosity value but also on pore geometry (Brantut & David, 2018; 399 Clauser & Huenges, 1995; O'Connell & Budiansky, 1974), and thus the relationships among these properties are complex. Therefore, we plotted downhole seismic velocity 400



Comparisons of downhole (d) density, (e) thermal conductivity (λ) , and (f) seismic velocity (p-wave velocity: Vp and s-wave samples for Hole BT1B. (a) Downhole volume fractions of quartz, magnesite, and dolomite. (b) Comparison of downhole porosity estimated from XCT images and from analysis of individual samples. (c) Volume fraction of heavy minerals (HM). (d-f) Figure 11. Downhole variation in physical property data from XCT images and from physical property measurements of individual velocity: Vs) estimated from XCT images and from analysis of individual samples.

23

403

and thermal conductivity calculated from XCT images and assuming no effect of porosity on these properties (Figure 11e and f).

404 Downhole porosity estimated from the CT images is slightly lower than that 405 measured using individual samples (Figure 13b). This might be due to not considering 406 pore space in this study, as we used results for fitting with $R^2 > 0.99$, and thus the high 407 porosity region might have been removed by this procedure owing to the low CT number 408 of air (-1000). For most of the listvenite section, porosity is less than 3%. The upper 409 listvenite and the lowermost listvenite subsections show slightly higher porosity values. 410 This may be explained by the density of cataclasite measured during the core description 411 on board D/V Chikvu (Kelemen et al., 2020c). The HM fraction is ~2 vol.% in the upper 412 listvenite subsection and <1 vol.% in the lower listvenite subsection. In the archive core 413 half section, surfaces show that the color of the upper listvenite subsection is more reddish (a high R value in RGB (red-green-blue color scale) and high a* in the La*b* color scale; 414 415 Kelemen et al., 2020c) than the lowermost listvenite subsection. The relatively high HM 416 fraction in the upper listvenite subsection might be due to a high hematite (Fe₂O₃) fraction 417 in the listvenite matrix, as hematite typically shows a rusty red color. Some peaks of the 418 high HM fraction correspond to enrichment of Cr-spinel (e.g., core section 45Z-3 at100 419 m depth; see VCD of Hole BT1B; Kelemen et al. (2020c).

Figure 11d shows a downhole comparison of density estimated from XCT images and physical property measurements conducted onboard D/V *Chikyu*. Values of density calculated from XCT images are reasonably consistent with the sample density measurements. The mean density is ~2850 kg/m³ through the depth range of 10–140 m and increases slightly to ~2950 kg/m³ below a depth of 140 m. This slight increase in density can be explained by the decrease in the fraction of quartz and the corresponding 426 increase in the fraction of dolomite.

427 Figure 11e shows a downhole comparison of thermal conductivity estimated from XCT images and physical property measurements conducted onboard D/V Chikyu. The 428 429 overall pattern of the thermal conductivity profile calculated from XCT images is similar 430 to that given by the sample measurements, although the values are shifted lower by ~ 2 431 W/m/K compared with the sample measurements. This difference can be explained by 432 the effects of porosity and pore geometry (e.g., the aspect ratio of cracks), given that the 433 thermal conductivity of water is about an order of magnitude lower than those of minerals 434 constituting the listvenite, and pore connectivity has a significant effect on bulk thermal 435 conductivity. Alternatively, the thermal conductivity values of each mineral in listvenite 436 in Hole BT1B might differ slightly from reference values reported in the literature 437 (Diment and Pratt (1988); Horai (1971); Newnham (2005) summarized in Clauser and Huenges (1995)). Nevertheless, regardless of any of the above effects, the thermal 438 439 conductivity of listvenite (~6 W/m/K) is clearly higher than those of dry peridotite (~5 W/m/K) and serpentinite (~3 W/m/K). The downhole thermal conductivity of listvenite 440 441 decreases below a depth of ~150 m on account of the decrease in the quartz fraction, as 442 quartz has the highest thermal conductivity (~8 W/m/K) of the various minerals in 443 listvenite.

Figure 11f presents a comparison of seismic velocity estimated from XCT images and physical property measurements conducted onboard D/V Chikyu. The downhole average physical properties of listvenite from Hole BT1B is summarized in Table 2. The P-wave velocity of listvenite from XCT images is about 7 km/s and increases slightly to ~7.6 km/s below a depth of ~150 m, probably due to the decrease in the fraction of quartz (6.04 km/s; Mavko et al. (2020) and the corresponding increase in the fraction of dolomite

450	(6.93 km/s; Mavko et al. (2020). The P-wave velocity estimated from XCT images, a
451	procedure that assumes 0% porosity, is systematically higher than that determined from
452	onboard sample measurements. Since seismic velocity is highly sensitive to thin cracks
453	(e.g., O'Connell & Budiansky, 1974; Kuster & Toksöz, 1974), this difference can be
454	explained by a few percent of porosity in the listvenite cores as calculated from the XCT
455	images (Figure 11b). In comparison with the seismic velocities of peridotite (Vp = ~ 8.0
456	km/s, Vs = ~4.5 km/s), lizardite (Vp = ~4.8 km/s, Vs = ~2.3 km/s), and antigorite
457	serpentinite (Vp = \sim 6.5 km/s, Vs = \sim 3.6 km/s; Christensen, 2004), the values of Vp and
458	Vs of listvenite lie between those of peridotite and antigorite serpentinite. In addition, the
459	seismic velocity of listvenite is close to that of 10%-30% serpentinized (lizardite-
460	chrysotile) peridotite. The average Vp/Vs ratio of listvenite is ~1.6. This value is slightly
461	smaller than that of peridotite and antigorite serpentinite (~1.8) while significantly
462	smaller than that of lizardite-chrisotile serpentinite (Christensen, 2004). These results
463	indicate that listvenite could be hard to identify using seismic observations, even if mantle
464	carbonation (i.e., listvenitization) occurs widely beneath the sea floor and subduction
465	zones.

Table 2. Average mineral fraction and physical properties of listvenite from Hole BT1B calculated from XCT data and from onboard measurements										
	Quartz [vol%]	Magnesite [vol%]	Dolomite [vol%]	Porosity [vol%]	Heavy minerals [vol%]	Density [kg/m ³]	λ [W/m/K]*	V _p [km/s]	V₅ [km/s]	Vp/Vs
CT data	37.6	49.1	13.4	1.15	0.44	2871	6.14	7.15	4.44	1.61
Onborad measurements	35.5 [#]	54.5	10.1 [#]	2.9	0.53 [#]	2860/2920 ^{\$}	5.16	6.41	-	-
*Thermal conductivity										

data from onboard XRD measurements 466 \$ Bulk density and grain density

467 4.4. Implications for fluid flow of CO₂-rich fluid and material transfer at the 468 subduction zone

Figure 12a shows the mole fraction of MgO as a function of mole fraction of SiO_2 (mean values of each core section in Hole BT1B). Data for $SiO_2 < 0.4$ show scatter away from predicted trends, reflecting Mg addition/loss and/or Si addition/loss (Falk & 472 Kelemen, 2015). These data correspond to dolomite-rich sections and are thus located 473 mostly near the basal thrust. Figure 12b shows a ternary plot of SiO₂-MgO-CaO mole fractions of listvenite from Hole BT1B. The SiO₂:MgO:CaO ratio is 43:51:5, and the 474 475 Mg/Si ratio estimated from XCT images is 1.19. The SiO₂:MgO:CaO ratio and the Mg/Si 476 ratio is nominally consistent with onboard geochemical data (SiO₂:MgO:CaO = 41:54:5, 477 $Mg/Si = \sim 1.31$: values ignoring the other elements; Kelemen et al., 2020c), whereas the 478 Mg/Si ratio of listvenite is lower than that of Oman harzburgite (SiO₂:MgO:CaO = 479 39:60:1, Mg/Si ~1.53: values ignoring the other elements; Godard et al., 2000). These difference of the SiO₂:MgO:CaO and the Mg/Si ratios between Oman listvenite and 480 481 harzburgite suggest that Mg loss and/or Si addition, as well as Ca addition, occurred during carbonation (listvenitization) as suggested by Falk and Kelemen (2015). 482



Figure 12. Element fractions for Hole BT1B. (a) Mole fraction of MgO as a function of mole fraction of SiO₂. Color of small circles indicates down-core depth. (b) Ternary plot of SiO₂–MgO–CaO fractions from XCT images. Color of small circles indicates down-core depth. Red, orange, and green stars indicate mean values of XCT data, onboard discrete XRF data, and results for Oman peridotite outcrops (Godard et al., 2000; Takazawa et al., 2003).

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485 Downhole mineral fractions inferred from XCT images indicate that dolomite 486 occurs in veins and is located mostly near the basal thrust. The abundance of Ca in Oman

peridotite is low (<1 wt.% for harzburgite, Godard et al., 2000; <3 wt.% for lherzolite, 487 488 Takazawa et al., 2003); therefore, Ca might have been supplied from fluids flowing along 489 the basal thrust. Ishikawa et al. (2005) reported that the metamorphic sole close to the 490 basal thrust is enriched with fluid-mobile elements such as B, Rb, K, and Ba, and argued 491 that these elements are traces of fluid flow along the plate boundary. Although the 492 chemical composition of the fluid might have been different from them during the 493 obduction, and the carbonation of the Oman peridotite occurred at a low temperature 494 (<250 °C; Benlich et al., 2020), it is still possible that the basal thrust (i.e., the plate 495 boundary thrust fault) acted as a pathway for Ca- and CO₂-rich fluids into the Oman 496 peridotite during the entire stage of obduction of the ophiolite, and potentially even before 497 the obduction.

498 Structural observations of listvenite cores from BT1B suggest that the carbonation 499 (i.e., listvenitization) occurred after the hydration (i.e., serpentinization) of peridotite in 500 Oman ophiolite (Kelemen et al., 2020b). This indicates that the physical property, 501 especially seismic velocities, of altering/altered mantle evolves with a complex manner 502 with different degrees of carbonation and hydration. For example, the carbonation of fresh 503 mantle peridotite decreases the Vp/Vs ratio from 1.8 to 1.6, which is in the opposite sense 504 of the change of the Vp/Vs ratio of mantle peridotite by "typical alteration" meaning 505 hydration (Figure 13). This kind of change in seismic property is more pronounced in the 506 case of the carbonation of lizardite serpentinite; the Vp/Vs ratio changes from 2.0 to 1.6 507 as observed in the Oman ophiolite in this study. This suggests that a significant volume 508 of listvenite (i.e., CO₂), which can be overlooked by seismic observations alone, could be 509 subducting from the subduction zones. We emphasize that magnesite is potentially stable 510 even at the lower mantle (Biellmann et al., 1993), listvenite can be a major host for carbon



Figure 13. (a) P-wave velocity (Vp), S-wave velocity (Vs) and Vp/Vs ratio of listvenite (this study), peridotite, lizardite serpentinite and antigorite serpentinite (Christensen, 2004). Vertical and horizontal axes are Vp and Vs, respectively. Gray dashed lines indicate Vp/Vs ratio from 1.6 to 2.1. (b) Similar to Fig. 13a but with possible changes of seismic velocities by hydration and carbonation of listvenite, serpentinites and peridotite. Carb.: carbonation.

514 **5. Conclusion**

515 We evaluated the quartz-magnesite-dolomite fraction of listvenite drilled at Oman 516 Drilling Project Hole BT1B from X-ray CT core images. For most core sections, XCT data indicate that the matrix of listvenite is composed of magnesite and quartz, consistent 517 with discrete XRD and XRF data. Veins are composed mostly of dolomite. Downhole 518 519 variation in the fraction of dolomite in Hole BT1B indicates that the basal thrust could 520 have acted as a pathway for Ca-, Si-, and CO₂-rich fluids during carbonation. Vp, Vs and density of listvenite is relatively close to that of peridotite, but very different form 521 serpentinite. A significant volume of listvenite (i.e., CO₂), which are being overlooked by 522 seismic observations alone, could be subducting from the subduction zones to the deep 523 524 of Earth's interior.

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546 Data availability

547 All raw XCT and XRF data used in this study are archived on the ICDP website 548 (https://www.icdp-online.org/projects/world/asia/oman/details/) and have already been

549	published in the initial report on the ICDP Oman Drilling Project
550	(http://publications.iodp.org/other/Oman/OmanDP.html). MATLAB codes and analytical
551	results of this study are archived in ZENODO (doi: 10.5281/zenodo.4555143).
552	
553	Figure captions
554	
555	Figure 1. Principal lithologies of recovered core samples from Hole BT1B.
556	
557	Figure 2. (a) MSCL-I image along the X–Z plane and (b) X-ray CT images along (b) the
558	X–Z plane and (c–h) X–Y planes for intervals between 100 and 600 mm along the Z-axis
559	of core section 49Z-1 from Hole BT1B.
560	
561	Figure 3. Histograms of CT number from images from Figure 2c-h for core section 49Z-
562	1 from Hole BT1B. (a) Histograms of CT number for entire images for each X-Y slice
563	along the Z-axis (i.e., depth). (b) Histograms of CT numbers for images cropped in a
564	circle with a radius of 100 pixels for each X–Y slice along the Z-axis.
565	
566	Figure 4. Comparison of (a) the MSCL-I image, (b) the XCT image, and (c) SiO ₂ , (d)
567	FeO, (e) MgO, and (f) CaO chemical mapping from the XRF scanner for core section
568	BT1B 49Z-1.
569	
570	Figure 5. Comparisons of CT number with XRF chemical data for listvenite core samples
571	from Hole BT1B. (a) CT number versus SiO_2 , (b) CT number versus MgO, and (c) CT

572 number versus CaO. Black lines in figures depict the linear relationship between XCT

number and element fractions, whereas actual parameters of the relationship among XCT
number and element fractions used for the downhole calculation are obtained using
multiple linear regression (see section 2.4).

576

Figure 6. (a) XCT image and (b) calculated mineral fractions from XCT images of core
section BT1B 49Z-1. (c-h) Examples of peak fitting results of XCT histograms at depths
(core section Z-axis) of 100–600 mm.

580

Figure 7. Downhole (a) lithology, (b) mineral volume fraction, and (c) element molar
fractions (SiO₂, MgO, CaO, and CO₂) of listvenite for Hole BT1B.

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Figure 8. Examples of the changing appearance of histogram peak fitting results with
different R² values. All histograms are for core section 49Z-1 of Hole BT1B.

586

Figure 9. Data selection using threshold R^2 values of the histogram peak fitting results with respect to downhole mineral fractions evaluated from XCT images of entire listvenite sections from Hole BT1B. (a) Calculated volume mineral fractions as a function of threshold R^2 value. (b) Number and fraction of data used for calculating downhole mineral fractions as a function of threshold R^2 value.

592

Figure 10. Downhole element and mineral fractions estimated from XCT images and from geochemical measurements of individual samples for Hole BT1B. (a) Downhole volume fractions of quartz, magnesite, and dolomite. (b–e) Element fractions of SiO₂, MgO, CaO, and CO₂, showing a comparison between data from XCT images and from

- 597 XRF and LOI measurements. (f and g) Comparison of mineral fractions estimated from
 598 XCT images and from thin section observations under an optical microscope.
- 599

Figure 11. Downhole variation in physical property data from XCT images and from physical property measurements of individual samples for Hole BT1B. (a) Downhole volume fractions of quartz, magnesite, and dolomite. (b) Comparison of downhole porosity estimated from XCT images and from analysis of individual samples. (c) Volume fraction of heavy minerals (HM). (d–f) Comparisons of downhole (d) density, (e) thermal conductivity (λ), and (f) seismic velocity (p-wave velocity: Vp and s-wave velocity: Vs) estimated from XCT images and from analysis of individual samples.

Figure 12. Element fractions for Hole BT1B. (a) Mole fraction of MgO as a function of mole fraction of SiO₂. Color of small circles indicates down-core depth. (b) Ternary plot of SiO₂–MgO–CaO fractions from XCT images. Color of small circles indicates downcore depth. Red, orange, and green stars indicate mean values of XCT data, onboard discrete XRF data, and results for Oman peridotite outcrops (Godard et al., 2000; Takazawa et al., 2003).

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Figure 13. (a) P-wave velocity (Vp), S-wave velocity (Vs) and Vp/Vs ratio of listvenite (this study), peridotite, lizardite serpentinite and antigorite serpentinite (Christensen, 2004). Vertical and horizontal axes are Vp and Vs, respectively. Gray dashed lines indicate Vp/Vs ratio from 1.6 to 2.1. (b) Similar to Fig. 13a but with possible changes of seismic velocities by hydration and carbonation of listvenite, serpentinites and peridotite. Carb.: carbonation.

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Supporting Information for

Major mineral fraction and physical properties of carbonated peridotite (listvenite) from ICDP Oman Drilling Project Hole BT1B inferred from the X-ray CT core images

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Contents of this file

Figures S1to S20 Tables S1 to S2 Reference



Figure S1. Geological map of the southeastern massif of the Samail ophiolite (after Nicolas et al., 2000) showing the drill site locations of the ICDP Oman Drilling Projects.



Figure S2. Comparison among (a) the XCT image, (b) SiO2, (c) FeO, (d) MgO and (e) CaO chemical mappings from the XRF scanner from the core section 12Z-1 84–89 cm.



Figure S3. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 13Z-4 5–15 cm.



Figure S4. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 14Z-2 0–61 cm.



Figure S5. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 16Z3 7–40 cm.



Figure S6. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 20Z-1 78–83 cm.



Figure S7. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 28Z-1 49–71 cm.



Figure S8. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 28Z-1 69–74 cm.



Figure S9. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 32Z-2 70–85 cm.



Figure S10. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 32Z-3 15–30 cm.



Figure S11. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 32Z-3 57–65 cm.



Figure S12. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 32Z-4 0–12 cm.



Figure S13. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 47Z-4 41–50 cm.



Figure S14. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 49Z-2 6–34 cm.



Figure S15. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 52Z-2 1–4 cm.



Figure S16. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 52Z-2 39–46 cm.



Figure S17. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 53Z-4 37–47 cm.



Figure S18. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 60Z-1 12–17 cm.



Figure S19. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 66Z-3 66–71 cm.



Figure S20. Comparison among (a) SiO2, (b) FeO, (c) MgO and (d) CaO, and (e) the XCT image, mappings from the XRF scanner and XCT from the core section 73Z-2 16–22 cm.

Hole Core-Section	Top depth (m Bottom depth		Z-axis (cm)		X-axis	(cm)	Total number
Interval	downhole)	(m downhole)	min	max	min	max	of spots
BT1B-12Z-1A, 84-89 cm	18.69	18.74	84.0	89.0	-3.0	3.0	143
BT1B-13Z-4A, 5-15 cm	23.82	23.92	5.0	15.0	-1.5	1.5	147
BT1B-14Z-2A, 0-64 cm	24.58	25.19	0.5	61.5	-3.0	3.0	1599
BT1B-16Z-3A, 7-40 cm	28.88	29.21	7.0	40.0	-3.0	3.0	871
BT1B-20Z-1A, 78-83 cm	39.98	40.03	6.5	10.5	-3.0	3.0	117
BT1B-28Z-1A, 49-70 cm	60.24	60.45	2.1	19.6	-2.5	2.5	396
BT1B-28Z-1A, 69-74 cm	60.44	60.49	8.3	12.3	-2.5	2.5	99
BT1B-32Z-2A, 70-85 cm	68.15	68.30	12.0	27.0	-3.0	3.0	403
BT1B-32Z-3A, 15-30 cm	68.57	68.72	15.0	30.0	-3.0	3.0	403
BT1B-32Z-3A, 57-65 cm	68.99	69.07	6.0	14.0	-3.0	3.0	221
BT1B-32Z-4A, 0-12 cm	69.27	69.38	0.0	12.0	-3.0	3.0	325
BT1B-47Z-4A, 41-50 cm	108.91	109.00	60.0	69.0	-1.5	1.5	133
BT1B-49Z-1A, 20-55 cm	111.55	111.90	20.0	55.0	-2.0	2.0	639
BT1B-49Z-2A, 6-34 cm	112.13	112.41	47.0	74.0	-2.0	2.0	513
BT1B-52Z-3A, 1-4 cm	119.65	119.68	4.5	9.0	-3.0	3.0	130
BT1B-52Z-3A, 39-46 cm	120.03	120.10	13.0	20.0	-3.0	3.0	195
BT1B-53Z-4A, 37-47 cm	124.08	124.18	60.0	70.0	-1.5	1.5	147
BT1B-60Z-1A, 12-17 cm	139.97	140.02	6.5	10.5	-3.0	3.0	117
BT1B-66Z-3A, 66-71 cm	160.60	160.65	6.0	10.0	-3.0	3.0	117
BT1B-73Z-2A, 16-22 cm	180.43	180.49	4.0	10.0	-2.25	2.25	130

Table S1. List of analyzed listvenite cores and areas measured by XRFCL

|--|

Constant SiO2 -5.16 ± 0.10 MgO -3.83 ± 0.10 CaO 1.26 ± 0.11 Intercept 3489.64 ± 8.80	Table S2. Parameters obtained from the multiple linear regression					
SiO2 -5.16 \pm 0.10 MgO -3.83 \pm 0.10 CaO 1.26 \pm 0.11 Intercent 3489.64 \pm 8.80		Constant				
MgO -3.83 ± 0.10 CaO 1.26 ± 0.11 Intercept 3489.64 ± 8.80	SiO2	-5.16	±	0.10		
CaO 1.26 ± 0.11	MgO	-3.83	±	0.10		
Intercept 3489.64 + 8.80	CaO	1.26	±	0.11		
	Intercept	3489.64	±	8.80		

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