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1 **Permeability profiles across the crust-mantle sections in the Oman**
2 **Drilling Project inferred from dry and wet resistivity data**

3

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24

25 **Abstract**

26 Permeability profiles in the crust-mantle sequences of the Samail ophiolite were
27 constructed based on onboard measurements of the electrical resistivity of cores
28 recovered during the Oman Drilling Project. For each sample, we measured dry and
29 brine-saturated resistivity during the description campaign on the drilling vessel *Chikyu*.
30 Owing to the conductive brine in the pore space, wet resistivity is systematically lower
31 than dry resistivity. The difference between dry and wet resistivity is attributed to the
32 movement of dissolved ions in brine that occupies the pore space. We applied effective
33 medium theory to calculate the volume fraction of pores that contribute to electrical
34 transport. Using an empirical cubic law between transport porosity and permeability, we
35 constructed permeability profiles for the crust-mantle transition zone and the
36 serpentinized mantle sections in the Samail ophiolite. The results indicate that: (1) the
37 gabbro sequence has a markedly lower permeability than the underlying mantle
38 sequence; (2) serpentinized dunites have higher permeability than serpentinized
39 harzburgites; and (3) discrete sample permeability is correlated with ultrasonic velocity,
40 suggesting that the permeability variations predominately reflect crack density and
41 geometry.

42

43 **Key Points**

- 44 • Brine-saturated resistivity is systematically lower than dry resistivity, with the
45 differences attributed to the volume fraction of pores.
- 46 • Permeability through the crust-mantle sequences was modeled using the effective
47 medium theory and resistivity data.
- 48 • The serpentinized dunite sequence is characterized by higher permeability than the
49 overlying gabbro and underlying serpentinized harzburgite sequences.

50
51

52 **Plain Language Summary**

53 Aqueous fluids that circulated beneath the seafloor play an important role in heat
54 transfer, chemical exchange, and microbial activity in the oceanic lithosphere. The
55 Oman Drilling Project was successful in obtaining continuous drill cores through the
56 crust-mantle sequences in the Samail ophiolite, where the paleo-oceanic basement was
57 thrust onto the continental crust in the Late Cretaceous. In this study, we constructed
58 profiles of permeability across the crust-mantle sections using the effective medium
59 theory and resistivity data, which provide insights into fluid circulation in the oceanic
60 lithosphere. The results indicate higher permeability in the uppermost mantle sequence
61 between the crust and the underlying mantle, suggesting that present-day fluid transfer
62 is predominant at the crust-mantle boundary. Although the fluid flow and chemical
63 reactions are likely coupled, the high permeability could promote the transformation of
64 crust-mantle materials and hence the recycling of water into the mantle. Application of
65 this technique to forthcoming deep drilling projects through the Mohorovičić

66 discontinuity (Moho) and into the upper mantle may provide insights into the
67 permeability structure and fluid circulation system in the oceanic lithosphere.

68

69

70 **1. Introduction**

71 Permeability is a key control on heat and chemical exchange in the oceanic
72 lithosphere, as well as microbial activity in the sub-seafloor (e.g., Stein and Stein, 1994;
73 Fisher, 1998; Furnes et al., 2001). In investigations based on ocean drilling projects, the
74 permeability is often inferred from resistivity data because electrical transport at the
75 crustal depths is controlled mainly by fluid flow. This approach uses an empirical
76 relationship between resistivity and porosity, such as Archie's law (e.g., Gueguen and
77 Palciauskas, 1994), and models the permeability from resistivity logging data and/or
78 resistivity measurements of recovered core samples (e.g., Becker et al., 1982; Anderson
79 et al., 1985; Carlson, 2011; Slagle and Goldberg, 2011). Archie's law is valid for a
80 conducting phase that saturates a non-conducting matrix. However, when the matrix has
81 a significant conductivity, the Archie's law is no longer applicable (Glover et al., 2000).
82 In serpentinized ultramafic sequences, hydration reactions are commonly associated
83 with the production of magnetite, which is a highly conductive material. As a result, the
84 conductivity of the serpentinized matrix varies with the degree of hydration and
85 chemical exchanges (e.g., Stesky and Brace, 1973).

86 We carried out systematic measurements of dry and wet resistivity on core samples
87 collected during the Oman Drilling Project from the crust to mantle of the Samail

88 ophiolite. Using effective medium theory (e.g., Mavko et al., 2009), we calculated the
89 permeability based on the brine-saturated and matrix resistivities, and determined the
90 relative changes of permeability across crust-mantle sections in the Samail ophiolite.
91 We show that this approach can be used to construct a first-order permeability profile
92 during oceanic drilling programs, although the permeability can be heterogeneous in the
93 oceanic lithosphere and scaling effects need to be evaluated.

94

95 **2. Core samples and methods**

96 The Oman Drilling Project obtained nine diamond-cored boreholes through the
97 Samail ophiolite from the dike-gabbro transition to the uppermost mantle (Fig. 1). The
98 total cumulative drilled core length is 5458 m with ~100% core recovery (Teagle et al.,
99 2018; Kelemen et al., 2018). In this study, we focused on three boreholes (CM1A, BA1B,
100 and BA4A) that are each ~300-400 m long. Hole CM1A samples the crust-mantle
101 transition from layered gabbros through dunites into harzburgites of the upper mantle
102 sequences. Hole BA1B comprises dunite (upper section) and harzburgite (lower section)
103 cut by numerous mafic dikes. Hole BA4A consists dominantly of dunite with minor
104 harzburgite and is crosscut by abundant mafic dikes. The mantle sequences are highly
105 altered, with >70% serpentinization, and contain few relicts of primary olivine and
106 orthopyroxene. The recovered core samples were systematically analyzed on the drilling
107 vessel *Chikyu* during the description campaigns in 2017 and 2018, including
108 mineralogical, geochemical, structural, and geophysical analyses (Kelemen et al., 2018).

109 Electrical resistivity, ultrasonic velocity, bulk/grain density, porosity, and thermal
110 conductivity were measured on selected discrete samples (Abe et al., 2018).

111 The core samples were cut into $\sim 2 \times 2 \times 2$ cm cubes, in which the x- and
112 y-directions were perpendicular and parallel to the split surface of the working halves,
113 respectively, and the z-direction was the down-hole axis. For the wet measurements,
114 samples were saturated with NaCl solution (3.5 g/L), equivalent to the salinity in
115 borehole water measured in the field (Paukert et al., 2012). The resistivity was
116 measured in three orthogonal directions using an Agilent 4294A Precision Impedance
117 Analyzer with a set of two stainless steel electrodes. Measurements were carried at
118 laboratory temperatures of 22.5 to 23.3°C, resulting in a temperature-induced resistivity
119 variation of $\sim 1\%$, which is broadly equivalent to the accuracy of sample dimensions.
120 Two paper filters soaked in brine for wet measurements and two stainless steel mesh
121 filters for dry measurements were placed between the steel electrodes and sample cube
122 on its top and bottom sides to enhance coupling. The magnitude ($|Z|$) and phase angle
123 (θ) of the complex impedance were measured at 25 kHz across the array from 40 Hz to
124 10 MHz. The resistivity was calculated from the sample impedance, length, and
125 cross-sectional area in each orientation. Blank tests yielded ~ 20 k Ω m, which is the
126 upper limit of the resistivity measurements. The detailed methodology of the resistivity
127 measurements was described by Hatakeda et al. (2015).

128

129 **3. Resistivity data**

130 The electrical resistivity results from Holes CM1A, BA1B and BA4A are shown as
131 a down-hole plot in Fig. 2. Circles indicate the averaged resistivity, and bars represent
132 the variation in the three orthogonal directions. Although some samples exhibit large
133 variations with measurement orientations, the resistivity anisotropy is relatively weak in
134 each borehole and there are no systematic variations with orientation (Fig. 3). Dry
135 resistivity varies from 26 Ω m to 13 k Ω m in Hole CM1A, 525 Ω m to 18 k Ω m in Hole
136 BA1B, and 952 Ω m to 15 k Ω m in Hole BA4A (the geometric mean and standard
137 deviation of each sequence are listed in Table 1). Although the resistivities in the dry
138 measurements nearly reached the upper limit of the measurement system, the large
139 variations can be attributed to mineralogical and textural variations, such as the
140 occurrence and connectivity of conductive phases. Wet resistivity varies from 2.5 Ω m
141 to 7.7 k Ω m in Hole CM1A, 13 Ω m to 12 k Ω m in Hole BA1B, and 48 Ω m to 6.4 k Ω
142 m in Hole BA4A, and is systematically lower than the dry resistivity in each borehole
143 (Table 1).

144 The gabbro sequence has a nearly constant and high resistivity, with occasional low
145 resistivity related to layers of wehrlite and dunite. In the mantle section, the
146 dunite-dominant sequence has a relatively low resistivity, consistent with the high
147 degree of alternation in dunite as compared to harzburgite. Mafic dikes in the upper
148 mantle section have a high resistivity, similar to similar lithologies in the gabbro
149 sequence. The brine-saturated resistivity generally shows trends similar to the dry
150 measurements, but is systematically lower than dry resistivity due to the presence of
151 conductive brine in the pore space (Fig. 2). The difference between wet and dry

152 resistivity is related to the pore volume and geometry, as discussed in the following
153 section.

154

155 **4. Permeability profile**

156 Given that the dry matrix has significant variations in resistivity, due in part to the
157 presence of variable amounts of magnetite associated with serpentinization, Archie's
158 law is not applicable to these data. Therefore, we used the Hashin-Shtrikman upper
159 bound (e.g., Mavko et al., 2009) to estimate the volume fraction of pores that contribute
160 to electrical transport (termed "transport porosity") as follows:

$$\sigma_{eff} = \sigma_f \left(1 - \frac{3(1 - \phi)(\sigma_f - \sigma_{dry})}{3\sigma_f - \phi(\sigma_f - \sigma_{dry})} \right)$$

161 where σ_{eff} , σ_f , and σ_{dry} are the effective, fluid, and dry conductivity (inverse of
162 resistivity), respectively, and ϕ is the transport porosity. The effective conductivity
163 corresponds to the wet measurement, and the fluid conductivity was set to 0.58 S/m
164 based in its salinity (Carmichael, 1982). Figure 4 shows profiles of the calculated
165 transport porosity in each borehole. The transport porosity inferred from the difference
166 between the brine-saturated and dry resistivities is generally lower than the bulk
167 porosity that was estimated from the moisture and density (MAD) analysis. Some
168 samples have an extremely high transport porosity because they have a low matrix
169 resistivity (i.e., high conductivity) that is close to the fluid resistivity. Moreover, if a
170 sample have a relatively small difference between wet and dry resistivity, then the
171 calculated transport porosity has a relatively large uncertainty.

172 There are several other models that describe multi-phase conducting mixtures. We
173 also applied a modified version of Archie's law that incorporates the effect of matrix
174 resistivity, as follows:

$$\sigma_{eff} = \sigma_{dry}(1 - \phi)^{\log(1-\phi^m)/\log(1-\phi)} + \sigma_f \phi^m$$

175 where m is the cementation exponent (Glover et al., 2000). The results are almost
176 identical to the calculations using the Hashin-Shtrikman upper bound, if an exponent of
177 $m = 1$ is used, although the large exponent in the modified Archie's law yields a higher
178 porosity that exceeds those inferred from the MAD analysis.

179 We then approximated an empirical relationship between transport porosity (ϕ) and
180 permeability (k), as follows:

$$181 \quad \quad \quad k = A\phi^n,$$

182 where A is a constant and the exponent n is related to pore geometry (e.g., Gueguen and
183 Palciauskas, 1994). A geometric exponent of $n = 3$ was used in our calculations,
184 because the pores are approximately planar cracks in these samples, as revealed by
185 ultrasonic measurements and structural observations during the onboard core
186 description (Abe et al., 2018; Kelemen et al., 2018).

187 To check and calibrate our calculations, we conducted a direct measurement of
188 permeability using an intra-vessel fluid flow apparatus, applying a constant pressure
189 gradient in the core sample (for details, see Katayama et al., 2012). This yielded a
190 permeability of $5.1 \times 10^{-19} \text{ m}^2$ for a dunite sample with 0.8% porosity inferred from the
191 resistivity data. This permeability is similar to those of low-temperature serpentinites

192 collected from the accretionary prism of the Mineoka belts, but slightly lower than those
193 of dredged samples from the ocean floors (Hatakeyama et al., 2017). Based on this
194 benchmarking test, we obtained $A = 9.2 \times 10^{-13}$, which was used to calculate
195 permeability from the transport porosity. Though it is treated as a constant, this term
196 may vary throughout the section, although the variation is usually less than one order of
197 magnitude (Carlson, 2011). Given that the permeability is proportional to the cube of
198 the porosity, the overall permeability profile is not sensitive to the constant term A , and
199 is sensitive to the transport porosity.

200 Figure 5 shows a down-hole plot of permeability in boreholes CM1A, BA1B, and
201 BA4A. Although the data are somewhat scattered, the calculated permeability clearly
202 increases from the gabbro to serpentized dunite sequences, and then decreases from
203 the dunite to serpentized harzburgite-dominated sequences in Hole CM1A. The
204 decrease in permeability from the dunite to harzburgite sequences is also observed in
205 Hole BA1B, and this trend is consistent with the relatively low permeability of the
206 harzburgite layers in Hole BA4A. In the crustal sections, wehrlite and dunite layers
207 locally exhibit high permeability and, in the mantle sections, the gabbroic dikes have
208 lower permeability than their surrounding ultramafic host rocks. The permeability
209 structure is also affected by fault zones, in which high permeability is associated with
210 the presence of abundant fractures. However, highly damaged samples from fault zones
211 were difficult to prepare for analysis, and we may overlook the presence of fracture
212 zones in these profiles.

213 It is important to note that permeability can be affected by many variables;
214 consequently, the modeled absolute values of permeability have large uncertainties.
215 However, the relative permeability changes are robust, because transport porosity is a
216 primary variable that reflects the electrical transport and fluid flow.

217

218 **5. Relationship between permeability and velocity**

219 The calculated permeability variations are caused primarily by the different pore
220 volumes and geometries in the analyzed core samples. Figure 6 shows the relationship
221 between the calculated permeability and P-wave velocity measured onboard during the
222 core description campaigns. The elastic wave velocity of the ultramafic rocks is
223 significantly lower than that of the gabbro and unaltered peridotite due to extensive
224 serpentinization. A negative correlation between permeability and velocity is observed
225 for the ultramafic rocks, whereby dunites are characterized by large permeability and
226 velocity variations as compared to harzburgites (Fig. 6). The gabbros exhibit a similar,
227 although weak, correlation that might reflect the limited velocity variations. In the Holes
228 504B and 1256D, a similar negative correlation between model permeability and
229 ultrasonic velocity has been reported based on logging data (Carlson, 2014).

230 Since the P-wave velocity of low-temperature serpentine is ~ 5 km/s (e.g.,
231 Christensen, 2004), the variations in ultrasonic velocity are potentially related to crack
232 density, as well as the degree of alteration. Violay et al. (2010) reported that resistivity
233 and velocity are also associated with microcracks in gabbro sampled in the Hole 1256D.
234 The development of a crack network significantly modifies the hydrological properties,

235 with theoretical models predicting that permeability is related to the fraction of crack,
236 crack density, and crack radius etc. (e.g., Simpson et al., 2003). This implies that
237 permeability variations obtained in this study are controlled primarily by damage in the
238 samples, possibly related to volume expansion during hydration reactions such as
239 serpentinization. Following from McDonald and Fyfe (1985) and O’Hanley (1992),
240 several recent papers have suggested that, once aqueous fluids access to rocks, the
241 volume change due to hydration can result in fracture development, maintaining or
242 increasing permeability and reactive surface in a positive feedback (e.g., Jamtveit et al.,
243 2008; Rudge et al., 2010; Kelemen and Hirth, 2012; Ulven et al., 2014; Shimizu and
244 Okamoto, 2016; Zhu et al., 2016; Malvoisin et al., 2017; Zheng et al., 2018; Uno et al.,
245 2019).

246

247 **6. Comparison with a hydrological model and other oceanic drilling sites**

248 In the Samail ophiolite, hydrological analyses have been undertaken using
249 stream-flow gauging and the chemical dilution method (Dewandel et al., 2005). These
250 approaches indicated that fluid flow is more efficient in gabbro and dolerite than in
251 peridotite. Although the hydrological results are different from the intrinsic permeability
252 inferred from our resistivity measurements, groundwater circulation in the hydrological
253 models is dominated by flow in a fissured near-surface horizon (<50 m depth). At such
254 depths, frequently observed joints and fractures are probably the main conduits for fluid
255 flow, while such features do not affect our resistivity measurements on discrete core
256 samples.

257 In the shallow oceanic crusts, *in-situ* permeability is often measured using borehole
258 packer tests, which indicate a decrease in permeability with depth down to $\sim 10^{-17} \text{ m}^2$ in
259 the upper crust (e.g., Fisher, 1998). This is generally consistent with electrical resistivity
260 logging data, whereby the apparent resistivity increases significantly from pillow lavas
261 to sheeted dikes and to massive units (e.g., Becker, 1989). The sharp increase in
262 resistivity in the underlying dike unit has been interpreted as reflecting a significant
263 reduction in porosity that limited hydrothermal circulation in the oceanic crust (Becker
264 et al., 1982). Carlson (2011) applied Archie's law to the resistivity logging data
265 obtained from Holes 504B and 1256D, and suggested that the permeability decreases
266 from the pillow lavas ($\sim 10^{-14} \text{ m}^2$) to the sheeted dikes ($\sim 10^{-18} \text{ m}^2$).

267 Although Archie's law can be applied to the mafic section of oceanic crust, due to
268 its nearly non-conductive matrix, it is not suitable for application to the mantle sequence
269 because of the sensitivity of matrix resistivity to the formation of magnetite associated
270 with serpentinization. We used effective medium theory to model the permeability in
271 crust-mantle sections in the Samail ophiolite. Our analysis yields permeabilities for the
272 gabbro cores of 10^{-19} to 10^{-21} m^2 , which are slightly lower than those of the sheeted dike
273 unit in Hole 504B and 1256D. However, this range of permeability is consistent with
274 direct permeability measurements on gabbro core collected from Hole 1256D (Gilbert
275 and Bona, 2016). Our calculated permeabilities show a marked increase in the dunite
276 sequence. These samples are extensively altered, and the permeability in the dunite and
277 harzburgite sequences sampled by the Oman Drilling Project was likely modified during
278 serpentinization.

279 Although our core-scale measurements do not show a systematic correlation in
280 resistivity in the discrete orientations, recent active-source electromagnetic
281 measurements have shown a clear electrical anisotropy in the oceanic lithosphere,
282 whereby conduction at crustal depths is enhanced in a direction sub-parallel to the paleo
283 mid-oceanic ridge (Chesley et al., 2019). Fisher (1998) noted that the permeability of
284 oceanic crust varies extensively due to the presence of fractures, and cannot simply be
285 determined from core measurements. We agree with this caveat regarding the
286 scale-dependence of permeability, and thus the electrical resistivity in the oceanic
287 lithosphere. Nevertheless, our analysis shows that core-scale permeability varies with
288 lithology and structure. These data provide the first clue of the background intrinsic
289 permeability through altered oceanic crust into serpentized mantle sequences.

290

291 **7. Conclusions**

292 We modeled the permeability across the crust-mantle sections sampled by the
293 Oman Drilling Project using dry and wet resistivity data and effective medium theory.
294 Although the absolute values of the calculated permeabilities are highly uncertain, the
295 relative permeability variations are robust. The dunite sequence has markedly higher
296 permeability than the overlying gabbro and underlying harzburgite sequences, which is
297 likely correlated with crack density and geometries, as well as the degree of alteration.
298 The proposed Mohole-to-Mantle (M2M) project aims to drill through the Moho and into
299 the upper mantle using the riser drilling vessel *Chikyu* (e.g., Umino et al., 2012).
300 Application of our technique to core samples, as well as down-hole geophysical logging

301 data, in this forthcoming project will provide insights into the permeability structure and
302 fluid circulation system in the oceanic lithosphere.

303

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311

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445

446 **Figure and Table captions**

447 **Fig. 1.** Geological map of the southeastern massif of the Samail ophiolite (after Nicolas
448 et al., 2000) showing the drill site locations of the Oman Drilling Projects. The
449 colored units are the ophiolite sequence. The inset shows a map of the Arabian
450 Peninsula, in which the location of the main figure is indicated by the dashed
451 box.

452 **Fig. 2.** Down-hole plots of resistivity in the three boreholes (CM1A, BA1B, and BA4A),
453 and borehole stratigraphy. Blue and red circles indicate measurements under wet
454 and dry conditions, respectively. The data represent the averaged resistivities in
455 three orthogonal orientations, and the bars indicate the variations in the
456 measurement directions.

457 **Fig. 3.** Resistivity perturbations of dry and wet measurements in Hole BA1B.
458 Perturbations were calculated as $(\log R_i - \log \bar{R}) / \log \bar{R}$, where R_i is the
459 resistivity of each orientation and \bar{R} is the averaged resistivity of the three
460 orthogonal orientations.

461 **Fig. 4.** Profiles of transport porosity calculated from the wet and dry resistivities. The
462 data represent the averaged porosities in three orthogonal orientations, and bars
463 indicate the range of values in all measurement directions. Gray symbols
464 indicate the bulk porosity estimated from the moisture and density (MAD)
465 analyses during the description campaign (Abe et al., 2018), and are mostly
466 higher than the calculated porosity.

467 **Fig. 5.** Profiles of permeability calculated from resistivity data using the effective
468 medium theory. The data represent the averaged permeabilities in three
469 orthogonal orientations, and the bars indicate the variations in the measurement
470 directions. Gray lines are the 20 m averaged permeability profiles.

471 **Fig. 6.** Relationship between calculated permeability and P-wave velocity for gabbro,
472 dunite, and harzburgite from boreholes CM1A, BA1B, and BA4A. The gabbro
473 samples include olivine gabbro and rodingitized samples. The ultrasonic velocity

474 was measured with an acoustic transducer of 230 kHz. Bars on the discrete data
475 indicate the variations in the measurement orientations. Fitting curves are shown
476 for gabbroic and ultramafic rocks.

477 **Table 1.** Mean resistivity and calculated transport porosity and permeability in each
478 borehole.

Figure1-6,Table1.

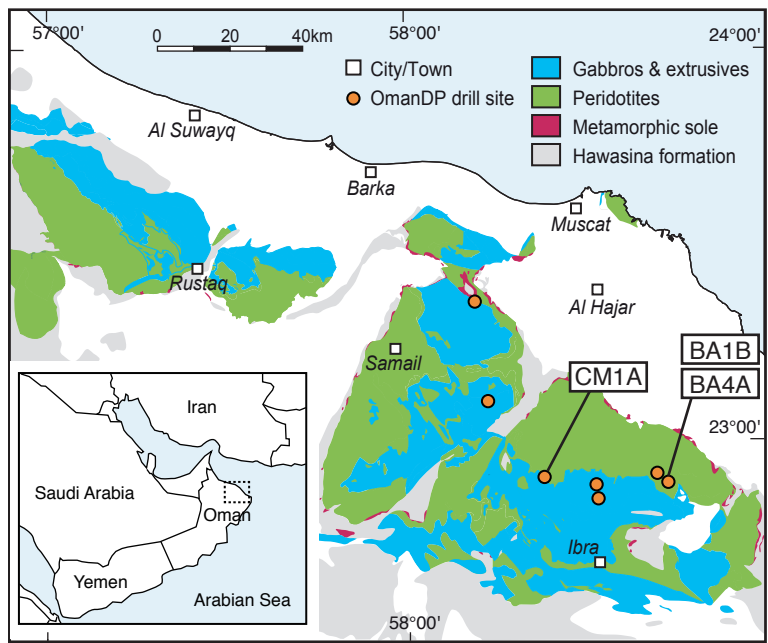


Figure 1

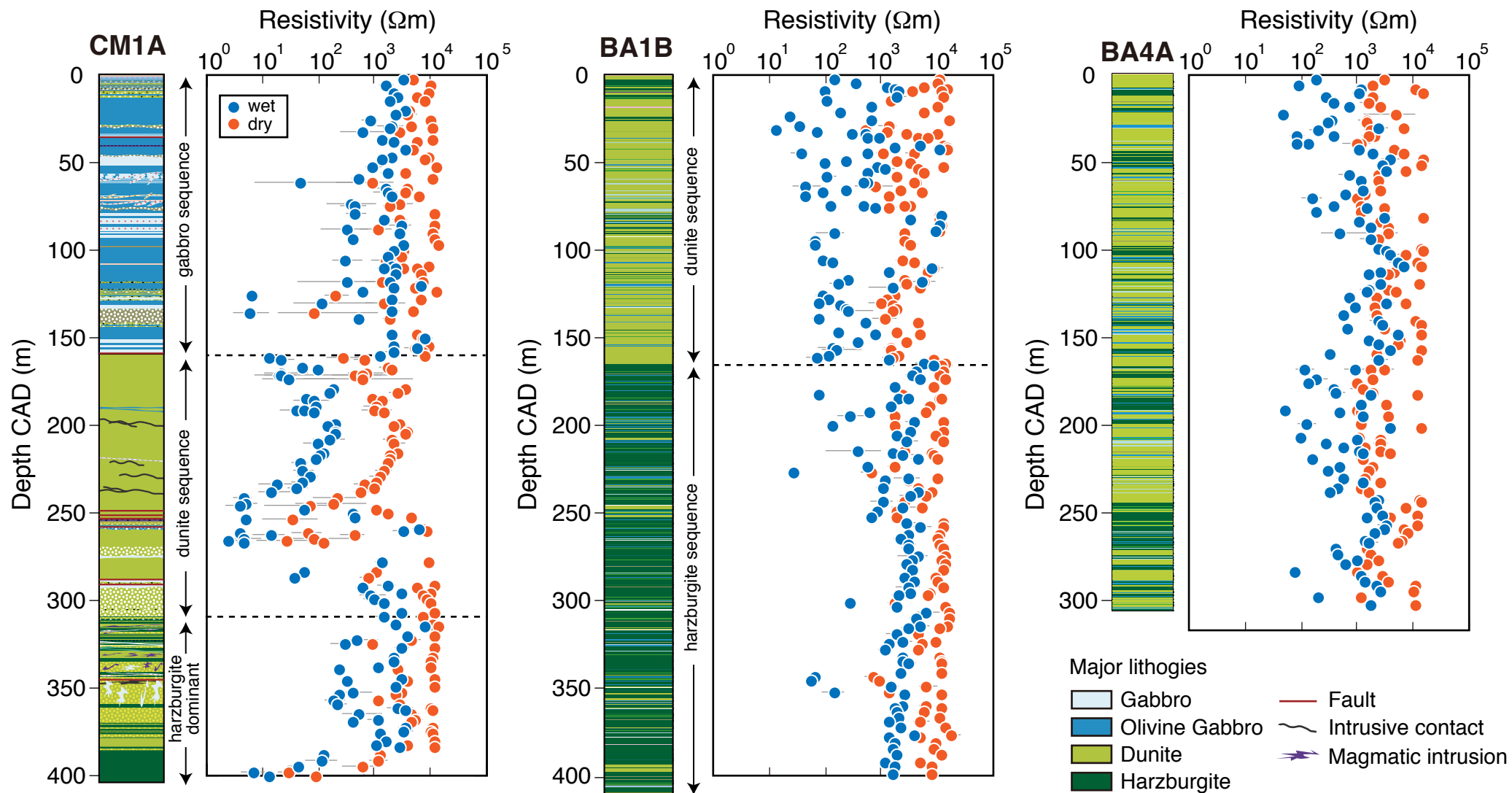


Figure 2

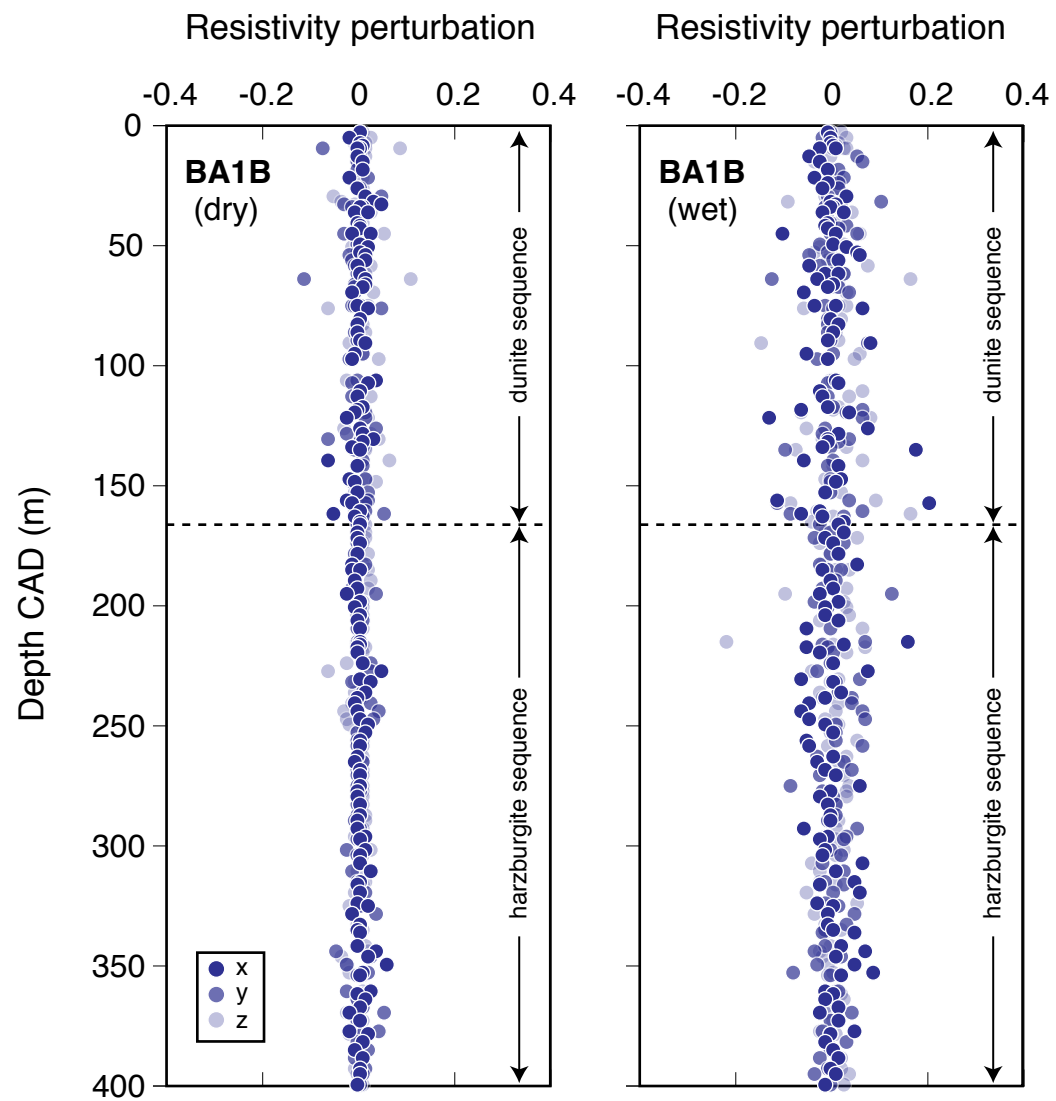


Figure 3

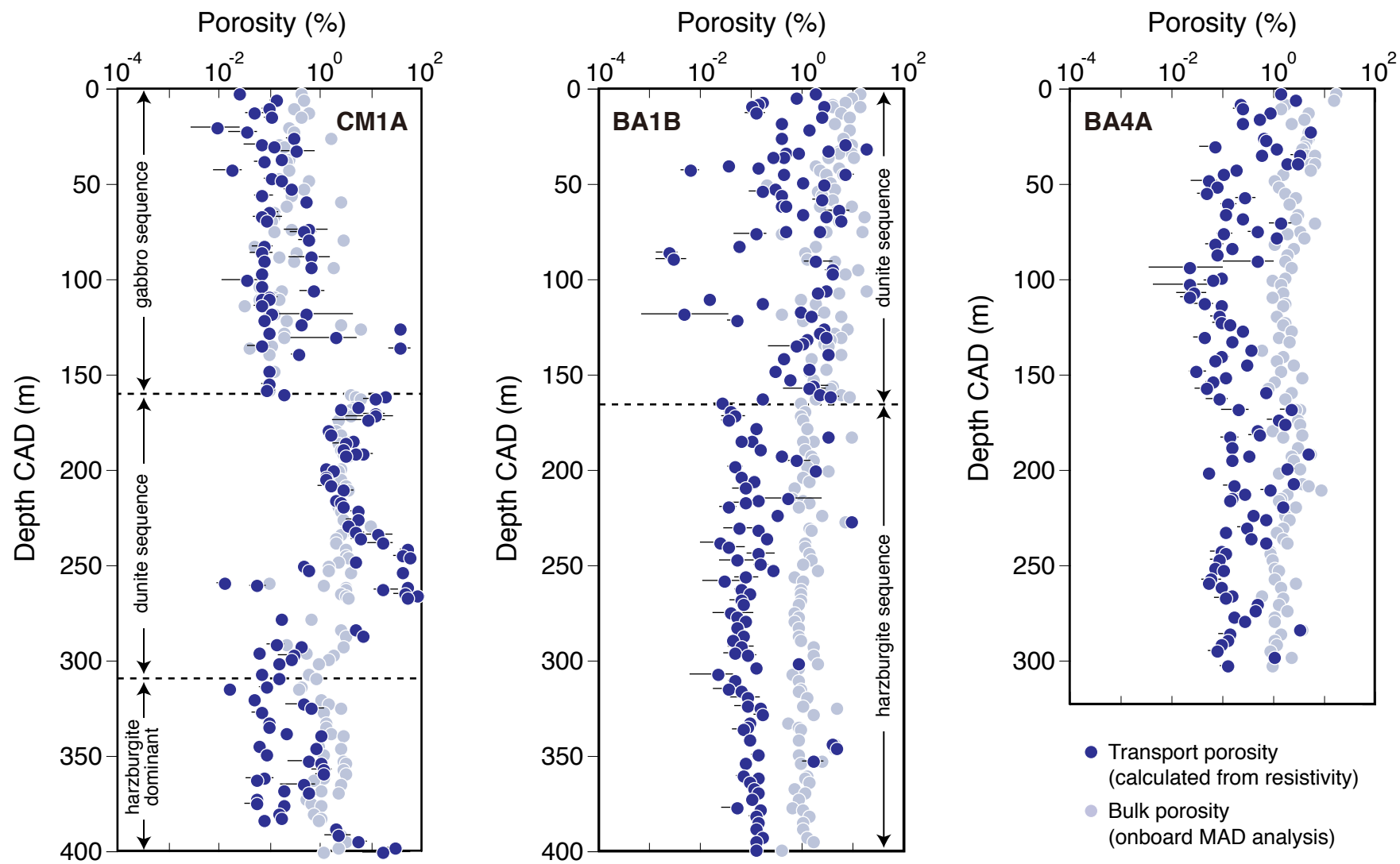


Figure 4

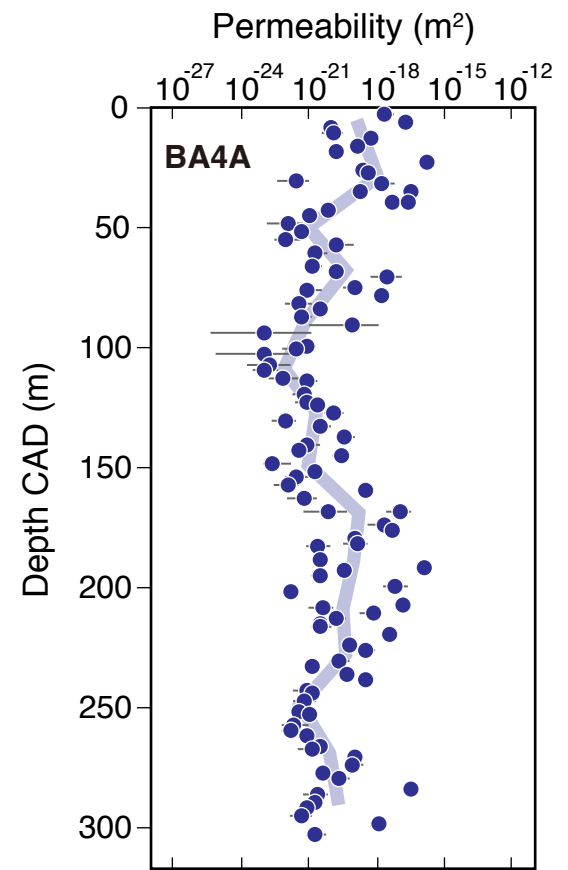
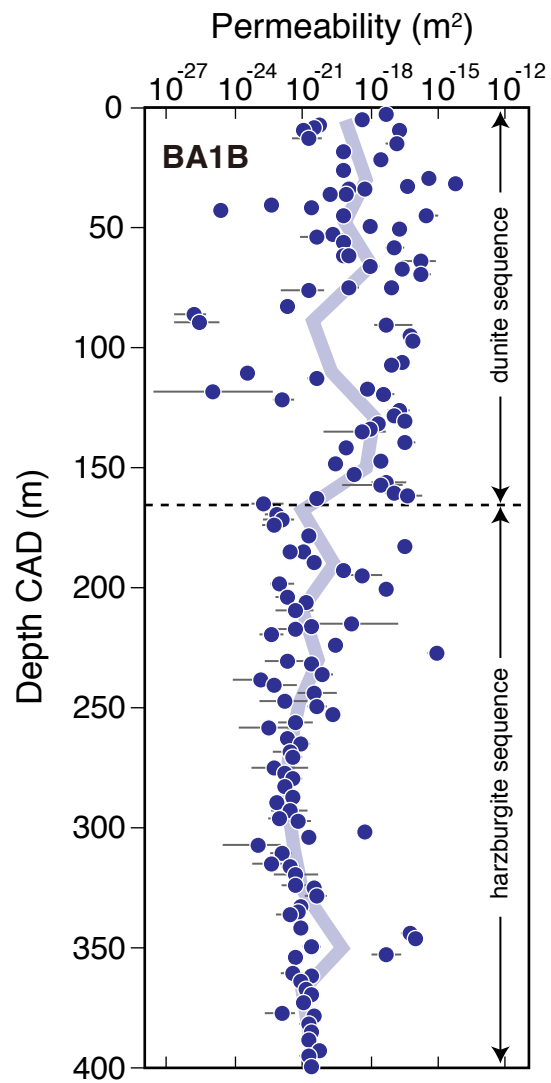
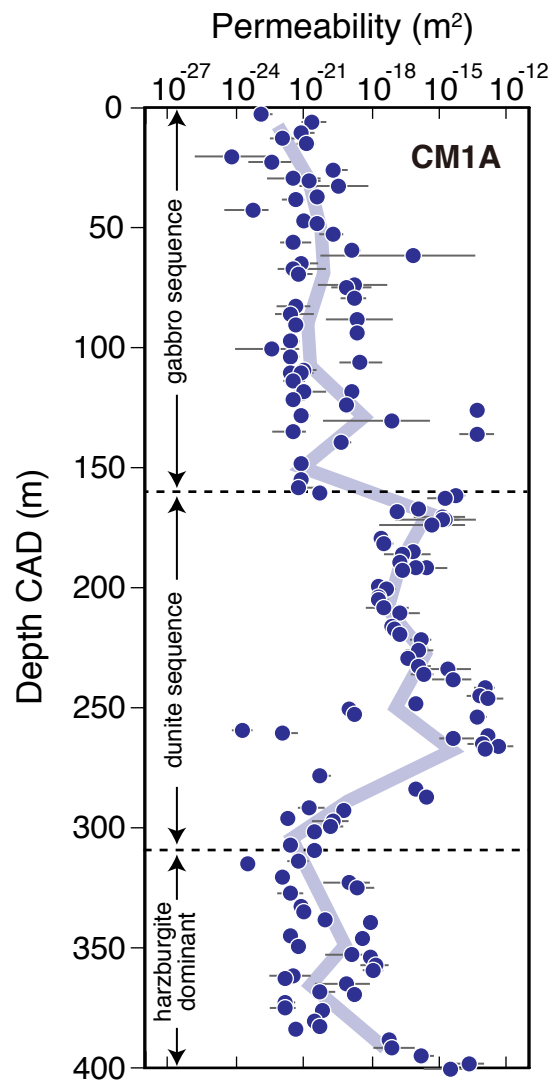


Figure 5

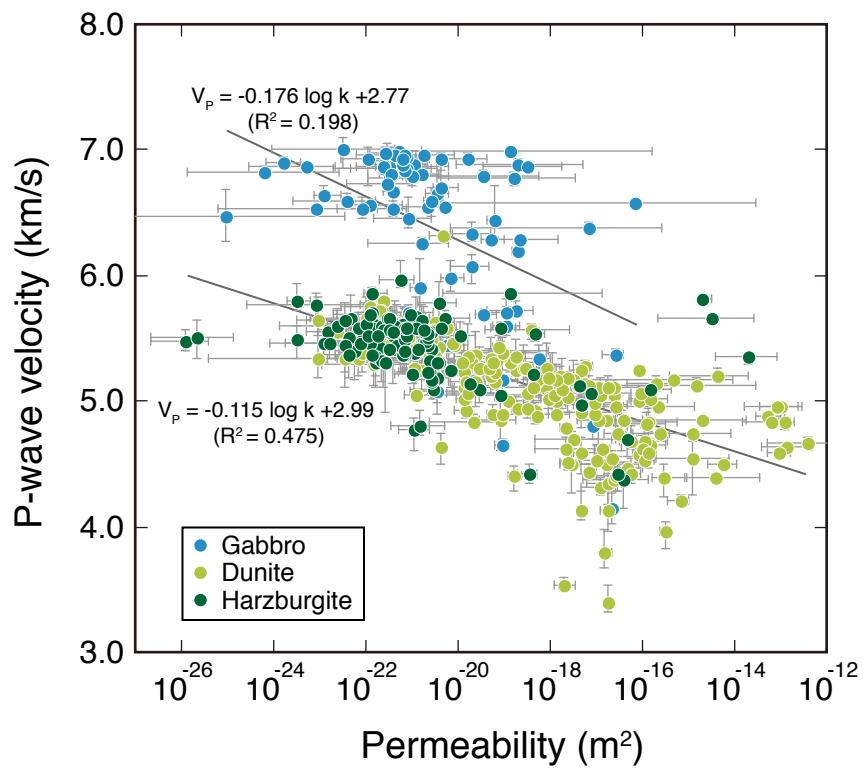


Figure 6

Table 1. Mean resistivity and calculated transport permeability in each borehole

		Resistivity (Ω m)		Transport porosity (%)	Permeability (m^2)
		dry	wet		
CM1A	gabbro sequence	4.94×10^3 (2.4)	1.23×10^3 (4.0)	0.12 (2.9)	5.39×10^{-21} (200)
	dunite sequence	1.10×10^3 (4.4)	6.60×10^1 (6.6)	3.43 (6.9)	2.00×10^{-17} (331)
	harzburgite sequence	3.45×10^3 (4.6)	5.44×10^2 (5.9)	0.38 (6.2)	2.44×10^{-20} (245)
BA1B	dunite sequence	3.27×10^3 (2.4)	3.13×10^2 (4.9)	0.63 (7.1)	2.26×10^{-19} (354)
	harzburgite sequence	6.86×10^3 (2.2)	1.56×10^3 (3.0)	0.12 (3.3)	1.57×10^{-21} (36)
BA4A	dunite sequence	2.38×10^3 (2.1)	5.20×10^2 (3.2)	0.34 (3.9)	3.77×10^{-20} (61)

*Mean values were calculated the geometric mean, and the number in parentheses represents the geometric standard deviation.