



Petrophysical contrasts across a faulted dunite–harzburgite boundary in Hole BA1B, Samail Ophiolite, Oman

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Abstract. Serpentinized peridotites commonly contain veins, fractures, and pervasive alteration, yet the controls on localized petrophysical variability remain incompletely understood. We integrate visual core descriptions, T12 porosity and wet electrical resistivity, ST1 gamma-ray attenuation density and magnetic susceptibility, and T07 whole-rock geochemistry from Hole BA1B in the Samail Ophiolite, Oman. Seven depth intervals (Zones A–G) were compared using 13 porosity and 12 wet-resistivity measurements, with emphasis on the fault-related interval at 159–163 m containing the principal dunite–harzburgite boundary at 161.87 m. Zone D records the highest mean porosity (8.95 ± 3.71 vol %), lowest mean wet electrical resistivity ($94.57 \pm 24.08 \Omega \text{ m}$), lowest mean gamma-ray attenuation density ($2.624 \pm 0.014 \text{ g cm}^{-3}$), and highest mean magnetic susceptibility [$(1617 \pm 344) \times 10^{-5} \text{ SI}$] among the selected intervals. Other zones reproduce individual components but not the complete Zone D signature. Broadly elevated loss-on-ignition and H₂O values across sampled peridotites show that bulk hydration is not unique to Zone D. Other dunite–harzburgite contacts did not show an equivalent response, although most lack nearby T12 measurements and remain inconclusive. The strongest observed contrast is therefore spatially associated with major deformation at the principal lithological boundary. This association is consistent with localized pore–fracture connectivity and alteration-related electrical conduction, but does not demonstrate enhanced in situ permeability. Zone D is consequently a priority interval for direct hydraulic, microstructural, and mineralogical investigation.

1 Introduction

Serpentinized peridotites are widespread in oceanic lithosphere and exposed ophiolitic mantle sections. Interaction between ultramafic rocks and aqueous fluids transforms primary olivine- and pyroxene-bearing assemblages into secondary minerals that commonly include serpentine, brucite, magnetite, and chlorite, with carbonate- and sulfide-bearing phases developing under appropriate chemical conditions (O’Hanley, 1996; Mével, 2003; Evans, 2004, 2010; Frost and Beard, 2007). These reactions modify rock volume, density, pore structure, elastic properties, electrical behavior, and magnetic response. They may also generate fractures or promote mineral precipitation within pre-existing voids, producing spatially heterogeneous physical properties even where the bulk degree of alteration is broadly similar (Falcon-Suarez et al., 2017; Bayrakci et al., 2018; Chibati et al., 2022; Uno et al., 2022). The hydraulic significance of this heterogeneity depends less on the presence of alteration or fractures alone than on the geometry, connectivity, and preservation of the pore–fracture network. Brittle deformation can generate connected pathways, whereas mineral precipitation, reaction-related volume changes, and subsequent deformation may partially or completely seal them (Caine et al., 1996; Faulkner et al., 2010; Menzel et al., 2022). Petrophysical measurements



can help identify such contrasts, but individual properties are not uniquely diagnostic. In fluid-saturated samples, relatively low electrical resistivity may be consistent with connected fluid-filled pores or fractures, yet the measured response can also vary with pore-fluid properties, saturation conditions, conductive mineral phases, and measurement geometry (Falcon-Suarez et al., 2017). Similarly, elevated magnetic susceptibility may indicate a greater contribution from ferrimagnetic minerals such as magnetite, but it does not independently establish pore connectivity or permeability (Evans, 2010; Fujii et al., 2016). Consequently, interpretation is more defensible when several independent physical properties converge within the same structural interval.

Previous studies have documented substantial variability in the porosity, permeability, electrical resistivity, elastic properties, and magnetic behavior of serpentinized ultramafic rocks (Falcon-Suarez et al., 2017; Bayrakci et al., 2018; Chibati et al., 2022). Electron-microscopy and numerical observations further demonstrate that porosity in serpentinites is heterogeneous at micro- to nanoscale and may include pores that do not form hydraulically connected networks at larger scales (Chogani and Plümer, 2023). These findings caution against inferring macroscopic fluid flow from a single physical property or length scale. A remaining problem is to determine how petrophysical anomalies are spatially related to specific geological structures, particularly where fault-related deformation coincides with a major lithological boundary.

Fault zones are especially relevant because their hydraulic behavior reflects the internal arrangement of fault cores, damage zones, fractures, foliated rocks, and mineralized veins. Depending on this architecture and its alteration history, a fault zone may act as a localized pathway, a barrier, or a structurally heterogeneous combination of both (Caine et al., 1996; Faulkner et al., 2010). Lithological boundaries introduce an additional source of heterogeneity because adjacent rock types may differ in mineralogy, texture, grain size, and deformation behavior. Dunite–harzburgite contacts are therefore plausible sites at which pre-existing material contrasts and later deformation may interact. However, the presence of such a contact does not by itself demonstrate localized fluid flow. Distinguishing the effect of a faulted lithological boundary from the effects of hydration, veining, deformation, or lithology considered individually requires comparison with other intervals in which only part of this geological configuration is present.

Hole BA1B of the Oman Drilling Project provides an opportunity to make this comparison within a continuously characterized section of the Samail Ophiolite, Oman. The borehole penetrates an upper sequence dominated by dunite and a lower sequence dominated by harzburgite. Their principal boundary occurs at 161.87 m within a major fault-related interval extending approximately from 159 to 163 m. The structural logs describe an approximately 3 m thick fault zone across this interval, including fractured dunite, a semi-brittle fault core, and a narrow shear zone associated with a gabbroic dike near its base (Kelemen et al., 2020). The coincidence of major deformation and the principal dunite–harzburgite boundary provides a geological basis for examining whether this interval displays a petrophysical response distinct from other veined, altered, fractured, or lithologically variable parts of the borehole.

Here, we conduct a comparative observational analysis of seven depth intervals (Zones A–G) by integrating visual core descriptions and available core images with T12 porosity and wet electrical resistivity, ST1 gamma-ray attenuation density and magnetic susceptibility, and T07 whole-rock geochemistry (Kelemen et al., 2020). The objectives are to characterize petrophysical variability among the selected intervals, determine whether the principal fault–boundary interval records a multi-parameter response not reproduced by the comparison zones, and assess the



extent to which the anomaly is spatially associated with the coincidence of fault-zone deformation and the principal lithological boundary. Because the measurements are sparse and no direct permeability data are available, the analysis does not test causality or quantify in situ fluid flow. Instead, it identifies the interpretation most consistent with the combined evidence and defines priorities for direct hydraulic and microstructural investigation.

2 Geological setting and Hole BA1B background

2.1 Site BA1 and regional context

Site BA1 is located in Wadi Lawayni near the eastern margin of the Tayin Massif in the Samail Ophiolite, Oman. It forms part of the Oman Drilling Project BA multiborehole observatory, together with nearby Sites BA3 and BA4. Drilling at Site BA1 targeted a variably serpentinized ultramafic section comprising predominantly dunite and harzburgite with subordinate mafic and pyroxenitic intrusions. The boreholes were designed to support integrated geological, petrophysical, hydrogeological, geochemical, and microbiological investigations of the mantle section (Kelemen et al., 2020). The regional position of Site BA1 and the location of Hole BA1B are shown in Fig. 1.

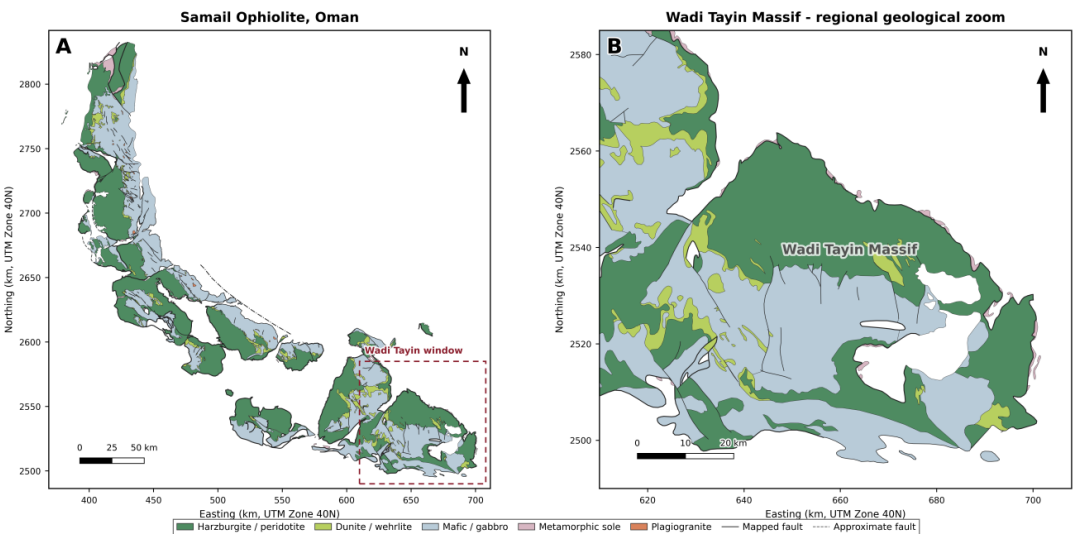


Figure 1. Geological setting of Hole BA1B. (a) Location of Site BA1 within the Samail Ophiolite, Oman. (b) Geological setting of the Tayin Massif and location of Hole BA1B. The maps were prepared using the geospatial dataset of Nothaft (2021), together with drill-site coordinates and geological information reported in the Oman Drilling Project Site BA1 documentation (Kelemen et al., 2020). The mapped lines delimit the study area and are not intended to represent internationally recognized political boundaries.

2.2 Lithological architecture of Hole BA1B

Hole BA1B penetrates a serpentinized ultramafic section dominated by dunite and harzburgite, with subordinate intervals of gabbro, olivine gabbro, clinopyroxenite, wehrlite, and leucocratic dikes. The lithostratigraphic framework comprises an upper Dunite with Gabbro Sequence and an underlying Harzburgite with Gabbro Sequence. The upper



sequence extends from approximately 0.7 m to the principal sequence boundary at 161.87 m, whereas the lower sequence continues from this boundary to the base of the borehole (Kelemen et al., 2020).

95 The upper sequence is predominantly dunitic but contains subordinate harzburgite intervals or patches and minor mafic intrusions. The lower sequence is dominated by harzburgite and includes thinner dunite bodies together with gabbroic and pyroxenitic intrusions. Accordingly, the boundary at 161.87 m represents the principal transition between two lithologically contrasting sequences rather than the only dunite–harzburgite contact in the borehole. Subordinate contacts occur elsewhere and are evaluated separately in the boundary-screening analysis.

100 **2.3 Alteration and veining**

Visual core descriptions indicate pervasive alteration throughout Hole BA1B. Logged alteration estimates are generally high, commonly ranging from approximately 85 % to 100 %, although somewhat lower values occur toward the bottom of the borehole (Kelemen et al., 2020). These percentages are visual estimates rather than direct mineralogical measurements and are used only to describe the broad alteration background.

105 Multiple generations of serpentine-, carbonate-, and other secondary-mineral-bearing veins occur in both major sequences. Their abundance, mineralogy, orientation, and cross-cutting relationships vary with depth, and veins are locally associated with dike margins and deformation zones. Neither high visual alteration nor the presence of veins is unique to the principal fault–boundary interval.

2.4 Structural framework and principal fault-related interval

110 Structural logging documents brittle and ductile-to-semi-brittle deformation features throughout Hole BA1B, including fractures, shear veins, cataclastic zones, fault zones, and intervals with crystal-plastic overprinting (Kelemen et al., 2020). The most prominent fault-related structure occurs near 160 m, close to the transition between the upper dunite-dominated and lower harzburgite-dominated sequences. It extends across multiple core sections and is interpreted in the Oman Drilling Project documentation as an approximately 3 m thick structure comprising strongly
 115 fractured dunite, a cohesive and foliated semi-brittle to crystal-plastic fault core, and a narrow shear zone associated with a gabbroic dike near its base.

For the present analysis, Zone D is defined as the 159–163 m comparison window that encompasses this fault zone and the principal dunite–harzburgite boundary at 161.87 m. The analytical window is slightly broader than the reported fault-zone thickness and should not be interpreted as a uniformly deformed fault core. The spatial relationships among

120 lithology, alteration, veining, fault-related deformation, and the principal sequence boundary are summarized in Fig. 2.

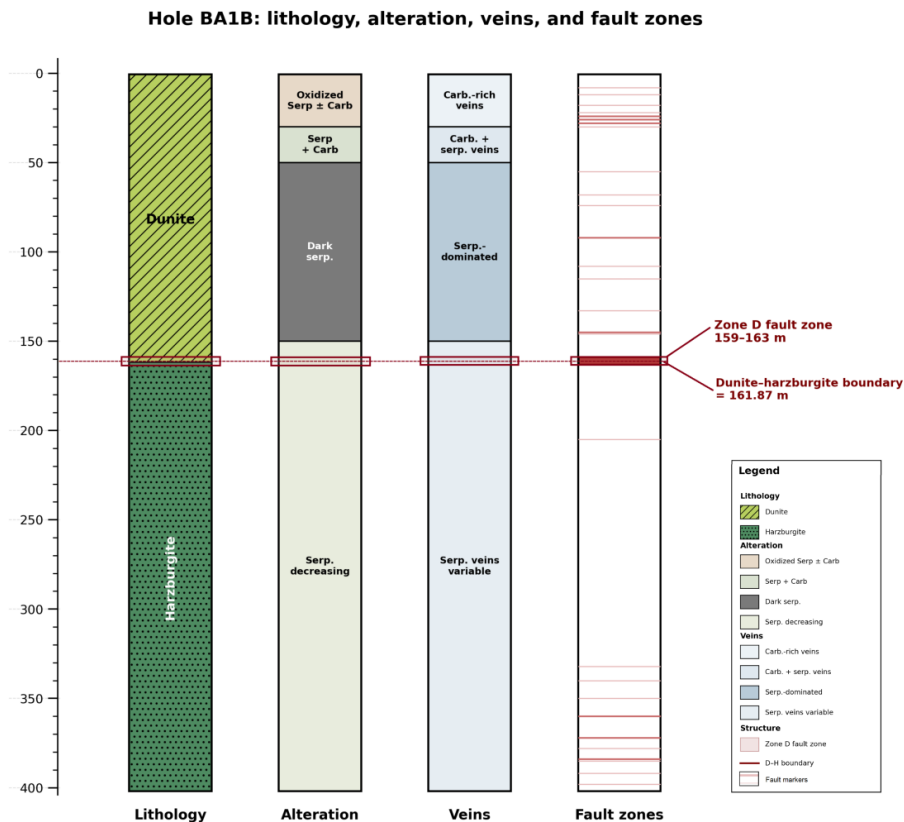


Figure 2. Simplified lithological and structural column of Hole BA1B showing the downhole distribution of the principal lithological units, broad alteration patterns, dominant vein assemblages, and logged fault-related intervals. The main boundary between the Dunite with Gabbro Sequence and the Harzburgite with Gabbro Sequence occurs at 161.87 m within the Zone D comparison window at 159–163 m. Zone D encompasses the approximately 3 m thick principal fault zone described in the Oman Drilling Project structural documentation. The column is schematic and does not reproduce all centimetre-scale variations. Compiled from Site BA1 lithological, alteration, vein, and structural logs reported in Kelemen et al. (2020).

2.5 Comparative framework

Six intervals above and below Zone D were selected to provide geological comparisons with the principal fault–boundary interval (Table 1). These zones contain different combinations of lithological variation, veining, brittle deformation, alteration, and crystal-plastic overprinting. They are comparative cases rather than experimental controls and are used to determine which components of the Zone D petrophysical pattern recur elsewhere in the borehole.



135 **Table 1. Geological context and comparative role of the selected depth intervals in Hole BA1B.**

Zone	Depth interval (m)	Lithological context	Position relative to principal boundary	Logged structural context
A	80–85	Mixed harzburgite and dunite within the upper dunite-dominated sequence	Well above	Veins and brittle structures present; no principal fault core reported in the selected interval
B	88–90	Mixed dunite–harzburgite interval within the upper sequence	Well above	Veined and fractured interval without the architecture documented for the principal fault zone
C	155–157	Predominantly dunite	Immediately above Zone D	Vein- and fracture-rich interval approaching the principal fault-related structure
D	159–163	Transition between the two principal sequences	Encompasses boundary at 161.87 m	Comparison window containing the principal fault zone, fractured dunite, a foliated fault core, and shear-related deformation
E	164–166	Predominantly harzburgite	Immediately below Zone D	Veined and locally sheared interval below the principal fault-related structure
F	217–220	Serpentinized harzburgite	Within the lower sequence	Moderately veined interval with crystal-plastic fabric; no association with the principal boundary
G	223–225	Serpentinized harzburgite	Within the lower sequence	Structurally overprinted and veined harzburgite with alteration halos

Note: Lithological and structural descriptions are summarized from the Hole BA1B visual core descriptions and structural logs (Kelemen et al., 2020). Zone boundaries are analytical intervals defined in this study and do not necessarily coincide with individual logged structural features.

3 Materials and methods

140 3.1 Data sources and analytical scope

The analysis integrates publicly available geological, structural, physical-property, core-scanner, mineralogical, and geochemical records from Hole BA1B of the Oman Drilling Project (Kelemen et al., 2020). Visual core descriptions (VCDs) and structural logs were used to establish lithology, alteration style, veins, fractures, shear fabrics, cataclastic zones, and fault-related features. T12 supplied discrete sample-scale porosity and wet electrical resistivity; ST1 supplied gamma-ray attenuation (GRA) density and magnetic susceptibility; T07 supplied whole-rock loss on ignition (LOI) and H₂O; and T06 supplied X-ray diffraction identifications from vein material. Dataset roles and measurement scales are summarized in Supplementary Table S1.

145 The datasets were treated as complementary but non-equivalent observations. T12 measurements represent discrete specimens, whereas ST1 measurements derive from core scanning and VCD observations describe intervals at core-log scale. T07 whole-rock analyses and T06 vein analyses also represent different materials and were not combined as if they measured the same rock volume. No variable was converted into permeability, and no direct hydraulic measurement is included in the analysis.



All depths are reported in metres below the borehole reference used in the source datasets. The principal sequence boundary is fixed at 161.87 m throughout the analysis. Zone labels A–G are analytical definitions introduced in this study and are not formal Oman Drilling Project stratigraphic units.

3.2 Selection of comparison intervals

Seven intervals were selected purposively from the lithological and structural records: Zone A, 80–85 m; Zone B, 88–90 m; Zone C, 155–157 m; Zone D, 159–163 m; Zone E, 164–166 m; Zone F, 217–220 m; and Zone G, 223–225 m. Zone D was selected because it encompasses the principal fault zone and the main dunite–harzburgite boundary. Zones C and E bracket Zone D, whereas Zones A, B, F, and G represent non-adjacent intervals containing different combinations of lithology, veining, alteration, and structural overprint.

Selection was hypothesis-guided rather than random or exhaustive. The zones were chosen to compare the principal fault–boundary interval with geologically informative alternatives, not to estimate borehole-wide population statistics. Consequently, all rankings and contrasts reported below apply only to the selected intervals and available measurements.

3.3 Lithological and structural classification

Dominant lithology and structural context were extracted from the Hole BA1B VCD and structural logs. For each zone, the assessment recorded the reported occurrence and character of veins, fractures, shear fabrics, cataclastic zones, fault-related structures, and crystal-plastic overprinting. Relative descriptors such as vein-rich, fractured, and structurally overprinted summarize the source logs; they are not numerical damage, connectivity, or rock-mass indices. Available core images were inspected qualitatively to check whether the visible lithology and deformation features were consistent with the log descriptions. No quantitative image segmentation, fracture-density measurement, aperture analysis, or connectivity analysis was performed. Inspected intervals and qualitative criteria are documented in Supplementary Table S6, with representative images in Supplementary Fig. S1.

The presence of a vein or fracture was not interpreted as evidence of hydraulic openness. Structural descriptions were first compiled independently of petrophysical interpretation and were then compared with the T12 and matched ST1 observations.

3.4 T12 porosity and wet electrical resistivity

T12 measurements were compiled for discrete physical-property specimens, mainly 20 x 20 x 20 mm cubes, whose depths fall within Zones A–G. Because sampling is discontinuous, these measurements characterize sampled depths rather than uninterrupted zone profiles. Porosity and wet electrical resistivity were retained in their reported units, and sample counts were tabulated separately because the two variables are not available for every specimen.

The Zone D specimen at 160.860 m records the highest porosity in the selected dataset but has no paired wet-resistivity value. It was retained in the porosity summary but excluded from any paired interpretation. The original physical-property documentation notes that unusually high porosity in altered or damaged specimens may partly reflect chip loss during moisture-and-density measurements; the 160.860 m value is therefore reported but interpreted cautiously



(Kelemen et al., 2020). Individual T12 measurements, depth-based record locators, and availability flags are provided in Supplementary Table S2A.

T12 density was not included in the zone comparison. Density comparisons use matched ST1 GRA density so that one density dataset and measurement basis are applied consistently across Zones A–G.

3.5 Descriptive statistical treatment

For each zone and variable, the number of observations, arithmetic mean, sample standard deviation, minimum, maximum, and observed range were calculated where data permitted. Standard deviations were calculated only for zones with at least two observations. Values from zones represented by one observation are reported as point observations and are not treated as zone-level estimates.

The reported standard deviations describe between-sample variability within the selected interval; they do not represent analytical uncertainty or confidence intervals. Given the small, unequal, and purposively selected samples, no inferential significance tests were performed and differences among zone means are interpreted descriptively.

3.6 ST1 GRA density and magnetic susceptibility

ST1 GRA density and magnetic susceptibility were extracted at, or nearest to, the selected T12 sample depths (Kelemen et al., 2020). The reported N values therefore count matched observations used in the comparison and not all scanner readings across an entire zone. Summary statistics describe the matched observations only. The focused matched-ST1 summary for Zones C–E is reported in Supplementary Table S2B.

Magnetic susceptibility was treated as a bulk physical-property measurement. It was not converted into mineral abundance and was not used alone to identify magnetite, sulfides, or any other magnetic carrier. GRA density and magnetic susceptibility summaries are reported in Table 3.

3.7 T07 whole-rock geochemistry

T07 whole-rock LOI and H₂O data were compiled for selected peridotitic samples within or immediately adjacent to the selected zones (Kelemen et al., 2020). Samples outside a zone are explicitly identified as adjacent, and non-peridotitic samples are not used to represent serpentinized host-rock behavior. The selected records should not be interpreted as statistically representative samples of entire zones.

LOI and H₂O are used as broad bulk volatile and hydration-related indicators rather than direct measures of serpentinization extent. LOI is not mineral-specific and may include volatile contributions other than structurally bound water. Neither variable is treated as a measurement of porosity, permeability, resistivity, or fracture connectivity. Sample depths, lithologies, values, and zone relationships are reported in Supplementary Table S3.

3.8 T06 vein mineralogy

T06 X-ray diffraction identifications from secondary vein material were consulted as mineralogical context (Kelemen et al., 2020). Because these analyses characterize veins rather than bulk host rock, they were not substituted for T07



whole-rock geochemistry and were not used to calculate hydration, serpentinization extent, or petrophysical properties.

3.9 Screening of dunite–harzburgite contacts

An exploratory coverage screen was applied to unambiguous dunite–harzburgite contacts identified in the compiled lithological and VCD records (Kelemen et al., 2020). The screen was designed to determine whether the listed contacts had selected T12 observations close enough to permit a local descriptive comparison with the principal boundary at 161.87 m. It was not treated as an exhaustive inventory of every centimetre-scale, gradational, interlayered, or uncertain contact in Hole BA1B.

For each listed contact, the absolute distance to the nearest T12 observation in the selected analytical subset was reported. No post hoc distance threshold was used to convert a non-local observation into a boundary measurement. Only the principal boundary had selected observations within 2.2 m; the ~99.81 m contact had only a non-local observation ~9.92 m away, and the remaining listed contacts had no selected local T12 constraint. These comparison contacts were therefore classified as inconclusive rather than as evidence for or against a boundary-related anomaly. The principal boundary at 161.87 m was retained as the fault-related target because it lies within Zone D and has selected observations at absolute distances of 0.384–2.185 m. The contact coverage, distances, data availability, and interpretive limits are reported in Supplementary Table S4. This screen cannot isolate lithological contrast from fault-related deformation or establish causation.

3.10 Evidence synthesis

Interpretation used a qualitative evidence matrix rather than a formal causal or statistical hypothesis test. Hydration context was assessed from T07; veins and structural features from VCDs and core images; porosity and wet resistivity from T12; density and magnetic susceptibility from matched ST1 observations; and lithological-boundary context from the contact screening.

A simple one-factor account was regarded as not consistently reproducing the selected observations when the relevant feature occurred elsewhere without the complete Zone D pattern. This qualitative comparison assesses consistency within purposively selected cases; it does not eliminate alternative mechanisms or isolate causal effects because the factors covary, measurement scales differ, and sample coverage is sparse. The evidence matrix is provided in Supplementary Table S5.

4 Results

4.1 Structural context of the selected intervals

The selected zones span the upper dunite-dominated and lower harzburgite-dominated sequences (Table 1; Fig. 2). Zone D is the only selected interval that encompasses both the principal boundary at 161.87 m and the approximately 3 m thick principal fault zone. Zones C and E occur immediately above and below this window, whereas Zones A, B, F, and G provide non-adjacent comparisons with veining, fractures, lithological variability, or structural overprint.



Deformation and veining occur in several comparison zones and are therefore not unique to Zone D. The distinctive geological attribute of Zone D within the selected set is the spatial coincidence of the principal sequence boundary and the major fault-related structure.

255 4.2 Zone-scale petrophysical variation

T12 porosity and wet electrical resistivity vary markedly among the selected intervals (Table 2). Because N ranges from one to three, the values are presented as descriptive summaries. Zone C and Zone G include variables represented by a single observation.

Table 2. T12 porosity and wet electrical resistivity for the selected intervals in Hole BA1B.

Zone	N Por.	Porosity Mean $\pm$ SD (%)	Porosity Range (%)	N Res.	Wet Res. Mean $\pm$ SD (Ω m)	Resistivity Range (Ω m)
A	2	1.52 $\pm$ 0.37	1.26–1.78	2	7659.84 $\pm$ 6317.65	3192.59–12127.09
B	2	2.70 $\pm$ 2.09	1.22–4.17	2	4732.46 $\pm$ 6468.85	158.30–9306.63
C	1	3.81	3.81	1	148.54	148.54
D	3	8.95 $\pm$ 3.71	5.43–12.83	2	94.57 $\pm$ 24.08	77.55–111.60
E	2	1.36 $\pm$ 0.59	0.94–1.78	2	4886.46 $\pm$ 1433.20	3873.03–5899.88
F	2	1.12 $\pm$ 0.20	0.98–1.26	2	2092.07 $\pm$ 730.12	1575.80–2608.34
G	1	0.83	0.83	1	4368.90	4368.90

260 **Note:** SD is not reported for a single observation. Zone D wet resistivity is based on two specimens because the sample at 160.860 m has no paired wet-resistivity measurement. SD describes between-sample variability, not analytical uncertainty.

Mean porosity ranges from 0.83 % in Zone G to 8.95 % in Zone D. The three Zone D measurements range from 5.43 % to 12.83 %, showing substantial sample-scale variability within the interval. Mean wet electrical resistivity ranges from 94.57 Ω m in Zone D to 7659.84 Ω m in Zone A. The two Zone D resistivity measurements are 77.55 and 111.60 Ω m.

265 Zone B is internally heterogeneous: one specimen has a wet resistivity of 158.30 Ω m and the other 9306.63 Ω m. Zone C has a single paired observation with 3.81 % porosity and 148.54 Ω m wet resistivity. Zones E, F, and G have lower porosity and higher wet resistivity than the available Zone D observations.



Table 3. Matched ST1 GRA density and magnetic susceptibility for the selected intervals in Hole BA1B.

Zone	N	GRA Density Mean $\pm$ SD (g cm ⁻³)	GRA Density Range (g cm ⁻³)	MS Mean $\pm$ SD ($\times 10^{-5}$ SI)	MS Range ($\times 10^{-5}$ SI)
A	2	2.677 $\pm$ 0.058	2.636–2.718	359 $\pm$ 193	222–495
B	2	2.665 $\pm$ 0.046	2.632–2.697	380 $\pm$ 68	332–428
C	1	2.639	2.639	1124	1124
D	3	2.624 $\pm$ 0.014	2.613–2.640	1617 $\pm$ 344	1221–1839
E	2	2.671 $\pm$ 0.037	2.645–2.697	444 $\pm$ 341	203–685
F	2	2.778 $\pm$ 0.002	2.776–2.779	980 $\pm$ 348	733–1226
G	1	2.744	2.744	1047	1047

Note: N counts ST1 observations selected at, or nearest to, T12 sample depths and not all scanner readings within each interval. SD is not reported for a single observation and represents variability among matched observations rather than instrumental uncertainty.

Mean matched GRA density ranges from 2.624 g cm⁻³ in Zone D to 2.778 g cm⁻³ in Zone F. Zone D values span 2.613–2.640 g cm⁻³. Mean magnetic susceptibility ranges from 359 $\times 10^{-5}$ SI in Zone A to 1617 $\times 10^{-5}$ SI in Zone D.

Elevated magnetic susceptibility is not unique to Zone D: Zones C, F, and G have values or means of 1124, 980, and 1047 $\times 10^{-5}$ SI, respectively. Within the selected dataset, Zone D nevertheless combines the highest mean porosity and magnetic susceptibility with the lowest mean wet resistivity and GRA density (Fig. 3).

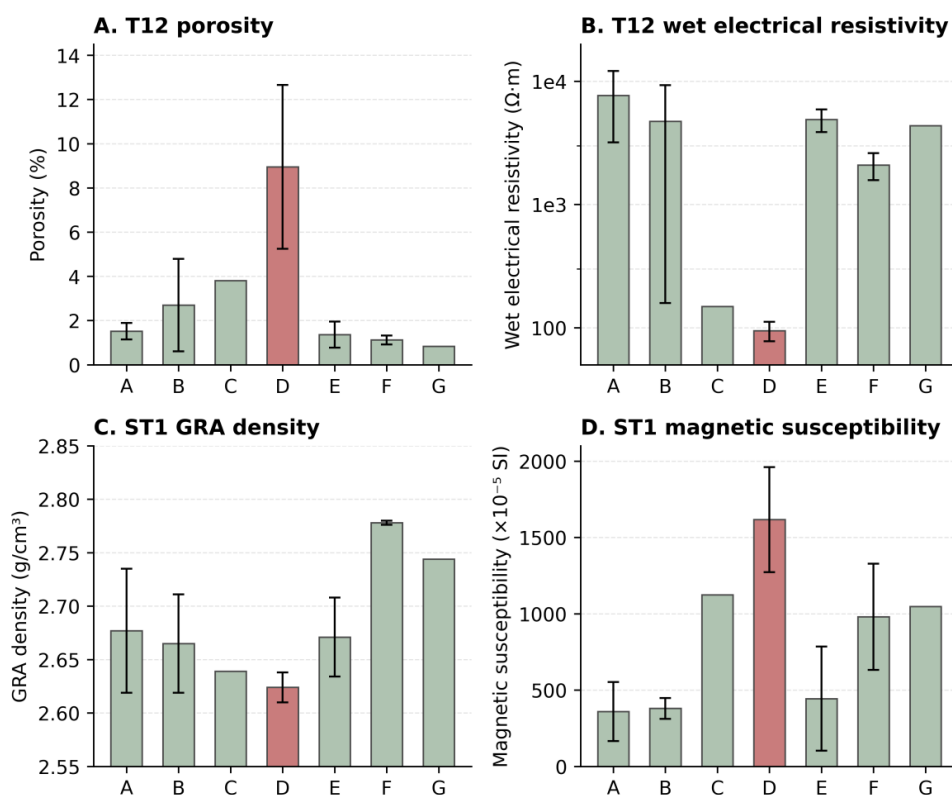


Figure 3. Descriptive comparison of the selected intervals using T12 and matched ST1 observations. Bars show zone means for (a) porosity, (b) wet electrical resistivity, (c) GRA density, and (d) magnetic susceptibility. Error bars show ± 1 SD for porosity, GRA density, and magnetic susceptibility where $N \geq 2$; wet-resistivity error bars show the observed minimum-maximum range. Single observations are plotted without error bars. The wet-resistivity axis is logarithmic. Comparisons apply only to the selected observations.

The four variables therefore converge most clearly in Zone D, although the small and unequal sample counts preclude inferential comparison of zone populations.

4.3 Depth distribution of T12 observations

Individual T12 measurements show that the largest porosity values in the selected dataset occur within Zone D (Fig. 4). Values of 5.43 %, 12.83 %, and 8.60 % occur between 159 and 163 m, whereas the two measurements in the immediately underlying Zone E are 1.78 % and 0.94 %.

The available Zone D wet-resistivity values are also the two lowest in the selected dataset. However, the 12.83 % porosity measurement at 160.860 m is unpaired, so the porosity maximum cannot be matched directly to a resistivity value at the same specimen depth.

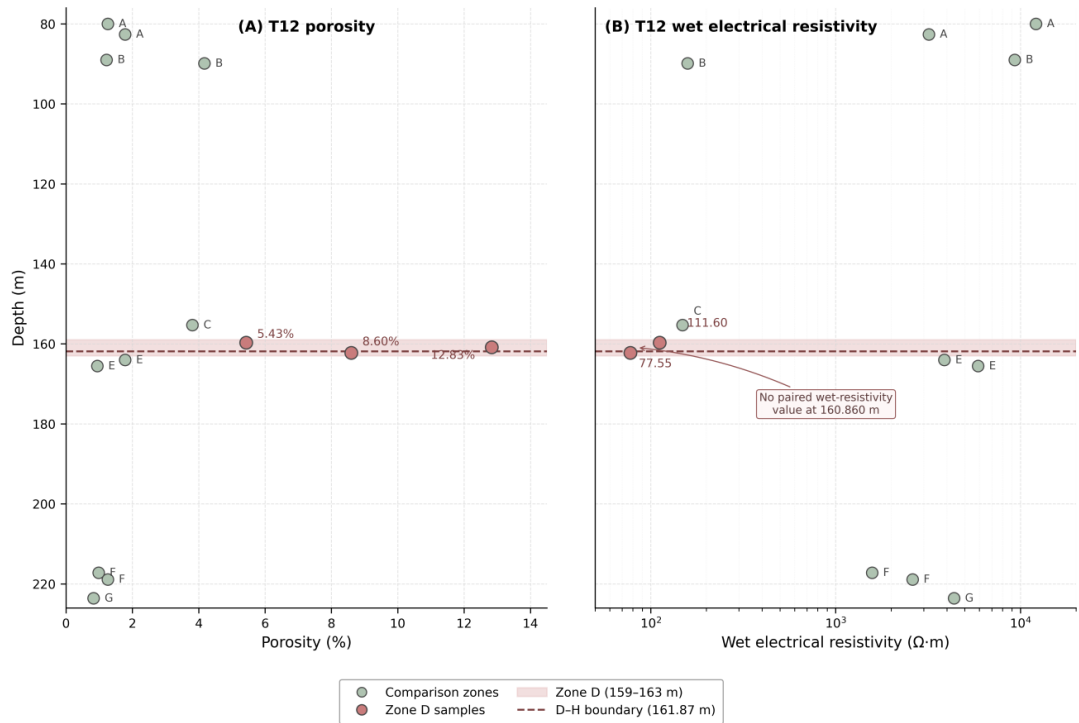


Figure 4. Individual T12 porosity and wet electrical resistivity observations for Zones A–G. The shaded interval marks Zone D at 159–163 m, and the dashed line marks the principal dunite–harzburgite boundary at 161.87 m. Wet electrical resistivity is shown on a logarithmic axis. The porosity observation at 160.860 m has no paired wet-resistivity measurement.

Low wet resistivity also occurs outside Zone D. Zone C records 148.54 Ω m, and one Zone B specimen records 158.30 Ω m. These values demonstrate that low resistivity is not unique to the principal fault–boundary interval.

What distinguishes Zone D descriptively is not an isolated resistivity minimum, but the interval-scale combination of relatively high porosity and consistently low resistivity among its available observations.

4.4 Focused comparison of Zones C, D, and E

Zones C, D, and E bracket the principal sequence boundary and provide the closest available comparison across the fault-related interval (Table 4; Supplementary Table S2B; Fig. 5). Zone C lies above Zone D in predominantly dunite, and Zone E lies below it in predominantly harzburgite.



Table 4. Descriptive comparison of Zones C, D, and E across the principal fault–boundary interval.

Parameter	Dataset	Zone C	Zone D	Zone E
Depth interval (m)	VCD / zone definition	155–157	159–163	164–166
Structural position	VCD / structural framework	Immediately above the fault-related boundary interval	Major fault-related D–H boundary interval	Immediately below the principal boundary
Porosity, N	T12	1	3	2
Mean porosity (%)	T12	3.81	8.95 ± 3.71	1.36 ± 0.59
Porosity range (%)	T12	3.81	5.43–12.83	0.94–1.78
Wet resistivity, N	T12	1	2	2
Mean wet resistivity (Ω m)	T12	148.54	94.57 ± 24.08	4886.46 ± 1433.20
Wet resistivity range (Ω m)	T12	148.54	77.55–111.60	3873.03–5899.88
GRA density, N	ST1	1	3	2
Mean GRA density (g cm ⁻³)	ST1	2.639	2.624 ± 0.014	2.671 ± 0.037
GRA density range (g cm ⁻³)	ST1	2.639	2.613–2.640	2.645–2.697
Magnetic susceptibility, N	ST1	1	3	2
Mean MS (×10 ⁻⁵ SI)	ST1	1124	1617 ± 344	444 ± 341
MS range (×10 ⁻⁵ SI)	ST1	1124	1221–1839	203–685

Note: Zone C is represented by one T12 and one matched ST1 observation. SD values describe between-sample variability and are not analytical uncertainties.

From Zone D to Zone E, mean porosity decreases from 8.95 % to 1.36 %, while mean wet electrical resistivity increases from 94.57 to 4886.46 Ω m. Mean matched GRA density increases from 2.624 to 2.671 g cm⁻³, and mean magnetic susceptibility decreases from 1617 to 444 × 10⁻⁵ SI.

Zone C shares the low-resistivity component of the Zone D pattern but is represented by only one observation and has lower porosity (3.81 %) and magnetic susceptibility (1124 × 10⁻⁵ SI). Thus, the available measurements show the largest multi-parameter contrast between Zones D and E, but do not establish the precise width or continuity of the transition.

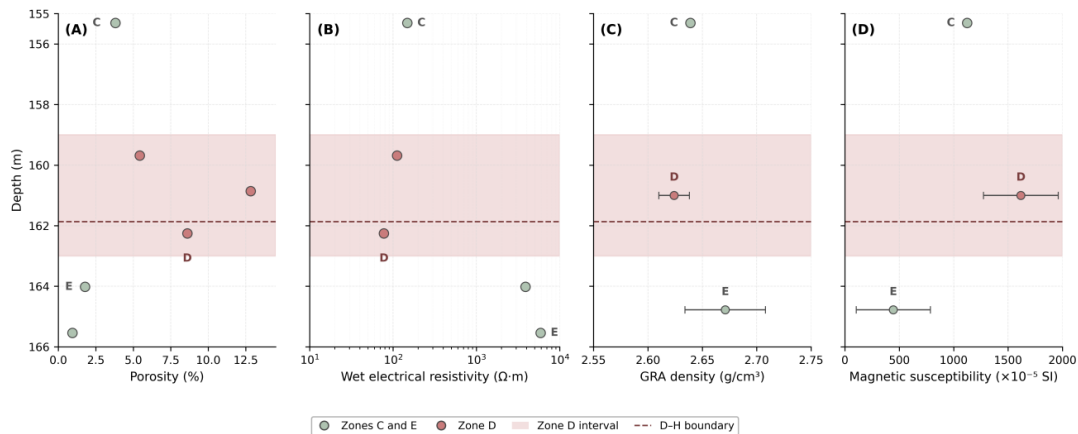


Figure 5. Focused comparison of Zones C, D, and E. Panels show (a) T12 porosity, (b) T12 wet electrical resistivity, (c) matched ST1 GRA density, and (d) matched ST1 magnetic susceptibility. Individual T12 observations are shown for porosity and resistivity; ST1 panels show zone means with ± 1 SD where $N \geq 2$. The shaded band marks Zone D, and the dashed line marks the boundary at 161.87 m. Zone C is represented by a single observation.

The focused comparison confirms that the selected observations immediately below Zone D do not continue the Zone D petrophysical pattern.

4.5 GRA density and magnetic susceptibility

Matched GRA density is lowest in Zone D and higher in the deeper harzburgite-dominated Zones F and G (Table 3; Fig. 3c). The limited spread of the three matched Zone D values contrasts with the wider range of its three porosity measurements, although the two datasets derive from different measurement methods and effective sample volumes. Zone D has the highest mean magnetic susceptibility, but high values also occur in Zones C, F, and G (Fig. 3d). Magnetic susceptibility therefore does not uniquely identify Zone D.

The ST1 data resolve variation in bulk magnetic response but not the mineral phase responsible for it. No phase abundance is calculated from magnetic susceptibility.

4.6 Whole-rock geochemical observations

Selected T07 peridotite samples within or adjacent to the comparison intervals generally have elevated LOI and H₂O values (Supplementary Table S3). Across the listed peridotitic samples, LOI ranges from 12.3 to 14.8 wt% and H₂O from 12.58 to 15.62 wt%.

The highest listed H₂O value occurs at 160.085 m in Zone D, but similarly high values occur in Zones A and B and in harzburgite immediately below Zone D. Samples at 163.440 and 163.940 m have LOI values of 13.5 and 14.1 wt% and H₂O values of 13.34 and 14.71 wt%, respectively.

The Zone F harzburgite sample at 217.305 m has 12.3 wt% LOI and 12.58 wt% H₂O. A clinopyroxenite at 219.340 m has lower values but is not used to characterize peridotitic host rock. The selected observations therefore show that elevated bulk volatile and hydration-related values occur in several intervals and are not confined to Zone D.



340 4.7 Integrated observational summary

Table 5 summarizes relative petrophysical rankings and structural context within the selected dataset. The categories are descriptive labels derived from Tables 2 and 3 and do not constitute independent measurements or threshold-based classifications.

Table 5. Integrated observational summary for the selected intervals in Hole BA1B.

Zone	Depth (m)	Lithology	Porosity	Wet Resistivity	GRA density	MS	Observational summary
A	80–85	Harzburgite–Dunite	Low	High	Moderate	Low–moderate	Veined and fractured interval without the principal fault core
B	88–90	Harzburgite/Dunite	Moderate	Variable	Moderate	Low–moderate	Veined and fractured interval with one low-resistivity observation and strong internal variability
C	155–157	Dunite-dominated	Moderate	Very low	Low–moderate	High	Near-boundary interval with one low-resistivity observation
D	159–163	Dunite–Harzburgite	Highest	Lowest	Lowest	High	Principal fault–boundary window with the strongest combined contrast
E	164–166	Harzburgite	Low	High	Moderate	Low–moderate	Low-porosity, high-resistivity interval immediately below Zone D
F	217–220	Serpentinized harzburgite	Low	Moderate	Highest	High	Dense harzburgite with crystal-plastic fabric and elevated susceptibility
G	223–225	Serpentinized harzburgite	Lowest	High	High	Moderate–high	Low-porosity, high-resistivity harzburgite with structural overprint

345 **Note:** Qualitative classes are relative to Zones A–G only. They do not define absolute petrophysical classes, hydraulic states, or permeability categories.

Zone D is the only selected interval combining the highest mean porosity and magnetic susceptibility with the lowest mean wet resistivity and GRA density. Zone C shares low resistivity and elevated susceptibility, whereas Zone B contains one low-resistivity specimen but is highly variable.

350 Zones F and G have elevated magnetic susceptibility without high porosity or low resistivity. Zone E provides the clearest adjacent contrast, with low porosity and high resistivity immediately below Zone D.

These observations establish the localization of a multi-parameter contrast within the selected dataset. Their geological and hydraulic implications are evaluated in Sect. 5.

5 Discussion

355 5.1 Nature and localization of the Zone D contrast

The principal result is a spatial association: among the seven selected intervals, Zone D contains the most coherent combination of high porosity, low wet electrical resistivity, low matched GRA density, and elevated magnetic



susceptibility, and it encompasses both the principal fault zone and the main dunite–harzburgite boundary. This is appropriately described as a multi-parameter petrophysical contrast rather than as direct evidence of permeability.

360 The adjacent D–E comparison makes the localization particularly clear. Over a few metres, the selected measurements change from relatively porous and electrically conductive in Zone D to low-porosity and resistive in Zone E (Table 4; Supplementary Table S2B; Fig. 5). This contrast argues against a simple gradual downhole trend, but sparse sampling prevents the position, thickness, and lateral continuity of the transition from being resolved.

The Zone D porosity data are internally heterogeneous, and the largest value at 160.860 m may be sensitive to chip
 365 loss reported as a potential issue for damaged specimens in the source documentation (Kelemen et al., 2020). Its missing paired resistivity measurement also prevents a specimen-scale test of whether the porosity maximum coincides with the resistivity minimum. The defensible inference is therefore interval-scale convergence, not a quantified porosity-resistivity relationship.

5.2 Evaluation of alternative explanations

370 The comparison zones do not isolate independent causal variables, but they help assess whether individual features recur without the complete Zone D pattern. Hydration-related T07 values are broadly elevated in several peridotitic intervals, including samples within or adjacent to Zones A, B, D, and E. Bulk hydration is therefore a regional background condition and does not, by itself, account for localization of the selected Zone D observations.

Veins and brittle structures are also widespread. Zone B contains veins, fractures, and one low-resistivity specimen,
 375 yet its second specimen is highly resistive and its mean porosity is lower than in Zone D. Zone G is structurally overprinted but has the lowest porosity and high resistivity. These comparisons show that the occurrence of logged deformation or veins is not a sufficient descriptive indicator of low resistivity or high porosity. They do not establish whether individual structures are open, sealed, or hydraulically connected.

The listed additional dunite–harzburgite contacts provide only limited leverage on lithological contrast. None has a
 380 selected T12 observation sufficiently local for a comparable boundary-scale evaluation; the ~99.81 m contact is represented only by an observation ~9.92 m away. The current selected dataset therefore leaves the effect of an unfaulted lithological contact untested rather than demonstrating its absence (Supplementary Table S4).

Magnetic susceptibility is likewise non-unique. Zones C, F, and G show elevated values without the full Zone D
 385 pattern. Susceptibility helps identify bulk physical and mineralogical variability, but it cannot serve as an independent explanation for the porosity and resistivity observations.

Taken together, these comparisons support a contextual spatial association between the Zone D pattern and the combined structural and lithological setting. They do not show that fault–boundary interaction caused the anomaly, because zone selection was purposive, measurements are sparse, observation scales differ, and the proposed factors covary.

390 5.3 Structural interpretation of the principal boundary interval

The Oman Drilling Project logs describe the principal fault zone as a heterogeneous structure containing fractured dunite, a foliated semi-brittle to crystal-plastic core, and a narrow shear zone associated with a gabbroic dike (Kelemen



et al., 2020). Such internal heterogeneity is compatible with spatially variable pore creation, preservation, and mineral filling rather than a uniformly open damage zone. More generally, fault zones can juxtapose conductive and sealing components over short distances because hydraulic behavior depends on fault-core and damage-zone architecture (Caine et al., 1996; Faulkner et al., 2010).

Dunite and harzburgite differ in modal mineralogy and texture, so their boundary constitutes a material heterogeneity on which later deformation may have localized. Peridotite deformation is sensitive to water content and grain size (Hirth and Kohlstedt, 1996; Warren and Hirth, 2006), but these variables were not measured across the BA1B contact. The proposed mechanical contrast is therefore plausible rather than demonstrated.

Reaction and deformation can also modify one another in serpentinized ultramafic rocks. Reaction-induced fracturing may create new void space, whereas precipitation and carbonation can reduce or redistribute it (Menzel et al., 2022; Uno et al., 2022). The available BA1B data do not resolve the sequence of deformation, alteration, opening, and sealing, so no unique process history can be assigned to Zone D.

The D–E contrast is consistent with structural partitioning across the boundary interval (Table 4; Supplementary Table S2B; Fig. 5), but alternative explanations remain possible, including sample-scale heterogeneity, variations in vein filling, differences in pore-fluid state during measurement, and unmeasured mineralogical contrasts. Zone-specific orientation statistics are also unavailable; whole-borehole orientation patterns cannot establish an orientation control for Zones D and E.

5.4 Interpretation of electrical and magnetic properties

The low wet resistivity of the available Zone D specimens is consistent with efficient electrical conduction, but electrical and hydraulic connectivity are not equivalent. In serpentinized peridotites, resistivity can vary with connected fluid-filled porosity, pore-fluid conductivity, saturation, tortuosity, crack geometry, pressure, and conductive mineral phases (Falcon-Suarez et al., 2017). Because the source measurements do not provide a common inversion for these contributions, resistivity cannot be converted into permeability in this study.

The interval-scale coexistence of relatively high porosity and low resistivity is compatible with a connected pore or fracture contribution, but it does not establish its geometry or hydraulic transmissivity. Chogani and Plümer (2023) show that serpentinite porosity is heterogeneous even at micro- to nanoscale, reinforcing the need to distinguish total pore volume from connected pathways across larger scales.

Zone D magnetic susceptibility is consistent with a greater contribution from ferrimagnetic phases, and magnetite production during serpentinization is plausible (Evans, 2010; Fujii et al., 2016). However, the exact carrier is unresolved. Logged magnetite-bearing veins and rare opaque or sulfide phases elsewhere in BA1B demonstrate possible candidates, but susceptibility alone cannot determine their abundance or location in the analyzed Zone D specimens (Kelemen et al., 2020).

Magnetic susceptibility should therefore be retained as a supporting component of the multi-parameter contrast, not as evidence of a specific reaction or fluid pathway. Mineral mapping, reflected-light petrography, scanning electron microscopy, or magnetic hysteresis measurements on the same specimens would be required to identify the carrier.



5.5 Conceptual synthesis

Figure 6 summarizes the observations without assigning a unique hydraulic state. Zones B and C reproduce low-resistivity components of the Zone D pattern, whereas Zones E and G demonstrate that veining or structural overprint may coexist with low porosity and high resistivity. Zone D is distinguished by convergence of the four measured properties within the principal fault–boundary setting.

A parsimonious working model is that deformation localized within a pre-existing lithological heterogeneity and produced or preserved a pore-mineral configuration with relatively high porosity and efficient electrical conduction. This model is consistent with the observations but is not uniquely verified; conductive alteration phases, measurement-scale effects, and incomplete sampling could contribute to the same pattern.

Structural–lithological coupling localizes the strongest integrated petrophysical anomaly

A ZONE B 88–90 m Localized partial response Vein/fracture-rich Variable wet resistivity Local conductive response No full multi-parameter anomaly	B ZONE C 155–157 m Near-boundary partial response Immediately above the fault–boundary interval Low wet resistivity Moderate porosity Incomplete anomaly	C ZONE D 159–163 m Major fault–boundary interval Principal D–H boundary at 161.87 m Strongest integrated petrophysical anomaly Highest porosity Lowest wet resistivity Low GRA density High MS (supporting signal)	D ZONES E AND G 164–166 m / 223–225 m Compact / overprinted comparison intervals <table><tr><td>ZONE E Low porosity High wet resistivity Lower MS than Zone D</td><td>ZONE G Low porosity High wet resistivity Relatively elevated MS</td></tr></table> No full Zone D-type anomaly	ZONE E Low porosity High wet resistivity Lower MS than Zone D	ZONE G Low porosity High wet resistivity Relatively elevated MS
ZONE E Low porosity High wet resistivity Lower MS than Zone D	ZONE G Low porosity High wet resistivity Relatively elevated MS				

Figure 6. Conceptual synthesis of partial and combined petrophysical responses in representative BA1B intervals. Zones B and C reproduce individual low-resistivity components, whereas Zones E and G remain comparatively low in porosity and high in resistivity despite veining or structural overprint. Zone D contains the strongest combined contrast and encompasses the principal fault zone and dunite–harzburgite boundary. The diagram summarizes observations and alternative interpretations; it is not a permeability model and is not to scale.

The model should be tested by direct permeability measurements under controlled pressure and fluid conditions, three-dimensional pore-network imaging, quantitative vein and fracture analysis, and co-located mineralogical measurements. These observations would distinguish hydraulic connectivity from electrical conduction and determine whether the Zone D response persists beyond the sampled core volumes.

5.6 Scope, limitations, and implications

The principal limitations are the small and unequal T12 sample counts, purposeful interval selection, incomplete pairing of porosity and resistivity, scale mismatch among VCD, T12, ST1, and T07 observations, and the absence of direct permeability or quantitative connectivity data. Zone means based on one to three measurements cannot characterize complete interval populations or support formal causal attribution.



The results are therefore specific to the selected BA1B observations. They should not be generalized to all dunite–harzburgite contacts, the full Samail Ophiolite, or serpentinized mantle sections elsewhere without independent testing. Likewise, low resistivity should not be used alone as a proxy for permeability or reactive fluid flow.

455 Within these limits, the integrated approach provides a useful screening strategy. Coincident structural, lithological, porosity, resistivity, density, and magnetic contrasts can identify intervals that warrant targeted hydraulic and microstructural investigation. The BA1B data identify Zone D as such a target, while the comparison zones show why a single property or descriptive feature would be insufficient.

460 The broader implication is methodological rather than universal: multi-parameter anomalies at faulted lithological boundaries may help prioritize sampling, but their hydraulic significance must be verified directly.

6 Conclusions

Among seven purposively selected intervals in Hole BA1B, Zone D (159–163 m) records the highest mean T12 porosity (8.95 %), lowest mean wet electrical resistivity (94.57 Ω m), lowest mean matched ST1 GRA density (2.624 g cm⁻³), and highest mean matched magnetic susceptibility (1617 $\times 10^{-5}$ SI). Zone D also encompasses the principal fault zone and the main dunite–harzburgite boundary at 161.87 m.

465 The anomaly is heterogeneous and constrained by sparse observations. The highest porosity measurement lacks paired resistivity and may be affected by chip loss, Zone C shares a low-resistivity component, and several additional lithological contacts lack nearby T12 data. Hydration-related geochemical values, veins, deformation, and elevated magnetic susceptibility also occur outside Zone D and do not individually reproduce its complete pattern within the selected dataset.

470 The combined evidence supports a spatial association between the Zone D petrophysical contrast and the principal fault–boundary setting. It does not establish that the boundary caused the anomaly, demonstrate a connected pore–fracture geometry, or quantify in situ permeability. Zone D should therefore be regarded as a priority target for direct permeability testing, co-located mineralogical analysis, and three-dimensional pore-network characterization.

475 More generally, this study shows that integrating structural context with multiple physical properties can identify candidate fluid-sensitive intervals while avoiding interpretation from porosity, resistivity, or magnetic susceptibility alone.

Code and data availability

480 The data supporting the findings of this study are publicly available through the Oman Drilling Project repositories hosted by the International Ocean Discovery Program. The T06, T07, T12, and ST1 datasets are available in the Site BA1 data tables, whereas the Hole BA1B visual core descriptions and core images are available in the Oman Drilling Project supplementary material archive (Kelemen et al., 2020; <https://doi.org/10.14379/OmanDP.proc.2020>).



Supplement link

Author contributions

485 SF conceived the study, compiled and analyzed the data, prepared the figures, and wrote and revised the manuscript.

Competing interests

The author declares that there is no conflict of interest.

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