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# Permeability of subducted oceanic crust revealed by eclogite-facies vugs

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## ABSTRACT

**We herein report the finding of rare eclogite-facies vugs forming millimeter- to centimeter-sized pockets in meta-ophiolites from the western Alps. Euhedral garnet crystals covering the vug walls display oscillatory chemical zoning for a wide range of major and trace elements including Cr, Mn and rare earth elements. Thermodynamic modelling reveals that closed-system fluid production through the breakdown of prograde glaucophane, lawsonite and chlorite between 505–525 °C can successfully explain porosity creation of ~4% and the mineralogical properties of the vugs. Available geological and geochronological constrains indicate that the eclogitization of the downgoing mafic crust spanned a window of at least 1 Myr. These observations can only be explained by the presence of extremely low permeability values ( $< 10^{-22}$  m<sup>2</sup>) to keep the fluid confined at the meter scale within vugs on such timescales. Our field-based report of eclogite porosity provides the first *in situ* confirmation of previous experimental data and geophysical estimates on active margins. A substantial amount of fluid trapped in this porosity may be carried deeper than expected into the Earth's mantle, with implications for volatile recycling budgets.**

## INTRODUCTION

Fluid production in the subducted lithosphere occurs due to prograde metamorphic dehydration reactions resulting in the release of fluids stored during seafloor hydrothermal alteration (Schmidt & Poli, 1998). Quantifying *in situ* petrophysical properties and fluid distribution of the downgoing lithosphere in active subduction zones is critical for understanding rheological and deformational processes across timescales (e.g. Kodaira et al., 2004; Shiina et al., 2013). Petrophysical properties of subducted oceanic crust have been determined using  $V_p/V_s$  ratios, for instance in the Cascades subduction zone where porosities in the range 2.7–4.0 vol.% and extremely low permeabilities of  $< 10^{-23}$  m<sup>2</sup> were estimated for the downgoing mafic crust undergoing incipient eclogitization (e.g. Peacock et al., 2011). Although these indirect constraints are fundamental for quantifying rock properties in active margins, they are subject to comparatively high uncertainties, with available estimates for the permeability of the downgoing lithosphere at 30–100 km depth spanning a range of 4 to 5 orders of magnitude (e.g. Ingebritsen & Manning, 1999; Kawano et al., 2011). More robust evidence can be obtained from metamorphic rocks exhumed from ancient subduction interfaces (provided the prograde record is adequately preserved), where *in situ* constraints permit direct quantification of fluid-rock interaction processes taking place along the plate interface at depth (Zack & John, 2007).

Mineral-filled vein systems commonly occur in high pressure metamorphic rocks and mark the passage or expulsion of free fluids during densification of the host (e.g. Etheridge et al., 1984; Thompson & Connolly, 1990; Philippot & Selverstone, 1991; Taetz et al., 2018). However, these porosity networks are transient and the relationship of vein systems to  $V_p/V_s$ -based petrophysical estimates is challenging to interpret (e.g. Healy et al., 2009). Natural examples of eclogite-facies porosity as documented by geophysical studies are lacking, most likely due to fluid escape and collapse during the protracted burial-exhumation history recorded by metamorphic rocks. We herein document an occurrence of exceptionally preserved eclogite-facies vugs in the western Alps (Monviso, Italy), and evaluate their implications for the petrophysical properties of the downgoing oceanic crust.

## GEOLOGICAL SETTING

The western Alps internal zones contain large coherent slivers of the slow-spreading Tethyan seafloor (including sediments, basalts, gabbros and serpentinites) that were subducted to eclogite-facies conditions during the Alpine cycle and subsequently exhumed during the Late Eocene (e.g. Agard, 2021 and references therein). Where they have escaped retrogression related to exhumation, eclogite-facies mafic rocks commonly contain garnet and omphacite with minor amounts of glaucophane, phengite and more rarely chloritoid and talc (**Fig.1**). In low-strain domains, cm-sized vugs are occasionally visible, either filled by euhedral talc flakes in Mg-rich metagabbros (Zermatt area, **Fig.1A**) or by omphacite and garnet in Fe-rich metagabbros (Monviso area, **Fig.1B**).

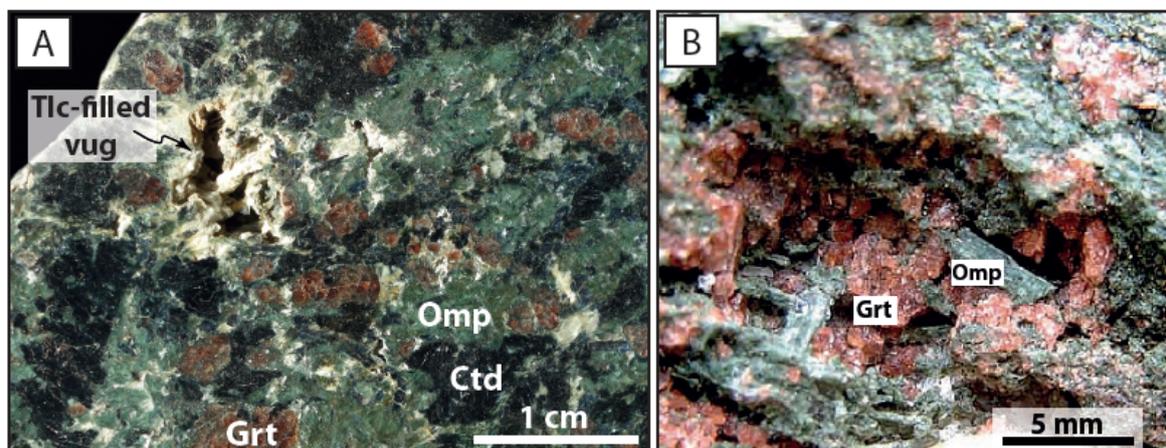


Figure 1

**Figure 1:** **A.** Hand specimen view of an eclogite-facies metabasite from the Pfulwepass area (Zermatt-Saas unit, Switzerland), showing a vug filled by talc flakes. The report of these vugs in the Zermatt-Saas unit confirms that the vug-formation process is likely ubiquitous along the entire eclogite-facies Alpine metamorphic belt. **B.** Outcrop view of an eclogite-facies Fe-Ti metagabbro from the Lago Superiore Unit (Monviso area), showing a vug containing euhedral garnet crystals and mm-sized omphacite needles. Abbreviations after Whitney & Evans (2010).

We herein focus on the Monviso Lago Superiore Unit (LSU) eclogites, which derive from fine-grained Fe-Ti gabbros that were variably mylonitized along crustal-scale shear zones (Angiboust et al., 2011). The studied locality is found along the Intermediate Shear Zone (ISZ), north of the Lago Superiore area (see **Fig.S1**), where eclogite-facies crack-seal veins have been reported (e.g. Philippot & Selverstone, 1991; Rubatto & Hermann, 2003; Spandler et al., 2011). In this area, peak burial conditions of 530–570 °C and 2.6–2.9 GPa were reached at c. 45 Ma (e.g. Rubatto & Angiboust, 2015; Locatelli et al., 2018).

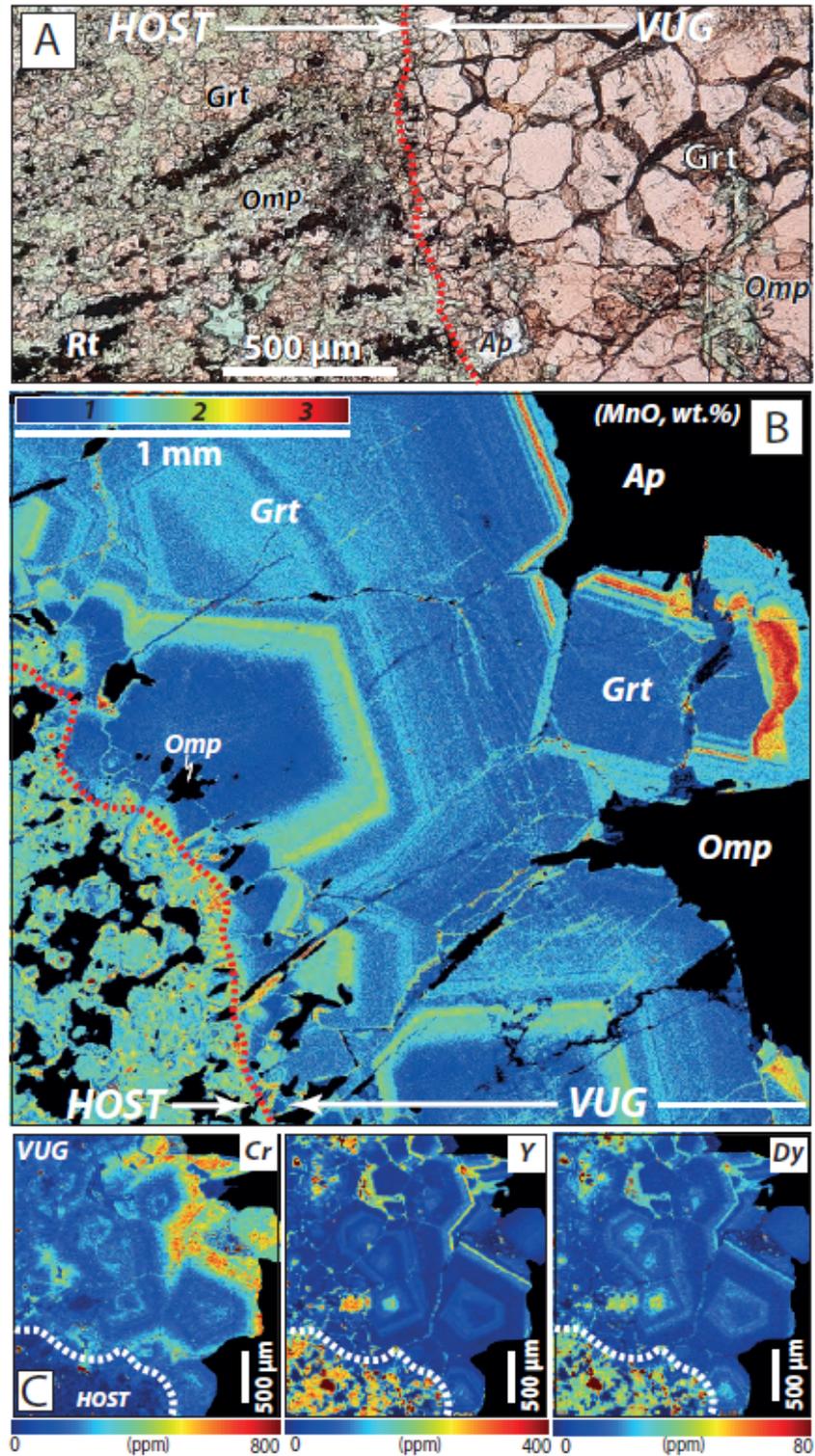


Figure 2

**Figure 2:** **A.** Thin section (transmitted plane polarized light) view of the contact between the fine-grained eclogite host (left) and the vug (right), marked by the red dashed line. Note the oscillatory inclusion trails parallel to the vug wall in garnet crystals (black arrows). **B.** X-ray map of MnO (wt%) in garnet from the matrix (left) and the vug (right). **C.** LA-ICP-MS trace element maps for Cr, Y and Dy (ppm) in an area adjacent to the map shown in panel B. White dashed line indicates the host-vug contact. Full quantified analytical dataset is provided in Fig. S4.

## PETROLOGY AND GEOCHEMISTRY

The studied eclogitic vugs (**Fig.1B**) are found in the variably strained Fe-Ti metagabbros lenses capping the top of LSU metagabbros (**Fig. S1**). The low-strain domains form meter-sized, boudin-like volumes (wrapped by vug-free mylonitized host rocks) and contain variable vug proportions from <1 vol.% up to several volume percent (field-based estimate using a comparison chart for volume-percentage estimation; Terry & Chilingarian, 1955). Vug distribution in low-strain domains is highly heterogeneous and does not seem to follow a systematic trend. The host rock surrounding the vugs comprises fine-grained garnet (0.1–1.0 mm) wrapped by an omphacite-rich matrix containing weakly oriented rutile stringers (**Fig.2A**). Locally, discrete pseudomorphs after lawsonite (mostly clinozoisite) and sub-micrometer flakes of a phengite-rich white mica are also observed in the matrix (see further details on mineralogy in Angiboust et al., 2012). The contact between the host rock and the cavity is lined with euhedral, mm-sized garnet-rich bands and omphacite needles (**Fig.1B**). Vug garnet crosscuts and overgrows the adjacent mylonitic fabric of the host (**Fig.2**).

Garnet crystals within the vug contain dark,  $\mu\text{m}$ -sized oscillatory fluid inclusion trails parallel to the vug walls (**Fig.2A**). Needles of omphacite-rich clinopyroxene are also abundant, intergrown with garnet and minor apatite and rutile. Electron probe analyses show that (i) the amplitude of major element garnet zoning is limited (less than 15 mol.% variation for all elements) and (ii) the compositions of garnet and clinopyroxene from the host rock and vug broadly overlap (**Fig.S2, Tab.S1**). X-ray mapping of a vug–host contact reveals a spectacular oscillatory pattern, well visible on the Mn map (**Fig.2B**) as well as for other major elements such as Ca, Fe and Mg (**Fig.S3**). Laser ablation ICPMS mapping shows an equivalent oscillatory structure for trace elements in garnet lining the vug, well visible on Cr, Y and Dy maps (see full analytical dataset in **Fig.S4**).

## THERMODYNAMIC MODELLING

### Setup

To model phase relationships during eclogitization of the Monviso ISZ Fe-Ti metagabbros, we use sample VI0917 described in Angiboust et al. (2012) and the pseudosection software Perplex (Connolly, 2005) in the  $\text{Na}_2\text{O}-\text{CaO}-\text{K}_2\text{O}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}-\text{O}_2$  (NCKFMASHO) system. The effect of manganese on the system is evaluated in the Supplementary Material. We neglect it in the first model presented here for the sake of simplicity, largely because Mn strongly fractionates within garnet cores, and thus has a greater impact on phase relationships nearing peak burial conditions. The model shown in **Figure 3A** has been calculated along the prograde  $P$ - $T$  path defined by Angiboust et al. (2012) and for a range of  $\text{H}_2\text{O}$  contents between 0.4–2.5 wt.% (in order to span a window from relatively dry to  $\text{H}_2\text{O}$ -saturated conditions). The set of solid solution activity models chosen, along with further model setup information, is given in the Supplementary Material.

### Results

The starting  $\text{H}_2\text{O}$  content is set to 2 wt.%, as expected for a mafic blueschist that has undergone mild hydrothermal alteration prior to eclogitization (e.g. Muñoz-Montecinos et al., 2020; Hernandez-Uribe et al., 2020). **Figure 3** shows that no free fluid is expected to be released during burial between 400–505 °C, until the saturation line is finally crossed associated with the partial breakdown of glaucophane and lawsonite and the full consumption of chlorite.

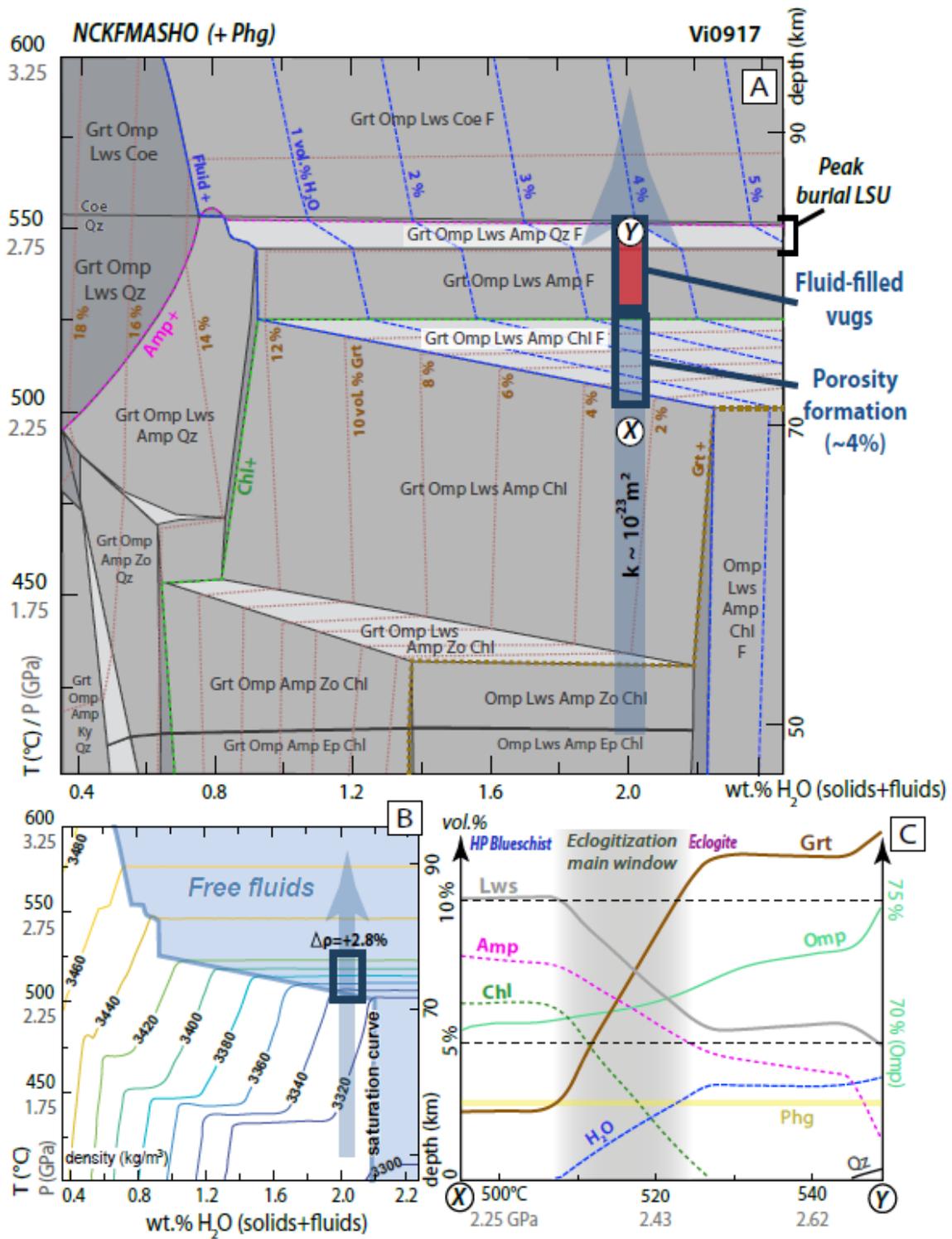


Figure 3

**Figure 3:** A. Pseudosection showing the stability fields of mineral assemblages during burial from blueschist to eclogite facies conditions as a function of the H<sub>2</sub>O content in the system. Thick blue arrow represents the path expected to be followed in a closed system. LSU: Lago Superiore Unit. F: fluid phase (pure H<sub>2</sub>O here). B. Equivalent P-T grid showing the density of the solid assemblage. The eclogitization window (blue rectangle) induces a densification of +2.8%. Also shown with light blue shading is the domain where free fluids are thermodynamically expected. C. Plot of the variations in mineral volumetric amounts within the blue square indicated in panel B.

According to this model (which assumes full thermodynamic equilibrium), eclogitization occurs within the narrow temperature range of 508–523 °C. Above 523 °C and up to peak burial conditions at 550 °C, only minor amounts of H<sub>2</sub>O are released. Eclogitization is marked by a sharp increase in garnet mode (see modelled garnet composition in **Fig.S2**) and accompanied by the release of 3–4 vol.% H<sub>2</sub>O (in agreement with calculations by Groppo & Castelli, 2010 for a similar composition). In addition, our calculations reveal that the solid density increases by 2.8%, resulting in the creation of approximately 4 vol.% of porosity. This porosity value is compatible with the volumetric proportion of vugs observed in the studied Monviso exposure, and supports the choice of 2 wt.% as the starting H<sub>2</sub>O content in our calculations (**Fig.3A**). For lower pre-eclogitization H<sub>2</sub>O contents (~ 1 wt.%), porosity creation would be much lower (<1 vol.%), leading to a situation where vugs may not develop or remain undetectable in the field record.

## VUG FORMATION MODEL

Densification of the Monviso ISZ Fe-Ti metagabbros during eclogitization was accompanied by the formation of crack-seal veins that enabled free dehydration fluids to leave the system. Locally, these veins make up 1–2% of the rock volume and appear to be the result of fluid drainage at scales between several centimeters and less than a meter, based on previous geochemical studies (Philippot & Selverstone, 1991; Spandler et al., 2011). Using experimental results and high-resolution observations from natural samples, Mibe et al. (2003), Ganzhorn et al. (2019) and Wirth et al. (2021) show that 1–2% porosity may exist in high pressure rocks, in agreement with geophysical-based estimates from Peacock et al. (2011) and Shiina et al. (2013).

Our thermodynamic modelling and integrated geochemistry suggest that pore fluids produced during eclogitization can under certain conditions remain trapped within vugs over Myr timescales (**Fig.4**). The crack-seal veins studied in previous works and the vugs investigated here share the same oscillatory nature as the minerals filling them (see Jamtveit et al., 1993 for similar zoning patterns observed in hydrothermal garnets; see also Spandler et al., 2011), suggesting that intermittent pulses of local fluid were fluxed into voids and cracks during eclogitization dehydration reactions (**Fig.3**). This is also supported by the similarity in composition between the host rock and vug mineral assemblages (**Fig.S2**). Within this closed system, the major and trace element zoning of garnet crystals can be directly related to transient intergranular fluid compositions produced via specific mineral reaction sequences (e.g. Hyppolito et al., 2019). This is supported by a strong correlation between the radial positions of satellite peaks for all elements (**Fig.S4**), suggesting that nutrient uptake was driven by fast diffusion under hydrous conditions and incremental changes to the garnet-forming reaction during prograde growth (Konrad-Schmolke et al., 2008; Raimondo et al., 2017; see also Gaidies et al., 2017). For instance, final chlorite breakdown at ~520 °C may explain the Cr, Mn and Mg enrichments visible along vug garnet rims, whereas highs in Y, Dy, Yb and other REE may mark the consumption of amphibole and lawsonite during eclogitization reactions (**Fig.2B,C**, **Fig.3**). Consistent with this interpretation, each satellite peak is defined by a gradual concentration increase sloping towards the core followed by a sharp decline towards the rim (**Fig.2C**, **Fig. S4**). This may reflect the progressive increase in nutrient availability as mineral breakdown reactions proceeded, followed by an abrupt decrease once these reactions ceased and/or the local chemical budget was quickly consumed by the rapid increase in garnet mode.

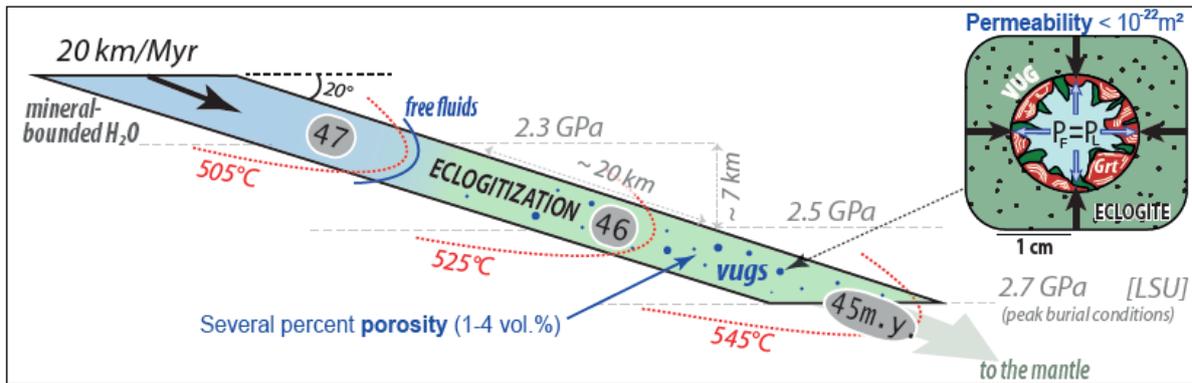


Figure 4

**Figure 4:** Sketch depicting the geometric and geodynamic model inferred for constraining the timing and conditions of vug formation. See text for details. A conversion factor of 32 km for 1 GPa assumed for these calculations. Temperature values are decreased by 20 °C when considering manganese in the thermodynamic model (see the corresponding data in the Supplementary Material).  $P_F$  = pore fluid pressure;  $P_L$  = lithostatic pressure.

### IMPLICATIONS FOR PERMEABILITY AND FLUID TRANSPORT IN ECLOGITES

Recent investigations in the western Alps eclogites using *in situ* Sm-Nd dating of garnet cores and rims have demonstrated that petrochronology-based burial rates are compatible with existing geodynamic constrains for the Alpine Eocene subduction event (Dragovic et al., 2020). These authors concluded that (i) garnet grew over a c. 3 Myr timespan along a 3 °C/km thermal gradient; and (ii) an approximate slab dip of 20° and a convergence rate on the order of 2 cm/yr are compatible with the  $P$ - $T$ - $t$  constrains calculated for these eclogites. These estimates, combined with pseudosection results presented in **Figure 3**, allow us to propose that eclogitization of the Monviso metagabbros occurred over a 7 km depth range (and in the 508–523 °C temperature range), roughly converting to 20 km along dip (**Fig.4**). Because uncertainties exist on some of the calculation parameters such as plate convergence velocity and the effect of Mn on the modelling results (see Supplementary Material for details), we propose that the massive H<sub>2</sub>O release associated with eclogitization occurred over an interval between 1 and 2 Myr.

The occurrence of vugs in meter-sized, weakly strained eclogites indicates that during eclogitization the fluid production rate is greater than the fluid outflow rate, supporting the idea that eclogite permeability must be extremely low. Using the Darcy flow calculation approach described in Peacock et al. (2011) (see Supplementary Material for calculation details and chosen parameters), we estimate that permeability values lower than  $10^{-22} \text{ m}^2$  are required for maintaining the trapped fluid content of a vug after eclogitization at Myr timescales and over spatial scales compatible with the studied exposure (i.e. meter-scale). These estimates are 2–3 orders of magnitude smaller than an extrapolation of the Ingebritsen & Manning (1999) permeability-depth relationship down to 80 km. The absence of vugs in mylonitized domains of the Monviso LSU eclogites, along with the observation of hydrous minerals forming trails along foliated domains of the Intermediate Shear Zone (e.g. lawsonite and phengite; Angiboust et al., 2011), confirms that deformation enhances permeability, with a fluid phase likely moving along grain boundaries through creep cavitation processes (e.g. Menegon et al., 2015). It is thus hypothesized that the exceptional escape of the Monviso and Zermatt-Saas metagabbro vugs from collapse is a consequence of the locally weak mylonitic overprint of prograde microstructures during peak burial.

**We conclude that eclogitic vugs in the Monviso metagabbros provide critical insights into the geometry, distribution and the fate of fluids in eclogites, and corroborate geophysical estimates pointing to several percent of fluid-filled porosity in the mafic crust undergoing eclogitization (e.g. Peacock et al., 2011). These vugs shed light onto the timescales at which pore fluids evolve and ultimately escape, to be collected along drains (fractures and shear zones) or consumed through retrograde mineral reactions upon exhumation. Once passed through the prograde dehydration window, the pores that remain undrained contribute to the advection of fluids into the Earth's asthenosphere, with key implications for mass transfer and global volatile budgets.**

## **ACKNOWLEDGMENTS**

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