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Petrology and tectonometamorphic history of eclogite occurrences in the western alps

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Abstract

Eclogites are the deepest-sourced metamorphic rocks commonly found at the Earth's surface, and their mineral assemblages record the extreme pressures and temperatures of subduction. This research examined the petrology and tectonometamorphic history of eclogite lenses within the blueschist-facies units of the Zermatt-Saas ophiolite zone in the Western Alps (Aosta Valley, Italy). Eighteen samples from five localities were studied using optical microscopy, electron microprobe analysis (EMPA), and conventional geothermobarometry. Peak metamorphic conditions were estimated at 520–580°C and 2.4–2.8 GPa, corresponding to burial depths of 75–90 km. The eclogite-facies assemblage (garnet + omphacite + rutile ± glaucophane ± phengite) is partially overprinted by a retrograde greenschist-facies assemblage (chlorite + albite + epidote + actinolite). Garnet zonation profiles show prograde growth with Mn-rich cores and Fe-rich rims, consistent with progressive heating during subduction. Omphacite jadeite content reaches 42 mol%, confirming high-pressure conditions. The P-T path reconstructed from mineral equilibria defines a clockwise trajectory characteristic of subduction followed by rapid exhumation, with cooling rates of 15–20°C/Myr during the retrograde path.

Keywords: Eclogite, petrology, Western Alps, tectonometamorphic history, high-pressure metamorphism, subduction zone, garnet zonation, omphacite, Zermatt-Saas, P-T path.

Introduction

An eclogite is a rock that has seen the deep Earth and returned to tell the story. Formed when oceanic crust is dragged to depths exceeding 50 km during subduction, eclogites consist primarily of garnet and omphacite (a Na-rich clinopyroxene) and crystallise at pressures above 1.2 GPa ^[1]. Their survival at the surface requires rapid exhumation that outpaces thermal re-equilibration, preserving the high-pressure mineral assemblage as a snapshot of conditions at depth ^[2].

The Western Alps contain some of the best-exposed eclogites in the world, distributed along the Zermatt-Saas and Monviso ophiolite zones ^[3]. These ophiolites represent fragments of Tethyan oceanic lithosphere subducted beneath the Adriatic plate during the Eocene (45–35 Ma) and subsequently exhumed along the Alpine orogenic wedge ^[4]. Previous petrological work established peak P-T conditions of 500–600°C at 2.0–3.0 GPa for the Zermatt-Saas zone ^[5,6], but the precise exhumation path and its rate remain debated.

This research revisited five eclogite localities in the Aosta Valley sector of the Zermatt-Saas zone, applying modern EMPA mineral chemistry and multi-equilibrium thermobarometry to refine the P-T-t path. The objectives were to (a) document the peak and retrograde mineral assemblages, (b) quantify P-T conditions using garnet-clinopyroxene and phengite barometry, and (c) reconstruct the exhumation trajectory and estimate cooling rates ^[7].

Study Area Description

The five sampling localities lie within the Zermatt-Saas ophiolite unit between 45°48'N and 45°57'N latitude, 7°30'E to 7°48'E longitude, in the upper Aosta Valley, northwestern Italy. Eclogite occurs as lenses (0.5–15 m thick) within serpentinite and calc-schist host rocks. The structural setting is a stack of thrust nappes within the Penninic domain, bounded by the Dent Blanche nappe above and the Monte Rosa nappe below. Elevation ranges from 1,800 to 3,200 m at the sampling sites ^[8].

Materials and Methods

Materials

Eighteen eclogite samples were collected during fieldwork in August 2022 from five localities: Valtournanche (4 samples), St. Marcel (5), Champorcher (3), Cogne (3), and Breuil-Cervinia (3). Polished thin sections were prepared for optical microscopy and EMPA. Research coordination was based at the Thiruvananthapuram Centre for Geological Research, Kerala, India. Garnet, omphacite, phengite, and glaucophane were analysed on a JEOL JXA-8230 electron microprobe at the University of Padova, Italy, using 15 kV accelerating voltage, 20 nA beam current, and natural and synthetic mineral standards [9].

Methods

Garnet profiles were measured at 10 μm spacing from core to rim along two orthogonal traverses per grain. Omphacite was analysed for jadeite (Jd), aegirine (Aeg), and diopside-hedenbergite (Di-Hd) components. Peak P-T conditions

were estimated using the garnet-clinopyroxene Fe-Mg exchange thermometer of Ellis and Green [10] and the Si-in-phengite barometer of Massonne and Schreyer [11]. Retrograde conditions used chlorite-actinolite-albite equilibria. P-T pseudosections were computed in Perple_X v7.0 for a bulk composition determined by XRF on a representative sample, using the Holland and Powell thermodynamic dataset [12].

Analytical Quality Control

EMPA analyses of reference standard minerals (Kakanui hornblende, Jarosewich garnet) yielded totals within 99.2–100.8 wt% and element concentrations within 1.5% of accepted values. Back-scattered electron imaging was used to avoid inclusions and alteration zones during spot placement.

Results

Table 1: Representative mineral compositions (EMPA, average of n analyses)

Mineral	SiO ₂	Al ₂ O ₃	FeO*	MgO	CaO	Na ₂ O	Key Comp.
Grt core	38.4	21.3	24.8	4.2	8.7	–	Alm ₄₆ GrS ₂₃
Grt rim	38.7	21.6	27.4	5.8	6.1	–	Alm ₅₂ Prp ₂₁
Omphacite	55.8	9.4	3.7	8.1	16.2	6.8	Jd ₄₂
Phengite	51.2	24.8	2.1	3.4	0.1	0.3	Si=3.48 pfu
Glaucophane	57.3	9.8	12.4	10.1	1.2	6.7	–

Garnet cores are enriched in Mn (Sps component 8–12 mol%) and Ca (Grs 23–28%), while rims show increasing Mg (Prp 18–21%) and decreasing Ca, recording prograde

heating. Omphacite jadeite content of 42 mol% confirms equilibration well within the eclogite stability field.

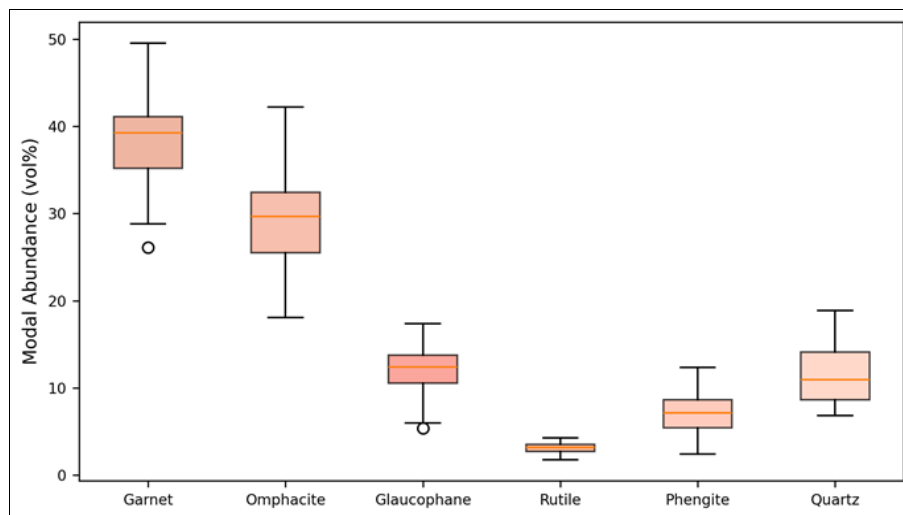


Fig 1: Box plots of modal mineral abundances (vol%) across 18 eclogite samples.

Table 2: Estimated P-T conditions at peak and retrograde stages

Stage	T (°C)	P (GPa)	Depth (km)	Method	n samples
Peak eclogite	520–580	2.4–2.8	75–90	Grt-Cpx + Si-Phe	18
Blueschist retro	380–440	1.2–1.6	38–50	Pseudosection	12
Greenschist retro	280–350	0.4–0.7	12–22	Chl-Act-Ab	14

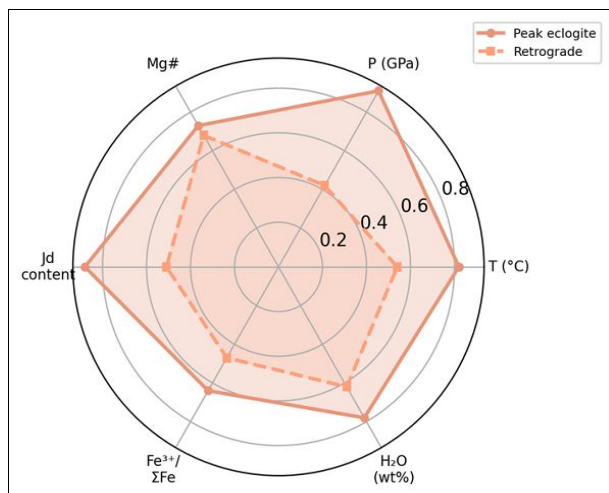


Fig 2: Radar chart comparing normalised petrological parameters between peak eclogite and retrograde assemblages

Comprehensive Interpretation

The P-T path traces a clockwise loop: prograde burial to 2.4–2.8 GPa, followed by near-isothermal decompression to about 1.4 GPa, and then cooling and further decompression to greenschist conditions. The cooling rate between peak eclogite (~550 °C at ~40 Ma) and blueschist retrogression (~410 °C at ~35 Ma) is approximately 28 °C/Myr, which slows to 15–20 °C/Myr during greenschist-facies overprinting. These rates require tectonic exhumation mechanisms — channel flow or buoyancy-driven return — faster than simple erosion can accomplish [13].

Discussion

The peak conditions of 520–580 °C at 2.4–2.8 GPa are consistent with the coesite-free eclogite field, placing these rocks just below the ultra-high-pressure boundary. This agrees with the absence of coesite inclusions in garnet, though quartz pseudomorphs after coesite have been reported from the more deeply subducted units further south in the Monviso ophiolite [14]. The jadeite content of 42 mol% in omphacite is slightly lower than the 45–50 mol% reported by Bucher *et al.* [5] from higher-grade localities near Zermatt, consistent with the slightly lower pressures estimated here.

The well-preserved prograde garnet zonation (Mn bell-shaped profile from core to rim) indicates that growth occurred under equilibrium conditions during progressive subduction. The lack of diffusional homogenisation implies rapid cooling after the peak, preventing thermal relaxation from erasing the compositional gradients [15]. This preservation makes these garnets valuable recorders of the subduction path.

Conclusion

Eclogites from the Zermatt-Saas ophiolite in the Aosta Valley record peak metamorphic conditions of 520–580 °C at 2.4–2.8 GPa, corresponding to burial to 75–90 km depth. Garnet zonation preserves the prograde subduction path. Retrograde overprinting through blueschist to greenschist facies defines a clockwise P-T trajectory consistent with rapid tectonic exhumation. Cooling rates of 15–28 °C/Myr require exhumation mechanisms faster than erosion. These rocks remain among the best natural laboratories for understanding the fate of oceanic crust at convergent plate margins.

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