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# The Chamrousse Ophiolite (Western Alps, France): Relict of a Devono-Carboniferous Ocean

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## ABSTRACT

The Chamrousse ophiolite (Western Alps, France) is one of the best-preserved Variscan relicts of Cambro-Ordovician oceanisation within the northern Gondwana margin. This study presents new in situ U–Pb isotope analyses on zircon grains from that ophiolite, revealing that the oceanic stage in Chamrousse has occurred 150 Ma later than estimated. The metabasite unit, previously interpreted as the ophiolite volcanic layer, yields Cambro-Ordovician zircon ages (460–520 Ma) with few Proterozoic inherited grains, suggesting a continental origin. Meanwhile, zircon grains from the ultramafic, gabbro and basaltic dike units yield new igneous U–Pb ages at 350–360 Ma. The Chamrousse ophiolite may thus be the relict of a marginal basin formed in a back-arc setting, at the onset of the Variscan collision, as are other Devono-Carboniferous ophiolites of the Variscan belt.

## 1 | Introduction

The European Variscan orogenic belt formed from the Devonian to Permian (ca. 380–300 Ma) as the result of the convergence between Gondwana and Laurussia involving the accretion of oceanic domains, magmatic arcs and continental terranes (Matte 2001). However, the structure of the Variscan belt remains discussed (Martínez Catalán et al. 2021; Schulmann et al. 2022) and models face difficulties regarding the identification of microcontinents and oceans resulting from the dismembering of the northern Gondwana margin. Despite a consensus on the opening of the Rheic Ocean between Gondwana and Avalonia continental blocks at around 480 Ma (Nance et al. 2010), the number and size of additional oceanic domains opened further south, within the Gondwana margin, are unsettled (Matte 2001; von Raumer and Stampfli 2008; Kroner and Romer 2013; Franke et al. 2017). Evidence for oceanisation within the Gondwana margin during the Early Palaeozoic is mainly inferred from the geochemical affinity of scarce Cambro-Ordovician mafic and ultramafic units. These units are, however, often dismembered or metamorphosed (Arenas and Martínez 2015; Paquette et al. 2017).

The Chamrousse mafic-ultramafic complex in the Western Alps is considered to date as one of the best-preserved pre-Variscan ophiolites, with a complete although inverted ophiolitic sequence (Ménot et al. 1988). The Cambro-Ordovician ophiolite age is established on dating of the basal metabasite unit (Figure 1), by conventional dissolution technique on zircon from a plagiogranite sample (496 ± 6 Ma, Ménot et al. 1988) and metabasite Sm–Nd isochron (497 ± 27 Ma, Pin and Carme 1987). The geodynamic context is still debated, within a spreading oceanic ridge

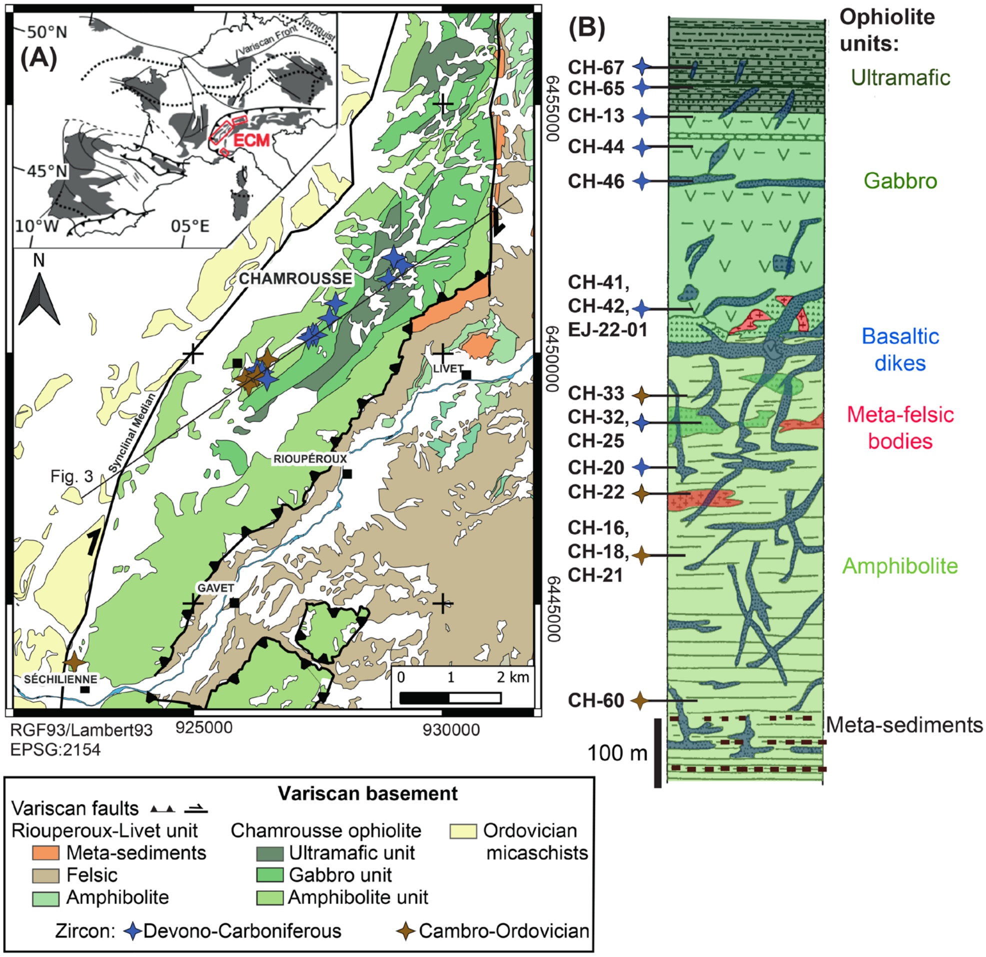


**FIGURE 1** | The Chamrousse ophiolite (A) Geological map of the southwestern Belledonne Massif. The line indicates the position of the cross-section shown in Figure 3. The stars show the sample position, with colour code depending on the new igneous ages. Inset: Location of the Belledonne ECM in the Variscan Belt (Jacob et al. 2022). (B) The inverted ophiolitic sequence of Chamrousse (modified after Ménot et al. 1988), with sample position and new U–Pb zircon age. [Colour figure can be viewed at wileyonlinelibrary.com]

(Bodinier et al. 1982), in an opening basin (Ménot et al. 1988) or in a supra-subduction context (Pin and Carme 1987; Guillot et al. 2009). Yet, the obduction stage of the Chamrousse ophiolite is not clearly established, ranging from mid-Ordovician (von Raumer and Stampfli 2008) to mid-Devonian ages (Guillot et al. 2009). Similarly, the potential suture of the Chamrousse paleo-ocean is not well localised in the Variscan basement of the External Crystalline Massifs (ECM), where only rare occurrences of eclogite with Cambro-Ordovician tholeiitic protolith have been found in association with migmatite and amphibolite bodies. These eclogite rocks were recently redated at 340 Ma (Rubatto et al. 2010; Jacob et al. 2021, 2022; Vanardois et al. 2022), coinciding with the onset of the Variscan collision and granite formation in the ECM (Fréville et al. 2024). This study presents new in situ geochronological data on zircon that challenge the accepted lithological succession of the ophiolite and question the age of the Chamrousse Ocean.

## 2 | The Chamrousse Ophiolite

The Chamrousse ophiolite is exposed along a 30 km-long NE–SW lineament, in the southwestern part of the Belledonne Massif (Figure 1). The ophiolite is laterally delimited by major Variscan tectonic contacts. On its western flank, the ophiolite is separated from an Ordovician micaschist unit by a late-Variscan transpressive dextral strike-slip fault (Synclinal Median, Figure 1A). On its eastern flank, it thrusts over the Devono-Carboniferous Riouperoux-Livet unit dated at 352 ± 1 Ma (Ménot 1988; Guillot et al. 2009; Fréville et al. 2018). The ophiolite tectonometamorphic record can be divided into a first high-temperature and low-pressure episode at the ridge axis, then thrusting and final N-S transpression during the Variscan collision (Bodinier et al. 1982; Guillot et al. 1992, 2009). The effects of the Alpine deformation and metamorphism are only minor and localised (Bellanger et al. 2015).

In its present position, the Chamrousse ophiolite is overturned, with amphibolitised volcanics at the base grading into gabbro and serpentinite at the top (Figure 1B). The amphibolite unit consists of the alternance of pluri-centimetric layers of fine- to coarse-grained mylonitised metabasite (amphibolite) banded with coarse-grained meta-trondhjemites that are referred to as ‘plagiogranite’ by Ménot et al. (1988). These lithologies have been retrogressed under green-schist facies conditions. It includes intercalated terrigenous meta-sediments at its base. The contact between volcanic and gabbroic units is marked by a poorly organised sheeted dike complex (Figure 1B; Ménot et al. 1988). The gabbro unit is made up of distinct lithologies, with dominant cumulate gabbro (Figure 1B) showing localised decimetre-wide shear zones and mylonitisation. The gabbro is associated with contemporary felsic patches or veinlets of diorite, tonalite, anorthosite and albitite (Ménot 1988). The top of the ophiolite sequence corresponds to serpentinised ultramafic rocks deriving from dunite, wehrlite and hornblendite (Ménot 1988; Figure 1B).

## 3 | Samples and Methods

Seventeen samples have been collected from the amphibolite ($n = 6$), gabbro ($n = 7$) and ultramafic ($n = 1$) units and from basaltic dikes ($n = 3$, Table S1 in the Supporting Information). Samples from the amphibolite unit were mainly collected from the meta-trondhjemite layers, except CH-22 and CH-60 (Table S1). In the gabbro unit, cumulate gabbro has been collected, but no zircon could be identified. Samples correspond to felsic patches and dioritic dikelets associated with the gabbro, except for two samples of amphibole-gabbro that crosscut the amphibolite unit (CH-25 and CH-32, Figure 1B) and are, in turn, crosscut by a basaltic dike. In the ultramafic unit, a coarse-grained hornblendite sample (CH-65) layered within serpentinised lithologies was collected. The three metabasite dike samples have been collected across the whole lithological sequence, in the amphibolite (CH-20), gabbro (CH-46) and ultramafic (CH-67) units (Figure 1B).

A classical mineral separation procedure has been applied to 4 amphibolite samples and to the dike sample crosscutting amphibolite (Table S1), in order to concentrate large zircon grains. Only 14 grains were recovered (Table S1). Smaller zircon grains were directly analysed on thin sections. Zircon microstructure and zoning were first characterised by cathodoluminescence (CL) images using a Vega3 Tescan secondary electron microscope.

U–Pb isotope analyses were conducted by laser ablation and inductively coupled plasma mass spectrometry (LA-ICP-MS), combining a RESOlution ArF excimer laser (LA) with an Agilent 8900 ICP–QQQ ICP-MS. The detailed analytical conditions and calibration procedures are given in Supporting Information S2. Uncorrected data for common Pb were filtered using the degree of discordance (=100 × '$^{206}Pb/^{238}U_{age}$'/'$^{207}Pb/^{235}Pb_{age}$'; Table S3) and only dates with discordance < 2% were considered meaningful. U–Pb isotope diagrams were generated with IsoplotR (Vermeesch 2018).

## 4 | Results

Most of the zircon grains are small (< 50 μm). They display domains with oscillatory, more rarely sector, zoning and Th/U ratio > 0.1, sometimes surrounded by a thin CL-bright rim (< 10 μm) that was not analysed. The geochronological dataset is given in Table S3. It includes 372 zircon U–Pb spot analyses obtained on 151 grains (137 grains from 17 thin section and 14 separated grains from 5 samples, Table S1). Only 178 analyses conducted on 95 grains are less than 2% discordant. Zircon texture and U–Pb dates for each sample are closely examined in Supporting Information S4.

In the amphibolite unit, zircon has been dated in amphibolite and meta-trondhjemite layers. Concordant analyses ($n = 101$, 50 grains) show two distinct U–Pb groups. The oldest one is only measured in 6 large crystals (17 concordant U–Pb analyses) recovered through mineral separation (Figure 2 and Supporting Information S4). These grains have a high Th/U ratio (> 0.35, Table S3) and yield Proterozoic ages ranging from 640 to 700 Ma (Figure 2), with no younger domain (Supporting Information S4). All the other zircon grains are Cambro-Ordovician. Their zoning pattern on CL images (Supporting Information S4) and Th/U ratio, mostly ranging from 0.10 to 0.30 (Table S3), point toward magmatic zircon. In the Cambro-Ordovician population, 90% of the dates range between 460 and 520 Ma. The age dispersion is observed at both sample and grain scales with no systematic

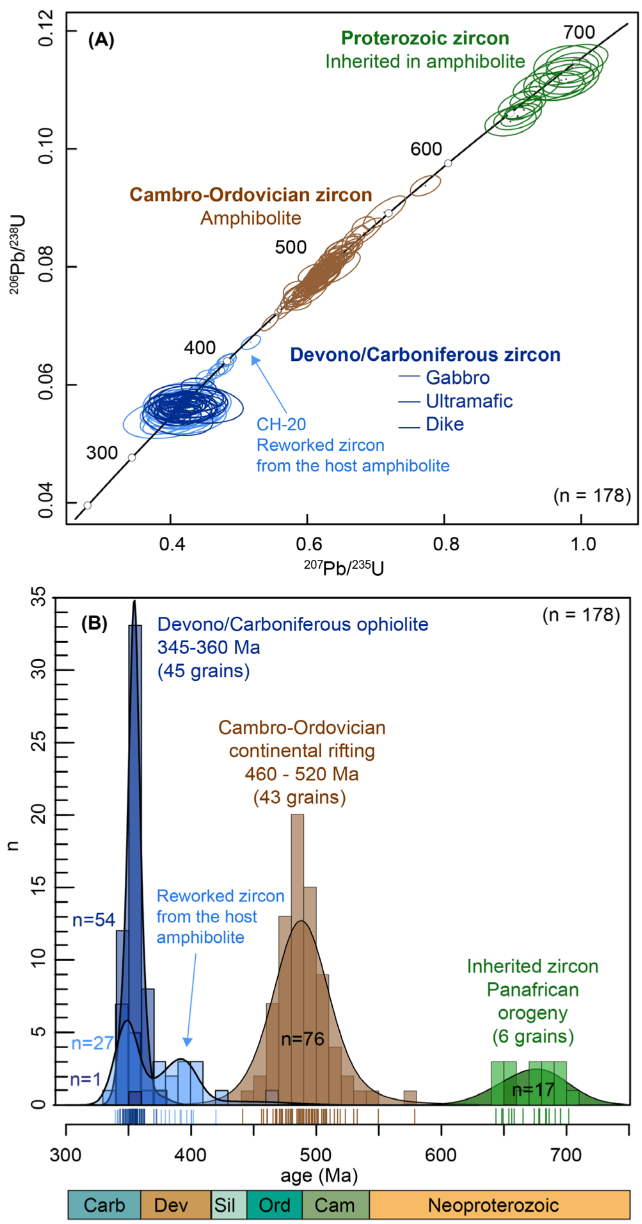


**FIGURE 2** | In situ U–Pb zircon dates. (A) Wetherill diagrams for Chamrousse zircon grains. Analyses with more than 2% discordance are not shown. (B) Concordia age distribution (Kernel Density Estimates with a 10 Ma bandwidth). [Colour figure can be viewed at wileyonlinelibrary.com]

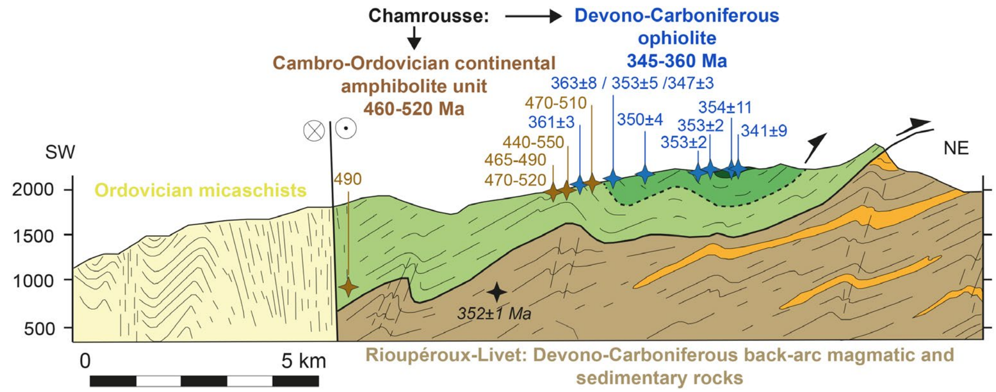


**FIGURE 3** | Structure of the Belledonne Massif revised according to the new in situ U–Pb zircon ages. The original cross-section, the tectonic boundaries and the age of the Rioupéroux-Livet sample are from Fréville et al. (2018). [Colour figure can be viewed at wileyonlinelibrary.com]

textural (e.g., CH-16 and CH-22; Supporting Information S4) or compositional (U, Th or Th/U ratios, Table S3) correlations. Few older dates ($n=5$, 520–580 Ma, Figure 2) were obtained in grains with dark corroded domains (Supporting Information S4).

In the gabbro unit, 54 concordant dates from 32 zircon grains have been obtained from felsic patches, dioritic dikelets, and amphibole-gabbro. The oscillatory zoning on CL images (Supporting Information S4) and high Th/U ratio ($0.34 \pm 0.12$, Table S3) of zircon indicate a magmatic origin. Zircon dates in the gabbro unit are much less dispersed than in the amphibolite unit and give new Devonian-Carboniferous ages (345–360 Ma, Figure 2 and Supporting Information S4).

In the hornblendite sample from the ultramafic unit, the only concordant analysis yields high Th/U (0.5, Table S3) and a date of $354 \pm 11$ Ma (Figure 2 and Supporting Information S4).

In the basaltic dikes crosscutting the gabbro (CH-46) and ultramafic (CH-67) units, U–Pb analyses of zircon grains yield high Th/U ratios ($0.44 \pm 0.12$) and Devono-Carboniferous ages (340–350 Ma, $n=13$, 9 grains, Table S1). The three separated zircon grains from the basaltic dike in the amphibolite unit (CH-20) show a wide date dispersion (Figure 2 and Supporting Information S4), from Devono-Carboniferous ages (360 Ma) to older ages, as those observed in the amphibolite unit (460 Ma).

## 5 | Chamrousse: Not an Inverted Cambro-Ordovician Ophiolite

New in situ zircon U–Pb analyses, completing those obtained by conventional dissolution dating (e.g., Rubatto et al. 2010; Jacob et al. 2021, 2022; Vanardois et al. 2022), challenge pre-Variscan paleogeographic reconstructions (e.g., von Raumer and Stampfli 2008) and related Variscan geodynamic models (e.g., Ballèvre et al. 2014). Accordingly, our new data show that the Chamrousse mafic-ultramafic complex is discontinuous and composed of two igneous units, with distinct ages (Figure 3).

The Cambro-Ordovician amphibolite unit, at the base of the sequence, contains magmatic zircon ranging in age from 460 to 520 Ma, with a peak around 490 Ma (Figure 2B), in agreement with previous geochronological data on this unit (Pin and Carme 1987; Ménot et al. 1988). The date dispersion can be multifactorial, including protracted crystallisation (Zhu et al. 2008), a mixture of several crystallisation stages (Sambridge and Compston 1994) in complex magma systems with periods of recharge and rejuvenation (Schaltegger and Davies 2017), and post-crystallisation disturbance such as Pb loss (Schaltegger 1993; Mezger and Krogstad 1997). The amphibolite unit contains Proterozoic inherited zircon grains with ages (650–700 Ma) similar to those of detrital zircons from the nearby Ordovician micaschist unit (Figure 3; Fréville et al. 2018) and characteristic of the Pan-African inheritance within the northern Gondwana margin (Melleton et al. 2010). These inherited grains suggest that the amphibolite unit formed within the northern Gondwana continental crust. This explains the unusual features of the amphibolite compared to typical ophiolite volcanics, such as the association with terrigenous sediments at the base of the sequence, the abundance of banded meta-trondhjemite levels and the continental influence noticed in the whole-rock chemistry (Ménot et al. 1988).

In the ECM, other Cambro-Ordovician (480–450 Ma) mafic occurrences include the tholeiitic protolith of eclogite lenses embedded in migmatites (Rubatto et al. 2010; Jacob et al. 2021, 2022; Vanardois et al. 2022). This mafic magmatism event also coincided with the production of anatectic felsic melt and emplacement of orthogneiss protolith (470–490 Ma; Fréville et al. 2024). We propose, therefore, that the regional-scale Early Palaeozoic mafic and felsic magmatism in the Belledonne massif, including the basal amphibolite unit of Chamrousse, represents a single episode of bimodal magmatism associated with the continental rifting of the northern Gondwana margin. This is supported by the magmatic record of other Cambro-Ordovician igneous suites emplaced across the Variscan allochthons (Melleton et al. 2010; Chelle-Michou et al. 2017; Paquette et al. 2017; García-Arias et al. 2018; Lotout et al. 2020; Couzinié et al. 2022; Collett et al. 2022; Nutman et al. 2023).

In this study, 82 in situ U–Pb concordant dates were obtained from 45 grains from lithologies for which there was no previous geochronological data: the gabbro unit, the ultramafic pile and the basaltic dikes (Figure 1B). Zircon yields similar ages in samples from the gabbro and ultramafic units, at 345–360 Ma (Figure 2). The basaltic dikes across the whole Chamrousse complex also appear coeval with these units (Figure 2). However, the date range observed in zircon grains from the dike crosscutting the amphibolite unit (Figure 2) indicates that host-rock zircon was reworked in the basaltic melt.

The newly discovered and unequivocal zircon crystallisation event in the gabbro, ultramafic and dike units at 345–360 Ma (Figure 2B) is interpreted as a Devonian/Carboniferous magmatic event. The field association of the three units (Figure 1B) is reminiscent of the oceanic crust lithological sequence. Moreover, the chemistry (Bodinier et al. 1982), texture, mineralogy and deformation in the gabbro unit (Guillot et al. 1992) closely resemble those of the gabbro layer from ocean crust and ophiolites (e.g., Natland and Dick 2009; Decrausaz et al. 2021).

The Devono-Carboniferous age questions the paleogeographic reconstruction of the ECM during the Variscan convergence. Indeed, the upper section of the Chamrousse complex appears contemporary with the underlying back-arc series of Rioupéroux-Livet (Figure 3, Ménot 1988; Fréville et al. 2018). In the Variscan belt, a similar Devono-Carboniferous age is also known from numerous back-arc ophiolites: the Brevennes unit in the French Massif Central at 365 ± 10 Ma (Pin and Paquette 1997), the Drain gabbro in Brittany at 382 ± 2 Ma (Paquette et al. 2017), the Klippen belt in the Vosges at 372 ± 18 Ma (Skrzypek et al. 2012) and the Versoyen ophiolite in the Lower Penninic unit at 340 ± 4 Ma (Masson et al. 2008). The gabbro, ultramafic and dike units of the Chamrousse complex in the ECM may thus form a Devono-Carboniferous ophiolite resulting from the closure of a short-lived back-arc ocean basin opened at the onset of the Variscan collision, within a previously rifted Cambro-Ordovician continental basement.

## 6 | Conclusion

The mafic-ultramafic complex of Chamrousse, in the Belledonne Massif, was long considered one of the rare Cambro-Ordovician ophiolites within the Variscan belt, even if the suture of the Chamrousse paleo-ocean was missing. U–Pb zircon ages, obtained on lithologies for which geochronological data were lacking, challenge this view and reveal that the Chamrousse complex formed through two distinct episodes, in different settings. Zircon ages in the lower amphibolite unit (460–520 Ma) are in agreement with the previously known Cambro-Ordovician age. However, the occurrence of Proterozoic zircon grains inherited from the northern Gondwana margin suggests this unit was emplaced in a continental setting during the rifting of Gondwana. New U–Pb data obtained for the upper section of Chamrousse (gabbro, ultramafic and dike units) yield new igneous ages at 345–360 Ma. This Devono-Carboniferous magmatic episode may record the existence of a back-arc ocean basin, 150 Ma younger than previously estimated. Over tens of kilometres, the Chamrousse complex thus records a snapshot of the evolution from Gondwana rifting to ocean opening.


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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section.