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Tracing anatexis and bottom-up crustal homogenisation with *in situ* Sm-Nd isotopes

T. Biget[1,2,3*], E. Bruand[2], A. Langone[4], M. Boyet[1], A. Caggianelli[5], P. Bonnand[2]

Abstract

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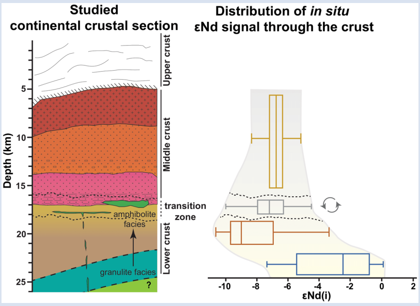

Whole rock Nd isotopes are commonly used to assess mantle-crust contributions in magma sources and to constrain the timing of magmatic and metamorphic events. However, such measurements provide limited insights into deep crustal roots, where complex processes (*e.g.*, open system melting, magma hybridisation) may occur. Here, we combine whole rock and *in situ* Sm-Nd isotopic analyses across a 25–30 km thick crustal section in Calabria (Italy). This section exposes lower crustal granulites and migmatites overlain by mid-crustal post-collisional granitoids, forming a 13 km thick batholith. The lower crust is strongly heterogeneous (whole rock $\varepsilon Nd_{(i)} = -10.5$ to $+1.7$) with isotopic variability evident from outcrop to grain scale. By contrast, the mid-crustal igneous rocks display remarkable homogeneity with consistent crustal signatures ($\varepsilon Nd_{(i)} \approx -7$). Our results indicate efficient isotopic homogenisation from a 1–2 km thick transition zone at the lower-middle crust boundary, where hybridisation between mafic and felsic magmas is evidenced at the grain scale using Sm-Nd isotopic analyses. A minor mantle contribution was likely involved in the batholith genesis but largely obscured by processes like crustal assimilation and cannot be resolved in the granitoids using the Sm-Nd system.

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Introduction

The Phanerozoic continental crust forms predominantly in magmatic arc settings (*e.g.*, Jagoutz and Kelemen, 2015) and can be reworked during subsequent orogenic stages by tectonic, magmatic, and metamorphic processes. These geological processes promote intracrustal differentiation through high temperature (HT) metamorphism and partial melting of lower crustal rocks, resulting in a chemically stratified crustal structure (*e.g.*, Rudnick and Gao, 2014). Consequently, segregation, extraction, and ascent of melts through the crust lead to the emplacement of granitoids in the middle crust. In addition, in most collisional/post-collisional environments, a wide variety of granitoids can be generated, including hybrid magmas (mantle and crustal sources) and pure crustal S-type magmas (Jacob *et al.*, 2021). However, accurately assessing the relative contributions of mantle and crustal components remains difficult. In particular, some studies suggest that commonly used geochemical proxies such as Hf isotopes in zircon can substantially underestimate the mantle component in post-collisional magmas (*e.g.*, Couzinié *et al.*, 2016). Another limitation is the restricted exposure of mantle rocks and deep crust where important melting and hybridisation processes occur (*e.g.*, Voshage *et al.*, 1990). One approach to overcome these limitations is to study exceptionally exposed crustal sections, with only ~15 examples worldwide (*e.g.*, Rudnick and Gao, 2014). This study focuses on a 25–30 km thick tilted Variscan crustal section in Calabria (Schenk, 1990), offering a unique opportunity to observe the two dominant products of crustal differentiation: (1) the lower crustal granulites and partially melted metasediments, and (2) the mid-crustal granitoids emplaced in a post-collisional setting. We present an extensive data set of Sm-Nd isotopes along this crustal section, including both whole rock analyses and *in situ* measurements on accessory phases, in order to (i) characterise isotopic variability at multiple scales (outcrop, thin section, mineral), (ii) assess the extent and spatial distribution of hybridisation processes and their impact on the final Nd isotopic signatures of granitoids, and (iii) investigate granitoid sources and petrogenesis. Our results reveal strong multiscale heterogeneities in the Calabria lower crust, contrasting with the notable Nd isotopic homogeneity of the granitoids. We also identify hybridisation processes at the lower–middle crust transition and finally discuss the relative contributions of crust and mantle to the genesis of these post-collisional magmas.

Geological Setting and Sample Selection

Calabria, along with the Peloritani Mountains in Sicily, forms an arcuate mountain belt formerly belonging to the western

1. Laboratoire Magmas et Volcans, Université Clermont Auvergne, France
2. Laboratoire Geo-Ocean, Université de Bretagne Occidentale, France
3. Department of Earth Sciences "Ardito Desio", University of Milan, Via Sandro Botticelli, 23, 20133 Milan, Italy
4. Department of Earth and Environmental Sciences, University of Pavia, Italy
5. Department of Earth and Geo-environmental Sciences, University of Bari, Italy
* Corresponding author (email: theo.biget@unimi.it)

Mediterranean Alpine chain and later disrupted after the Oligo-Miocene tectonic evolution of the region. The Calabria massifs consist of a stack of basement nappes tectonically juxtaposed during the Alpine orogeny (*e.g.*, Schenk, 1990). The uppermost nappe preserves a 25–30 km thick crustal cross section exposed in the Serre Massif and Capo Vaticano Promontory (CVP) area (central Calabria; Fig. S-1). This section, considered as nearly complete and unaffected by major thrust zones, was primarily formed during the late Variscan orogeny and later tilted by Alpine-Apennine tectonics (*e.g.*, Schenk, 1990). The lower crust comprises two units affected by late Variscan (300–290 Ma) HT metamorphism: (1) the 2–3 km thick Granulite Unit, composed of mafic and felsic granulites, which underwent peak *T* of 850–900 °C, overlain by (2) the 5–6 km thick Metapelite Unit consisting mostly of granulite to upper amphibolite facies migmatitic paragneisses (peak *T* ranging from 650 to 850 °C; SI), interspersed by small mafic intrusions (Schenk, 1990; Caggianelli *et al.*, 1991). The transition between migmatites and the deepest mid-crustal granitoids is marked by the Migmatitic Border Zone (MBZ), which shows diffuse evidence of partial melting. This zone contains a wide variety of lithologies, including garnet-bearing tonalites/diorites, amphibole gabbros, migmatites, leucogranites, and minor augen gneisses (*e.g.*, Caggianelli *et al.*, 2013).

Middle crust granitoids are late Variscan, as indicated by emplacement ages ranging from 306.4 ± 1.6 Ma to 292.2 ± 2.6 Ma (Langone *et al.*, 2014; Fiannacca *et al.*, 2017). They form a ~13 km thick batholith composed, from the base to the top, of quartz diorites, tonalites, granodiorites and two-mica granites and granodiorites. Based on whole rock major and trace elements and Sr-Nd isotopic compositions of these granitoids, earlier petrogenetic models suggest either (1) an (almost) exclusively crustal origin (*e.g.*, Fiannacca *et al.* 2015), or (2) a mixing between mantle and crust-derived melts (Rottura *et al.*, 1991; Fornelli *et al.*, 1994).

In this study, we use the Sm-Nd isotopic systematics, combining whole rock and *in situ* analyses of accessory minerals (apatite, monazite, allanite, titanite) on 26 samples representative of the lower and middle crust of the Serre Massif and CVP (Fig. S-1, Tables S-1 and S-2). Petrographic descriptions of the samples and additional age information are available in the Supplementary Information (SI).

Results

Whole rock and *in situ* Sm-Nd analyses by LA-MC-ICP-MS on apatite, allanite, monazite, and titanite grains are presented in Figure 1. Analytical details are provided in the SI and the complete Nd isotope data set in Tables S-3 and S-4. All initial isotopic ratios and $\varepsilon Nd_{(i)}$ were calculated for an age of 290 Ma, marking the end of granitoid magmatism and *T* peak of late Variscan metamorphism in Central Calabria (*e.g.*, Schenk, 1990; SI).

Samples from the Granulite Unit exhibit a wide whole rock $\varepsilon Nd_{(i)}$ range, particularly in mafic rocks (+1.7 to −4.6), indicating mantle-like to crustal affinities (Fig. 1, Table S-3). In contrast, two felsic granulites show crustal signatures around −7 (Fig. 1). The Metapelite Unit also displays heterogeneous whole rock isotopic compositions (from −3.8 to −10.5), falling within the broad range of Nd isotopic compositions previously reported for the Serre Massif migmatitic metasediments (from +1.1 to −12.5; Rottura *et al.*, 1990; Caggianelli *et al.*, 1991; Del Moro *et al.*, 2000). The MBZ samples show narrower whole rock $\varepsilon Nd_{(i)}$ ranging from −6.5 to −8.6 (Fig. 1). Interestingly, even the mafic rocks (VAL-30 and GASP-55; Table S-3) yield highly negative whole rock $\varepsilon Nd_{(i)}$ close to −7. Mid-crustal granitoids show a restricted whole rock $\varepsilon Nd_{(i)}$ range from −6.2 to −7.6 with a mean $\varepsilon Nd_{(i)}$ of −7.1 ± 1.4 (2 s.d.) mostly overlapping the range of the MBZ rocks, but sharply contrasting with the heterogeneous lower crust (Fig. 1). Although more radiogenic Nd isotopic compositions were occasionally reported in some tonalites and two-mica granodiorites (up to $\varepsilon Nd_{(i)} = +0.3$) by Rottura *et al.* (1990), no such compositions could be replicated in this study.

Overall, accessory minerals yield isotopic compositions broadly consistent with their host rocks, except in the three shallowest migmatitic metapelites (CAP-19, SNIC-20A, PETRI-51; Fig. 1, Tables S-3 and S-4), where monazite $\varepsilon Nd_{(i)}$ are ~1 εNd unit higher than whole rock values. In other cases, significant grain scale isotopic variations are observed. For instance, in the MROS-13D gneiss (Fig. 2a1) composed of alternating orthopyroxene-bearing and metapsammitic layers, monazite shows significant $\varepsilon Nd_{(i)}$ variation (~4.5 εNd units) within a single thin section (Fig. 2a2). The least negative isotopic compositions ($\varepsilon Nd_{(i)} = -3.4$ to −4.9) are found in the orthopyroxene-bearing layers, while monazite from the metapsammitic layers displays the most negative values ($\varepsilon Nd_{(i)} = -7.2$ to −8.1). This difference is also observed in some grains at layer interfaces (Fig. 2a3). In these grains, the rims exhibit Nd signatures similar to monazite from the orthopyroxene-rich layers, while the cores yield more negative isotopic compositions, matching with monazite from metapsammitic layers and approaching the whole rock composition of a nearby metapsammitic sample located ~3 m away (MROS-13A; $\varepsilon Nd_{(i)} = -8.1$; Fig. 1).

In another specific case from the MBZ (GASP-55 mafic rock; Fig. 3a), apatite grains show isotopic variations that can be linked to internal zoning and chemistry. Two populations can be distinguished: (1) cathodoluminescence (CL)-bright rims enriched in Rare Earth Elements (REE) and an average $\varepsilon Nd_{(i)}$ of −7.2 ± 1.4 (2 s.d.), compared to (2) CL-dark cores with systematically lower REE contents and an average $\varepsilon Nd_{(i)}$ of −5.6 ± 1.1 (2 s.d.) (Fig. 3b–d). The latter population aligns with the average $\varepsilon Nd_{(i)}$ (−5.5 ± 1.2; 2 s.d.) of allanite from the same sample (Figs. 1, 3d).

Discussion

Nd isotopic heterogeneities of the lower crust: from km to grain scale. The middle and lower crust levels of the Serre section display contrasting Nd isotopic compositions. While the former is globally homogeneous with whole rock $\varepsilon Nd_{(i)}$ values around −7, the lower crust exhibits pronounced isotopic heterogeneities. This variability likely reflects diverse source contributions: radiogenic mafic rocks forming the protoliths of the mafic granulites; ancient and mature (>600 Ma) sediments constituting most protoliths of the metapelites (e.g., Schenk, 1990), and younger greywackes derived from the erosion of igneous rocks possibly related to upper crustal Paleozoic volcano-sedimentary sequences (Rottura *et al.*, 1990; Del Moro *et al.*, 2000; Fiannacca *et al.*, 2015).

Our results show that *in situ* Nd isotopic compositions generally match whole rock values, with minimal inter-mineral variability. This supports previous findings that accessory phases become isotopically homogenised for the Sm-Nd system above ~550 °C within a given bulk lithology, at the cm to dm scale (*e.g.*, Hammerli and Kemp, 2021; Biget *et al.*, 2024). However, some mineral-whole rock discrepancies or grain scale isotopic variations revealed by *in situ* measurements in some composite samples can reflect more complex geological processes not resolvable at the whole rock scale.

In the composite gneiss MROS-13D, Nd isotopic variations of up to 4 εNd units occur at the cm scale between

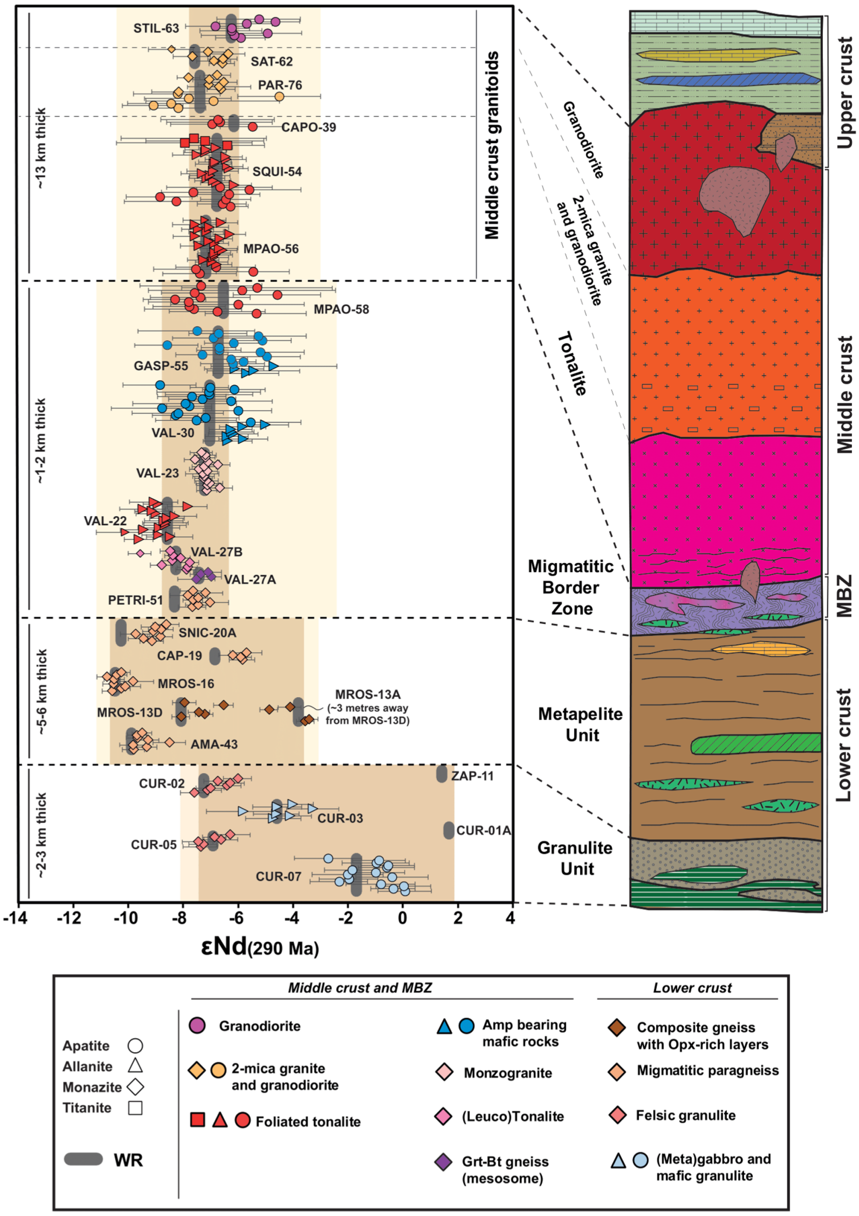

Figure 1 Compilation of whole rock and *in situ* Nd isotopic compositions ($\varepsilon Nd_{290\ Ma}$) for apatite, monazite, allanite, and titanite from the studied lower and mid-crustal samples, ordered by increasing $^{147}Sm/^{144}Nd$ for each mineral. Error bars are ± 2 s.e. Light-brown and light-yellow fields illustrate whole rock and *in situ* isotopic variability, respectively. Samples are arranged by approximate palaeo-depth within the crustal section, following the lithostratigraphic column in Figure S-1. Vertical spacing among samples is schematic and not to scale.

alternating orthopyroxene-bearing and metapsammitic layers (Fig. 2a1–3). Such variations may reflect inherited cm scale compositional heterogeneities in a protolith originally composed of finely alternating psammo-pelitic and more greywacke-like layers (Johnson *et al.,* 2008), deriving from isotopically distinct sources. In this case, the core–rim isotopic zoning of monazite at layer interfaces may suggest interaction of monazite with melt derived from anatexis of metagreywacke layers. Alternatively, the isotopic zoning of monazite could reflect the injection of mafic melts (orthopyroxene-bearing layers) into migmatites.

The three uppermost migmatites display clear mineral–whole rock discrepancies (Fig. 1) most likely resulting from *open system melting* and the infiltration/percolation of isotopically distinct anatectic melts, a common feature in migmatitic terrains (*e.g.,* Hammerli *et al.,* 2018). This is further exemplified by VAL-27 diatexite, where whole rock and monazite analyses differ by ~1 εNd unit between mesosome and leucosome (Fig. 2b), suggesting that the tonalitic leucosome may not form *via in situ* partial melting of the garnet-biotite gneiss.

Magma hybridisation and isotopic homogenisation in the Migmatitic Border Zone (MBZ). The MBZ displays limited Nd isotopic variability despite encompassing a wide range of lithologies, including leucogranites, migmatites, and mafic rocks (gabbros, norites), intimately imbricated at the outcrop scale. The study of mafic rocks provides key evidence for hybridisation processes. In particular, in an amphibole-bearing mafic sample (GASP-55), apatite exhibits pronounced reverse chemical zoning with CL-dark cores depleted in REE (+Th and U), and CL-bright rims enriched in these elements (Fig. 3c, Table S-8). Similar patterns, documented elsewhere, have been interpreted as the result of mixing between compositionally distinct magmas (e.g., Bruand *et al.,* 2014; Laurent *et al.,* 2017). According to the apatite compositional database of Xu *et al.* (2024), apatite cores likely crystallised from low SiO_2 melts (45–55 wt. %), whereas

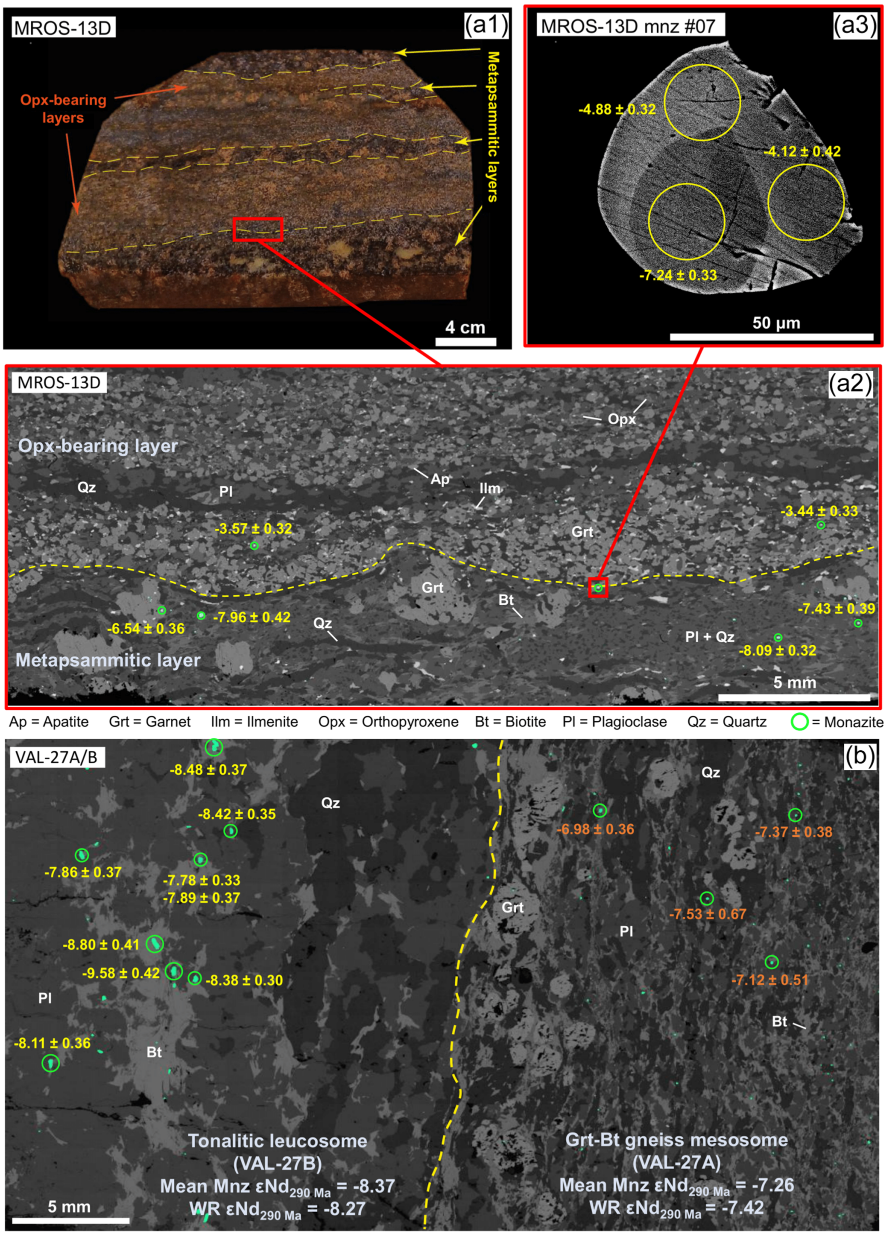

Figure 2 Illustration of the multiscale Nd isotopic heterogeneities of monazite from MROS-13D composite migmatite. **(a1)** Hand specimen, **(a2)** thin section (backscattered electron (BSE) image) and **(a3)** mineral (monazite). **(b)** Thin section scale isotopic variability of monazite between leucosome and mesosome in the VAL-27A/B diatexite. Hand specimen is displayed in Fig. S-7c. Values in yellow and orange correspond to $\varepsilon Nd_{290\ Ma} \pm 2$ s.e.

rims reflect melts with higher SiO2 contents (55–65 wt. %; Fig. S-14). Nd isotopic compositions, though mostly similar within uncertainties, tend to correlate with this zoning: dark domains yield $\varepsilon Nd_{(i)}$ values around −5, while bright domains show more negative values near −7 (Fig. 3b,d). These chemical and isotopic variations record the interaction between a gabbroic magma with less negative $\varepsilon Nd_{(i)}$ and a felsic melt with a more negative signature.

Isotopic homogenisation towards $\varepsilon Nd_{(i)} \approx -7$ may result from various processes during melt migration from source to emplacement, including hybridisation during transport into melt channelways (Hasalová *et al.*, 2011), mixing between multiple magma batches, or assimilation of crustal components enhanced by prolonged convection and diffusion driven exchange (Poitrasson and Pin, 1998). Altogether, field observations, isotopic homogenisation of igneous rocks, and grain scale Nd isotopic heterogeneities indicate that the Migmatitic Border Zone (MBZ) acted as a key site for magma hybridisation and homogenisation prior to possible ascent and emplacement at shallower crustal levels. These features echo those of lower crustal *MASH Zones* (*e.g.*, Hildreth and Moorbath, 1988) or *Deep Crustal Hot Zones* (Annen *et al.*, 2006), where mafic and crustal-derived magmas hybridise and homogenise in arc settings. In a field based study, Schwindinger and Weinberg (2017) suggested that analogous zones could exist at shallower crustal levels (similar to the MBZ location), where repeated magma injections supply heat and H_2O, promoting local anatexis, hybridisation and homogenisation through a positive feedback loop. The example of the MBZ in Calabria suggests that such hybridisation zones at the transition between lower and middle crust might be more widespread than previously reported in crust dominated, (post-) collisional settings.

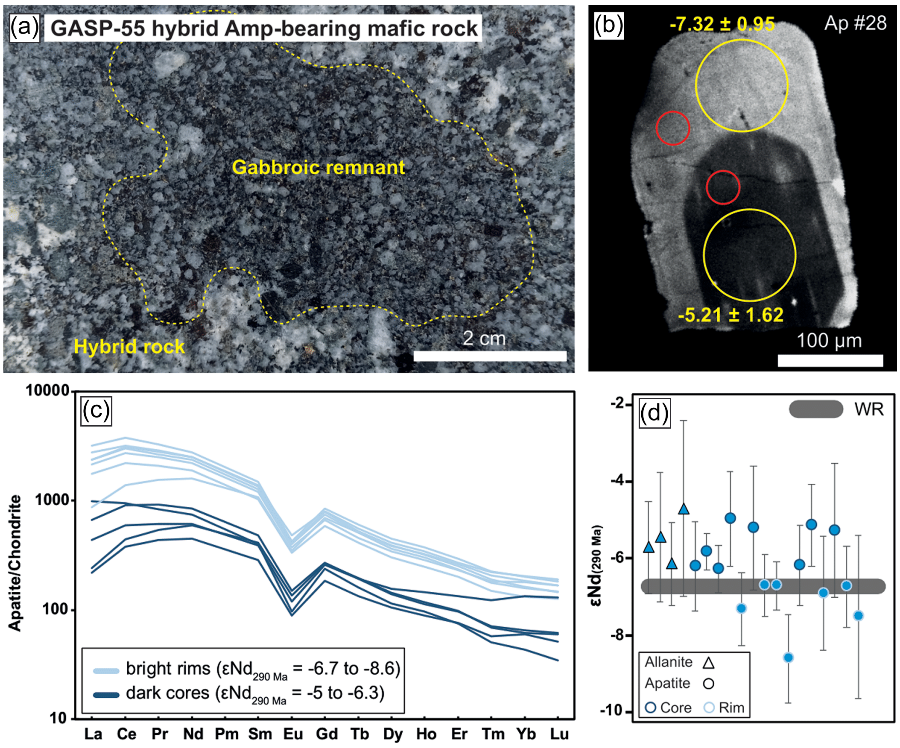

Figure 3 **(a)** Macroscopic view of GASP-55 hybrid mafic rock. **(b)** Representative CL image of apatite showing core–rim zoning with trace element (red circles) and Sm-Nd isotope (yellow circles) analytical spots with ±2 s.e. uncertainties. **(c)** Chondrite normalised (McDonough and Sun, 1995) REE patterns for GASP-55 apatite. **(d)** GASP-55 whole rock, apatite, and allanite Nd isotopic compositions ($\varepsilon Nd_{(i)}$) with ±2 s.e. error bars.

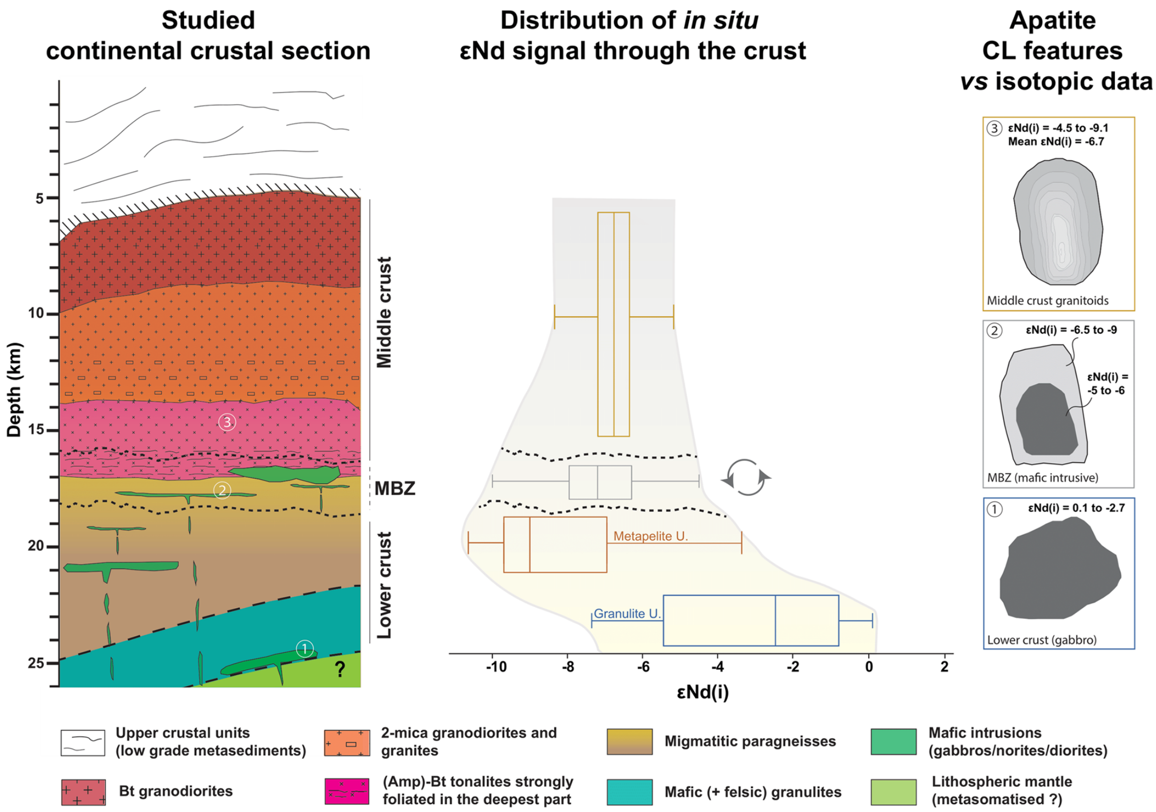

Figure 4 Sm-Nd isotopic scan of the Serre Massif–Capo Vaticano crustal section, illustrated with box plots for the Granulite Unit, Metapelite Unit, MBZ, and middle crust granitoid *in situ* data sets (SI). Box plots display minimum, maximum, median, and 25th–75th percentiles, highlighting isotopic homogenisation from the MBZ. On the right side, representative apatite CL features and isotopic data from igneous rocks (mafic intrusives and granitoids) across the crustal section.

Middle crust granitoids' "amnesia" toward their sources. Nd isotopic analyses show that all granitoids, including tonalites, display a consistent crustal signature at both the whole rock and accessory mineral scales (average $\varepsilon Nd_{(i)} \approx -7$). The Nd isotopic variability of the lower crust, observed in metasediments and mafic bodies, is notably greater than the apparent homogeneity of the granitoids. This contrast highlights the middle crust's isotopic "amnesia" to source heterogeneities (Fig. 4), although certain parts of the batholith may locally escape homogenisation and retain isotopic compositions close to their source rock, as indicated by more radiogenic values reported by Rottura *et al.* (1990). If only granitoid isotopic data were considered, mantle contributions would appear weak or even absent (*e.g.*, Fiannacca *et al.*, 2015, 2017). However, the occurrence of small mafic bodies (norites, amphibole gabbros, and diorites) within the lower crust and the MBZ of both the Serre and adjacent Sila crustal sections (*e.g.*, Schenk, 1990; Caggianelli *et al.*, 1994) supports a mantle input to the genesis of the Calabrian granitoids (Rottura *et al.*, 1991; Fornelli *et al.*, 1994).

Mafic intrusives (locally olivine-bearing) from the Sila crustal section display whole rock $\varepsilon Nd_{(i)}$ values between −2.4 and −7.4 (Caggianelli *et al.*, 1994), comparable to certain mafic rocks from the Serre section. These negative $\varepsilon Nd_{(i)}$ values do not reflect pristine mantle composition but likely result from (i) metasomatisation of the mantle source, or (ii) modification by crustal assimilation and contamination of the magmas during underplating or ascent through the lower crust. Indeed, a mantle metasomatised by crustal-derived fluids can display similarly negative $\varepsilon Nd_{(i)}$ values (down to −5.2 in the Ivrea-Verbano Zone; Voshage *et al.*, 1990, and references therein), potentially masking its contribution to mid-crustal granitoid genesis (Jacob *et al.*, 2021). In the Serre section, rare phlogopite-bearing peridotite remnants at the base of the lower crust (Rizzo *et al.*, 2001) suggest the presence of a metasomatic agent in the lithospheric mantle, although no Nd isotopic data exist for these rocks. Alternatively, negative $\varepsilon Nd_{(i)}$ values may result from assimilation of crustal material by mantle-derived melts at the roof of mafic intrusions emplaced within metasediments (*e.g.*, gabbros with $\varepsilon Nd_{(i)} = -3.1$ to −6.4, Ivrea-Verbano Zone; Voshage *et al.*, 1990). In the Serre crustal section, both processes could have contributed to the negative $\varepsilon Nd_{(i)}$ values observed in mafic intrusions.

Although the Serre batholith formed in a crust dominated system, this study demonstrates that the diversity of lower crustal sources cannot be resolved using the Sm-Nd system in the granitoids. On the other hand, *in situ* analyses from the MBZ constitute a powerful tool for detecting hybridisation processes before complete isotopic homogenisation (Fig. 4). At this stage, the quantification of the mantle contribution remains speculative without constraints on the local mantle isotopic composition and may be underestimated in such crust-dominated systems.

Conclusions

Whole rock and *in situ* Sm-Nd analyses of accessory minerals provide an isotopic overview of a crustal section in central Calabria (Italy). The lower crust exhibits significant source heterogeneity (whole rock $\varepsilon Nd_{(i)} = -10.5$ to +1.7), dominated by crustal isotopic signatures, with a subtle mantle affinity recorded in some of the deepest mafic granulites and metagabbros. *In situ* data also reveal heterogeneities at the thin section or grain scale and highlight *open system melting* in some migmatites. Conversely, mid-crustal igneous rocks composing the batholith are remarkably homogeneous, with whole rock and mineral $\varepsilon Nd_{(i)}$ close to −7. This homogenisation arises from a 1–2 km thick transition zone (Migmatitic Border Zone; MBZ) between the lower and middle crust, where hybridisation occurred between anatectic melts and mafic magmas. Although the granitoids display pronounced crustal Nd signatures suggesting derivation through partial melting of the lower crust, locally hybridised gabbro-norites at various crustal levels — particularly within the MBZ — suggest a mantle contribution. However, their original isotopic signature was likely obscured by metasomatisation of the mantle source or by intense crustal assimilation and hybridisation with anatectic melts during magma ascent. The relative proportions of crustal and mantle components remain difficult to constrain using the Sm-Nd system.

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Additional Information

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Geochemical Perspectives Letters

Tracing anatexis and bottom-up crustal homogenisation with *in-situ* Sm-Nd isotopes

T. Biget, E. Bruand, A. Langone, M. Boyet, A. Caggianelli, P. Bonnand

Supplementary Information

The Supplementary Information includes:

- 1. Sample Selection: *petrographic description of the samples and additional information on the formation ages.*
- 2. Analytical Techniques
- 3. Supplementary Figures S-1 to S-14
- 4. Supplementary Tables S-1 to S-9
- 5. Supplementary Information References

1. Sample Selection

1.1. Petrography

In this section, the samples studied in this contribution are described in detail.

1.1.1. Lower crust samples

Twelve samples were selected from the two units constituting the lower crust of Calabria (Granulite Unit, Metapelite Unit; Table S-1) whose mineral assemblages are described in the section below. Additional data on whole rock and accessory mineral petrography and geochemistry can be found in Biget (2024).

1.1.1.1. Granulite Unit samples

In the Granulite Unit, six samples were studied (four mafic granulites/gabbros and two felsic granulites; Fig. S-1c; Table S-1).

Mafic granulites/Metagabbros

CUR-07 is an amphibole-bearing metagabbro sampled in the Acconia quarry near Curinga (Figs. S-1c; S-2a). It comprises brown hornblende (pargasitic in composition) and plagioclase with minor clinopyroxene (Fig. S-2d), and alternates with coarser-grained hornblendite veins at the cm- to m-scale. This sample is characterised by large (up to 1 mm long), rounded apatite grains, mostly enclosed in amphibole, though some occur at plagioclase-amphibole boundaries or within plagioclase. In CL images, apatite is generally homogeneous but occasionally cross-cut by a complex network of bright veinlets and patches (Fig. S-3a).

CUR-01A and CUR-03 are mafic granulites from the Turrino quarry near Curinga (Figs. S-1c; S-2c,f). CUR-01A is composed of green pargasitic hornblende (~60%) and plagioclase (~35%) with minor clinopyroxene (<2%) and biotite (~1%) grains at hornblende boundaries. Accessory minerals include apatite, ilmenite, and rare zircon. CUR-03 is composed of plagioclase (~65%), orthopyroxene (~15%), biotite (~8%), with minor K-feldspar (<5%), clinopyroxene, sulfides, and quartz. Apatite, ilmenite, allanite, and zircon are the main accessory phases. In this sample, only allanite has been analysed and characterised. This mineral, up to 300 µm long, is found in association with orthopyroxene or enclosed in biotite and shows either homogeneous, patchy, or sector zoning in BSE (Fig. S-3b).

ZAP-11 is a mafic granulite sampled near the locality of Zappaterra. It consists of plagioclase (~60%), green pargasitic hornblende (~25%), clinopyroxene (~10%), orthopyroxene (~4%) and minor biotite (± quartz and K-feldspar) with ilmenite, apatite, and zircon as the main accessory phases. Numerous Fe-oxide grains are also present.

Felsic granulites

CUR-05 is a felsic granulite that occurs as lenses in metagabbros and hornblendites of the Acconia quarry (north of the Serre Massif), which is crossed by the Curinga-Girifalco Line fault (Fig. S-2a,b,e). Its mineralogical assemblage is composed of plagioclase, garnet, quartz, biotite ± K-feldspar. Plagioclase (55%) and garnet (35%) are the dominant minerals, and accessory minerals are, in order of decreasing abundance, rutile (~1%), monazite, zircon, and rare apatite grains. Garnet grains are often grouped into mm- to cm-sized aggregates surrounded by quartz–feldspar matrix. They are highly fractured, commonly associated with Fe-oxide, and contain inclusions of plagioclase, quartz, and biotite, as well as accessories such as rutile, apatite (± monazite and zircon). Biotite is highly deformed and sometimes chloritised and its modal abundance is generally very low (<2%). Epidote is found in altered matrix zones.

CUR-02, another felsic granulite, was sampled from tectonic boudins in contact with mafic granulites in the Turrino quarry near Curinga (Fig. S-2c,g). Its modal mineralogical composition differs substantially from the previous sample, and consists of plagioclase (33%), quartz (30%), K-feldspar (19%), garnet (13%), and biotite (5%). In this sample, garnet grains are smaller (<1 mm) and contain some inclusions of quartz and plagioclase. Biotite is more abundant than in CUR-05. The main accessory minerals are, in order of decreasing abundance, rutile, ilmenite, apatite, zircon, and monazite.

In felsic granulites, monazite grains are generally small (<30 µm) and mainly located in the matrix. In CUR-02, some larger grains, up to 100 µm, can nevertheless be found as inclusions in garnet, mainly at its rim or in association with apatite. In CUR-05, monazite grains are occasionally rimmed by epidote-allanite coronas. In BSE, most monazite grains from both samples appear unzoned (Fig. S-4), though rare core–rim zoning with Th-rich rims is observed in CUR-02 (Fig. S-4).

1.1.1.2. Metapelite Unit samples

Six migmatitic paragneisses derived from pelitic to psammitic protoliths were sampled along a north-south transect through the Metapelite Unit (Fig. S-1c; Table S-1). This transect is characterised by a temperature gradient ranging from ~850 °C at the base of the unit to ~650-700 °C at the top (Schenk, 1984; 1990; Acquafredda *et al.*, 2006; 2008; Fornelli *et al.*, 2012; Festa *et al.*, 2024). As already noted by previous studies (*e.g.*, Caggianelli *et al.*, 1991; Fornelli *et al.*, 2002), the deepest rocks present a very restitic appearance with a quantity of leucosome gradually increasing towards the top of the unit.

AMA-43 is the deepest and most restitic sample. It contains large (up to 10 cm) garnet crystals wrapped by mesosomes defining the main foliation and includes large and prismatic sillimanite, biotite flakes as well as minor quartz and K-feldspar (Fig. S-5a). Garnet is marked by a fairly pronounced alteration at its edges, which tends to penetrate the grain interior along the fractures, forming zones enriched in iron oxide and clay minerals such as kaolinite. Mineral inclusions identified in these garnet grains include quartz, biotite, sillimanite, ilmenite, rutile, zircon, and monazite. A recent study showed that these large garnets formed by the coalescence of peritectic crystals during the migration of melt in pull-apart structures which subsequently clogged the melt extraction channels (Festa *et al.*, 2024). At the interface between garnet and the mesosome, a small volume of leucosome, composed mainly of quartz and K-feldspar, can be found with rare occurrences of biotite, garnet, and sillimanite. Accessory minerals are rutile, ilmenite, monazite, and zircon, which are essentially located in the mesosome. In this sample, most monazite grains are observed in the mesosome, associated with biotite or sillimanite, or as inclusions in garnet, while rare grains are present in the leucosome. Their sizes are generally much larger than those found in felsic granulites, with some grains reaching up to 200 µm. In this sample, monazite is generally relatively homogeneous on the BSE images, except for rare grains showing Th-rich and LREE-poor rims (Fig. S-4).

MROS-13D is a composite gneiss composed of metasedimentary (psammitic) layers interbedded with sub-concordant cm-thick orthopyroxene-bearing layers (Fig. S-5b). In thin section, this rock shows pronounced mineralogical contrasts between the metapsammitic layers composed of biotite, garnet, plagioclase, and quartz and the orthopyroxene-bearing layers that exhibit an orthopyroxene–garnet–plagioclase–quartz mineralogical assemblage. Accessory phases also differ between the two lithologies. The metapsammitic layers include rutile, ilmenite, zircon, and monazite (up to 150 µm), while the orthopyroxene-bearing layers contain ilmenite, apatite, and zircon. Although rare, small monazite grains (<50 µm) are also observed in this lithology (Fig. 2, main text). Notably, some monazite grains at the interface between the two lithological domains show distinct core–rim zoning with BSE-bright rims enriched in Th (Figs. 2, main text; S-4).

MROS-13A is a migmatitic metapsammitic gneiss sampled approximately 3 m away from MROS-13D whose mineralogy closely matches that of the metasedimentary layers of the composite gneiss, consisting mainly of quartz, plagioclase, biotite, and garnet.

MROS-16 is a migmatitic paragneiss of semipelitic composition. The mesosome, defining the foliation, comprises quartz, plagioclase, biotite, sillimanite, and garnet, while the leucosome consists of quartz, plagioclase, and K-feldspar with abundant garnet and minor biotite and sillimanite. Accessory minerals include rutile, ilmenite, monazite, and zircon. Monazite grains occur both in the quartz-feldspathic matrix and as inclusions within garnet, with sizes reaching up to 100 µm. As in AMA-43, most monazite grains appear homogeneous in BSE (Fig. S-4), although a few show patchy zoning or core–rim zoning, with Th-enriched rims.

CAP-19 and SNIC-20A are migmatitic paragneisses derived from pelitic protoliths. Macroscopically, both display concordant leucosomes aligned with the foliation (stromatic migmatites from the nomenclature of Sawyer (2008); Fig. S-5c,d). CAP-19 comprises biotite (10–15%)–garnet–prismatic sillimanite–cordierite (± quartz ± plagioclase) mesosomes, along with quartz–plagioclase–K-feldspar leucosomes. The accessory phases, in order of decreasing abundance, are rutile, monazite, zircon, and apatite. SNIC-20A shows a similar mineralogy but lacks K-feldspar. Its accessory minerals include apatite, rare xenotime and rutile, which is partially replaced by ilmenite. In this sample, biotite is more abundant, comprising up to 30% of the mesosome. Monazite grains in both samples are typically located in mesosomes, associated with biotite or sillimanite. They range from large grains (100–150 µm) to smaller ones (<50 µm) included in garnet. In BSE images, CAP-19 monazite often exhibits complex internal patchy zoning with Th- and Y-rich domains (Fig. S-4). Monazite from SNIC-20A displays complex patchy or core–rim zoning with irregular Y-rich rims and a porosity network, consistent with coupled dissolution–reprecipitation processes (*e.g.*, Varga *et al.*, 2020; Fig. S-4).

1.1.2. Migmatitic Border Zone samples

1.1.2.1. Migmatites

One migmatitic paragneiss (PETRI-51) was sampled in a quarry near Petrizzi, very close to the contact between the top of the Metapelite Unit and the Migmatitic Border Zone (Figs. S-1c; S-6a). Its mineralogy closely resembles that of SNIC-20A with abundant biotite and large crystals of cordierite, particularly visible at outcrop (Fig. S-6b). This sample is also characterised by the presence of carbonate (siderite) and andalusite as partial replacement products of cordierite. This type of reaction (Crd + CO_2 → Carb + And/Ky + Qz) has already been observed in these shallow samples from the Metapelite Unit (Schenk, 1990) as well as in other amphibolite- to granulite-facies metapelites worldwide (*e.g.*, Ellis and Hiroi, 1997). In Calabria, it was interpreted as a record of isobaric cooling at P <4 kbar following the peak of metamorphism (Schenk, 1990). Accessory minerals include monazite, zircon, and ilmenite, with rare apatite and rutile. Monazite is mostly found in the mesosome and commonly shows strong core–rim zoning with Y-rich rims, while other grains are more homogeneous in BSE (Fig. S-4). Another migmatite (diatexite) was sampled in the Vallelonga quarry (VAL-27A/B). The mesosome is represented by a garnet–biotite gneiss (VAL-27A), composed of biotite, quartz, plagioclase, and garnet, with foliation defined by biotite. This gneiss is pervasively intruded by trondhjemitic–tonalitic melts (VAL-27B; Fig. S-7c), consisting of quartz, plagioclase, and garnet that constitute the leucosome. Some of these leucosomes are isoclinally folded on the cm- to dm-scale, a common feature in the Serre Massif (Schenk, 1984), which indicates deformation subsequent to their formation. Accessory minerals in VAL-27A include ilmenite, monazite, zircon, and rare apatite, whereas VAL-27B contains ilmenite, zircon, and exceptionally large monazite grains (up to 500 µm in thin section), displaying complex core–rim, patchy, or oscillatory zoning (Fig. S-8a).

1.1.2.2. Igneous rocks

In this zone, a large diversity of igneous rocks crop out. Samples VAL-22, VAL-23 and VAL-30 were collected from complex outcrops in the Vallelonga quarry (Figs. S-1a; S-7a–f). They consist of: strongly foliated garnet-bearing tonalite (VAL-22), monzogranite (VAL-23) and strongly foliated cummingtonite-bearing mafic rock occurring as a dm-sized lens (VAL-30). Two other samples from the MBZ were collected between Gasperina and Montauro localities: (i) an amphibole-bearing mafic rock (GASP-55; Fig. S-7g) and (ii) a foliated garnet-bearing tonalite (MPAO-58) sampled 1 km west of Montepaone (Figs. S-1c; S-7h).

VAL-22 is a strongly foliated garnet-amphibole tonalite at the contact with the garnet-biotite gneiss (Fig. S-7d). This rock is composed of biotite (defining the foliation), plagioclase, quartz, hornblende (developing around cummingtonite cores), and garnet. Accessory phases are allanite (up to 300 µm, with dark cores and bright rims; Fig. S-8e), apatite (up to 400 µm, homogeneous in CL), zircon, and rare patchy-zoned monazite.

VAL-23 is a sheared K-feldspar–quartz–plagioclase monzogranite, which intrudes the main garnet-biotite gneiss body (Fig. S-7e). Accessory minerals are ilmenite, monazite, zircon, and apatite. Monazite grains can reach exceptionally large sizes (up to 500 µm in thin section) and exhibit oscillatory or patchy zoning (Fig. S-8b), similar to VAL-27A.

VAL-30 is a strongly foliated cummingtonite-bearing mafic rock, composed of abundant plagioclase (>50%), biotite, aggregates of cummingtonite commonly occurring at plagioclase joints and texturally associated to orthopyroxene, and minor quartz. Accessory minerals include ilmenite, apatite, allanite, and rare zircon (Fig. S-7f). Apatite (up to 400 µm) and allanite (up to 200 µm) are texturally related to biotite and cummingtonite (as inclusions or at their edges). Apatite is unzoned in CL, while allanite shows either a bright core–dark rim zoning or is relatively homogeneous in BSE (Fig. S-8c).

GASP-55 is a hybrid amphibole-bearing mafic rock that displays cm-sized gabbroic remnants (Fig. S-7g). It contains plagioclase (>50%), green hornblende (magnesio-hornblende to pargasite), cummingtonite aggregates, and minor biotite and quartz. Accessory minerals are ilmenite, apatite, zircon, and allanite, in order of decreasing abundance. Apatite (up to 400 µm) is mostly enclosed or at the edges of hornblende and cummingtonite and shows variable CL zoning from core–rim (with a dark core surrounded by a bright rim) to more homogeneous textures (Fig. S-8d). Allanite is scarce in thin section and is almost homogeneous in BSE (Fig. S-8d).

MPAO-58 is a foliated garnet-bearing tonalite composed of feldspar, quartz, biotite (defining the foliation), and garnet (Fig. S-7h) with minor chlorite replacing biotite. Accessory minerals include ilmenite, apatite, zircon, and opaques. Apatite occurs as crystals (up to 400–500 µm) mainly associated with biotite, although some grains can also be found in quartz or feldspar (Fig. S-8f). In CL images, apatite can be homogeneous or exhibit a clear bright-to-dark rimward zoning (Fig. S-8f). A few grains show core–rim zoning with dark cores and bright rims (*e.g.*, grain #54; Fig. S-8f).

1.1.3. Middle crust granitoids samples

1.1.3.1. Samples selection

Six granitoid samples representing the main magmatic units of the Serre batholith were selected (Table S-2). For the tonalite unit, we sampled one foliated tonalite at the western extremity of Montepaone village (MPAO-56; Fig. S-1c) and one foliated amphibole-bearing tonalite approximately 2 km south of Squillace (SQUI-54; Fig. S-1c). In these localities, the granitoids are moderately to strongly foliated with the presence of mm- to dm-sized stretched Microgranular Mafic Enclaves (MME). They represent the deepest and oldest granitoids of the Serre batholith (*e.g.*, Caggianelli *et al.*, 2000; Fiannacca *et al.*, 2017). An unfoliated amphibole-bearing tonalite (CAPO-39) was also collected in the Capo Vaticano Promontory (CVP) area (Fig. S-1a). Two samples from the two-mica granite/granodiorite unit were selected; one belonging to the porphyritic facies, characterised by cm-sized K-feldspar megacrysts, sampled near Parghelia beach at the CVP (PAR-76; Fig. S-1a) and a two-mica equigranular granite collected ~2 km east of Satriano in the Serre Massif (SAT-62; Fig. S-1c). Finally, a granodiorite from the uppermost and youngest magmatic unit was collected (STIL-63; Fig. 1c). This sample comes from the top of the granitic body, 5 km west of Stilo near the contact-metamorphic aureole affecting the Stilo-Pazzano phyllites (Fig. S-1a; Festa *et al.*, 2013). These outcrops also contain globular MME.

1.1.3.2. Mineral assemblages

In the following, a detailed petrographic description of the selected granitoids is provided. Their mineralogical assemblages are summarised in Table S-2.

(Amphibole) tonalites

MPAO-56 and SQUI-54 are two medium- to coarse-grained tonalites showing a moderate to strong foliation (Fig. 9a). They display a hypidiomorphic texture with, in order of decreasing abundance, unzoned to weakly zoned euhedral to subhedral plagioclase, subhedral biotite, and anhedral quartz (Table S-2). SQUI-54 also includes subhedral green hornblende. Their main accessory minerals are apatite, zircon, allanite, and titanite with modal proportions varying from one sample to another. Apatite is present in both samples, typically associated with biotite (or amphibole) and less frequently with quartz or plagioclase. Grains reach 300–350 µm and display oscillatory or, less commonly, core–rim zoning in CL (Fig. S-10a,c). Tiny zircon grains included in apatite are frequent, especially at the interface between dark and bright domains (*e.g.*, grain #04 in MPAO-56; Fig. S-10a). Titanite is rarely present in MPAO-56 and common in SQUI-54, reaching up to 400 µm. It is consistently associated with biotite or amphibole at grain edges or within cleavages and is generally homogeneous in BSE, though patchy zoning can occur (Fig. S-10c). Allanite, found in both samples, occurs as large (up to 400 µm) crystals often rimmed by epidote and associated with biotite or amphibole. BSE textures range from homogeneous to sector and patchy zoning (Fig. S-10a,c).

CAPO-39 is an amphibole-bearing tonalite composed of plagioclase, quartz, biotite, and K-feldspar with minor amphibole, chlorite and secondary epidote (Table S-2). Apatite, titanite, and zircon are the main accessory minerals. Apatite grains are up to 300–400 µm long and are typically associated with biotite and less commonly enclosed in quartz or plagioclase. In CL images, most grains show pronounced oscillatory zoning (S-10b). Less commonly, grains display core–rim zoning with a dark, unzoned core and a bright, oscillatory-zoned rim. These zones are separated by irregular interfaces suggesting a dissolution–

reprecipitation process. (*e.g.*, grain #10; Fig. S-10b). Titanite typically occurs as small (<50 µm), anhedral crystals located within biotite cleavages, although larger subhedral grains, up to 300 µm, are also present. In BSE images, titanite appears homogeneous (Fig. S-10b).

Two-mica (porphyritic) granodiorites and granites

The two-mica granodiorite PAR-76 is medium to coarse grained and shows a porphyritic texture with cm-sized K-feldspar megacrysts commonly aligned by magmatic flow. The matrix consists of euhedral to subhedral weakly zoned plagioclase, subhedral to anhedral K-feldspar (microcline), anhedral quartz, euhedral biotite, and subhedral to anhedral muscovite (Fig. 9b; Table S-2). Accessory minerals include zircon, ilmenite, apatite, monazite, titanite, and secondary allanite. Apatite (up to 200 µm) is commonly associated with biotite, muscovite, and K-feldspar megacrysts, and less frequently with plagioclase and quartz. CL images show mostly homogeneous textures with common inclusions of tiny monazite and zircon (<20 µm; Fig. S-11a). Monazite (up to 50 µm) occurs within K-feldspar megacrysts or matrix minerals, mainly alongside biotite, and often displays weak zoning in BSE (Fig. S-11a). Complex intergrowths of apatite, monazite, allanite, zircon, and ilmenite are common (Fig. S-11a1–3). Evidence of monazite breakdown into apatite + allanite suggests a low-grade metamorphic overprint or metasomatic influence (*e.g.*, Schulz, 2021; Fig. S-11a2,3).

Sample SAT-62 is a medium-grained, isotropic, equigranular two-mica granite with a hypidiomorphic texture consisting of anhedral to subhedral weakly zoned plagioclase, anhedral quartz, subhedral K-feldspar, and muscovite/biotite plates. Accessory minerals include apatite, ilmenite, zircon, and monazite with minor xenotime, secondary allanite, and titanite (Table S-2). Apatite occurs as small crystals (<50 µm), enclosed in plagioclase and K-feldspar, and could not be separated for analysis. Monazite grains (up to 100 µm) are either homogeneous or display patchy and sector zoning (Fig. S-11b).

Biotite granodiorite

STIL-63 is a medium-grained isotropic granodiorite showing a hypidiomorphic texture and composed of plagioclase, quartz, biotite, and K-feldspar by order of decreasing modal abundance (Fig. 9c; Table S-2). Plagioclase is commonly sericitized and biotite is sometimes altered to chlorite. Accessory minerals include ilmenite, apatite, and zircon with rare allanite and titanite.

Only apatite was characterised in this sample. Grains are enclosed within or located at biotite edges and less commonly in plagioclase and quartz and can reach 400 µm in size (Fig. S-12). In CL images, apatite is homogeneous or shows weak oscillatory zoning. Most grains are cross-cut by a complex network of bright veinlets and patches (Fig. S-12). A few grains display dark core–bright rim zoning (*e.g.*, grain #11 in STIL-63; Fig. S-12).

1.2. Ages of the formations

The protoliths of the paragneisses and felsic granulites are inferred to derive from arenite–pelite sequences deposited during the Neoproterozoic (Schenk, 1990; Fornelli *et al.*, 2020). U–Pb dating of monazites from the lower-crustal samples analysed in this study yields mostly concordant dates between 270 and 300 Ma, with a peak at 290 Ma in the Kernel Density Estimation (KDE) diagram, corresponding to the late Variscan magmatic event (Fig. S-13; Biget, 2024). Monazites analysed for Sm–Nd isotopes in this study all fall within this age range. Approximately 10% of the dates exceed 325 Ma, likely reflecting prograde monazite growth or inherited monazites, whereas ~10% are younger than 270 Ma, possibly recording later geological events that remain poorly constrained, potentially related to the opening of the Tethys Ocean or pre-Alpine tectono-metamorphic activity (Biget, 2024). The emplacement ages of lower-crustal metagabbros and mafic granulite protoliths remain poorly constrained and debated, potentially ranging from Ediacaran to Cambrian, although some intrusions of Variscan age are also possible (e.g., Schenk, 1980; Caggianelli *et al.*, 2013; Fiannacca *et al.*, 2024). Despite these uncertainties regarding the timing of the intrusions, all εNd values of the mafic rocks in this study were recalculated at 290 Ma, corresponding to the end of the regional metamorphic peak in Calabria. By contrast, granitoid emplacement ages are generally well constrained, occurring between 306.4 ± 1.6 to 295.0 ± 1.4 Ma (Langone *et al.*, 2014) or 297.3 ± 3.1 to 292.2 ± 2.6 Ma (Fiannacca *et al.*, 2017). Sm–Nd isochrons from some samples of this study also yield dates of the same range, albeit with larger uncertainties (Biget, 2024).

2. Analytical techniques

2.1. Whole rock Sm-Nd analyses

Whole rock Sm-Nd analyses (Table S-3) were carried out at the Geo-Océan laboratory (Pôle Spectrométrie Océan-IUEM) at Brest. The Nd separation protocol is derived from Pin *et al.* (1994) and Chauvel *et al.* (2010). 1.5 mL of the sample stock solution (HCl 2.5 N) was loaded into the BioRad AG 50-X8 cationic resin in order to isolate the REE. This REE fraction was then taken up with HCl 0.2 N and processed through the Ln Spec resin columns to collect Nd. The monoelemental fraction of Nd obtained after column separation was diluted into 1 to 6 µL of HCl 1 N (variable according to the amount of Nd collected). 1 µL of this solution was then pipetted on a Re filament (99.95% purity). The Nd isotope analyses were performed in dynamic mode on the IUEM ThermoScientific Triton® TIMS usingdouble Re filaments. Each run consisted of 20 blocks × 10 cycles (8.389-s integration time per line) with a 30-s baseline measurement every block. Isotopic ratios were mass-fractionation-corrected using an exponential law with $^{146}Nd/^{144}Nd$ = 0.7219. Repeated measurements of the JNDi-1 reference material gave $^{143}Nd/^{144}Nd$ = 0.512094 ± 15 (2SD, n = 9) and are consistent with the value of 0.512099 ± 5 measured using a dynamic routine (Garçon *et al.*, 2018). AGV-2 and BHVO-2 gave respectively $^{143}Nd/^{144}Nd$ = 0.512767 ± 5 (2SE) and 0.512996 ± 5 (2SE) and are consistent with published values reported in the GeoReM database ($^{143}Nd/^{144}Nd$ = 0.512786 ± 14 for AGV-2 and 0.512979 ± 14 for BHVO-2).

2.2. In situ analyses

This section details the imaging and *in situ* analyses performed on the studied samples and relevant for this study.

Monazite analyses from all samples and allanite analyses from CUR-03, VAL-30 and GASP-55 were acquired on polished thin sections, whereas apatite and titanite for all samples as well as allanite grains from MPAO-56 and SQUI-54 were analysed on epoxy mounts. These grains were separated using conventional magnetic and density separation techniques, mounted on Epoxy resin discs, and polished for *in situ* analyses.

2.2.1 Image acquisition

BSE images were acquired using a Scanning Electron Microscope (SEM) Thermofisher (formerly FEI) QUANTA 200 with an accelerating voltage of 20 keV equipped with an EDS Oxford XMAX 80 detector in Brest, France. Thin sections and accessory mineral images were processed using the Oxford Aztec software and accessory phases were identified using the "Particle mode". Cathodoluminescence images of apatite were obtained with a KeDev Centaurus CL detector housed on a JEOL JSM-5910LV SEM (accelerating voltage: 15 keV) at the Laboratoire Magmas et Volcans (LMV) in Clermont-Ferrand, France.

2.2.2 Electron Probe Microanalyses (EPMA)

Quantitative chemical analyses for apatite were carried out using the CAMECA SX 100 microprobe from the Microsonde Ouest laboratory (Brest, France) with an accelerating voltage of 20 keV and a beam current of 40 nA. LLIF crystal was used for Mn and Nd, TAP for Na, Si and Y, PET for P and Ca, PC1 for F and LPET for Cl and S. Kα X-ray line was used for Cl, P, Ca, S, Mn, F, Na and Si, while Lα X-ray line was used for Y and Nd. Durango was used as a standard for quality control (Table S-7). A defocused beam of 10 µm was applied to avoid migration effects described for halogens (F, Cl; Pyle *et al.*, 2002). Peak and background counting time for all elements are provided in Table S-7.

2.2.3. In situ Sm-Nd analyses

In situ analyses were conducted on all samples except for three lower crust samples (CUR-01A, ZAP-11 and MROS-13A). Detailed results are provided in Table S-4. Monazite, apatite, and allanite *in situ* Sm-Nd analyses were performed during three sessions on the LMV Thermo Fisher Scientific™ Neptune Plus™ mass spectrometer coupled with the 193 nm Resonetics Resolution M-50E laser following the protocol described in Doucelance *et al.* (2020). Titanite analyses were acquired at the Geo-Océan laboratory (Pôle Spectrométrie Océan-IUEM) at Brest on a Thermo Fisher Scientific™ Neptune Plus™ mass spectrometer coupled with a COMPexPro 193 nm Excimer laser (GeoLas HD system). The first 20 cycles of every measurement were used to evaluate the baseline level of each Faraday cup. Analyses usually consisted of 90 measurement cycles. Depending on the run, a spot size of 12, 15 or 20 µm was used for monazite; 20 or 33 µm for allanite; 120 µm for titanite; and 133, 120 or 107 µm for apatite. Rasters (120 * 80 µm or 117 * 93 µm) were also performed on apatite to minimise analytical uncertainties. For thin sections, the laser frequency was set to 4 Hz and the fluence to 3.0-3.4 J/cm^2. For grains analysed on mounts, frequency was increased to 6 Hz with similar fluence. For titanite analysed with the GeoLas system, the frequency was set to 8 Hz and the fluence to 12 J/cm^2. Helium flow rate was 700-800 ml/min while N_2 flow rate varied between 2.3 and 8.5 ml/min, depending on session conditions. The oxide level (ThO^+/Th) at the beginning of the session was minimised to avoid a $^{145}Nd/^{144}Nd$ drift, as described by Fisher *et al.* (2020) and Doucelance *et al.* (2020). JNdi-1 doped glass was analysed regularly during the sessions to monitor potential instrumental drift (Fisher *et al.*, 2011; Doucelance *et al.*, 2020). Primary standards STK for monazite ($^{143}Nd/^{144}Nd$ = 0.511895; Fisher *et al.*, 2020), Durango for apatite ($^{143}Nd/^{144}Nd$ = 0.512473; Doucelance *et al.*, 2020), Connecticut for allanite ($^{143}Nd/^{144}Nd$ = 0.512106; Wang *et al.*, 2022), and MKED-1 for titanite ($^{143}Nd/^{144}Nd$ = 0.511630; Spandler *et al.*, 2016) were analysed regularly under the same conditions as the unknowns and were used for normalisation and instrumental drift correction when necessary (Tables S-5). Gale allanite ($^{143}Nd/^{144}Nd$ = 0.512999; Wang *et al.*, 2022), Tory Hill apatite ($^{143}Nd/^{144}Nd$ = 0.512048; Fisher *et al.*, 2020), and Khan titanite ($^{143}Nd/^{144}Nd$ = 0.511632; Xu *et al.*, 2018) were used as secondary standards for quality control (Tables S-6). A value of $^{145}Nd/^{144}Nd$ = 0.348415 (Wasserburg *et al.*, 1981) was used as a reference for internal quality control of the analyses. Isotopic ratio calculations were performed off-line using an in-house Microsoft Excel™ spreadsheet. The $\varepsilon Nd_{(i)}$ were calculated using the decay constant $\lambda = 6.54.10^{-12}$ s^{-1} (Lugmair and Marti, 1978) and CHUR parameters from Bouvier *et al.* (2008). Error propagations on the $\varepsilon Nd_{(i)}$ were carried out using the spreadsheet from Ickert (2013).

2.2.4. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)

Trace elements of GASP-55 apatite (Table S-8) were analysed by LA-ICP-MS using the Thermo Element XR linked with a COMPexPro 193 nm Excimer laser (GeoLas HD system) at Geo-Océan laboratory (Pôle Spectrométrie Océan-IUEM) at Brest. Each analysis consisted of 25 s of background acquisition and 85 s of ablation using spot sizes of 32 or 24 µm, a 5 Hz repetition rate, and a laser fluence of 15 J/cm^2. Elemental concentrations were calculated using a sample bracketing method, with NIST-610 (Jochum *et al.*, 2005) as the primary standard to calculate elemental concentrations and to correct instrumental drift. ^{43}Ca concentration, previously measured by EPMA, served as the internal standard for data normalisation. To ensure data quality, USGS glass NIST-612 (Jochum *et al.*, 2005) and standard Durango apatite (Marks *et al.*, 2012) were regularly analysed under identical conditions (Table S-9). Data were processed using GLITTER® software (Van Achterbergh *et al.*, 2001; Griffin *et al.*, 2008).

3. Supplementary Figures

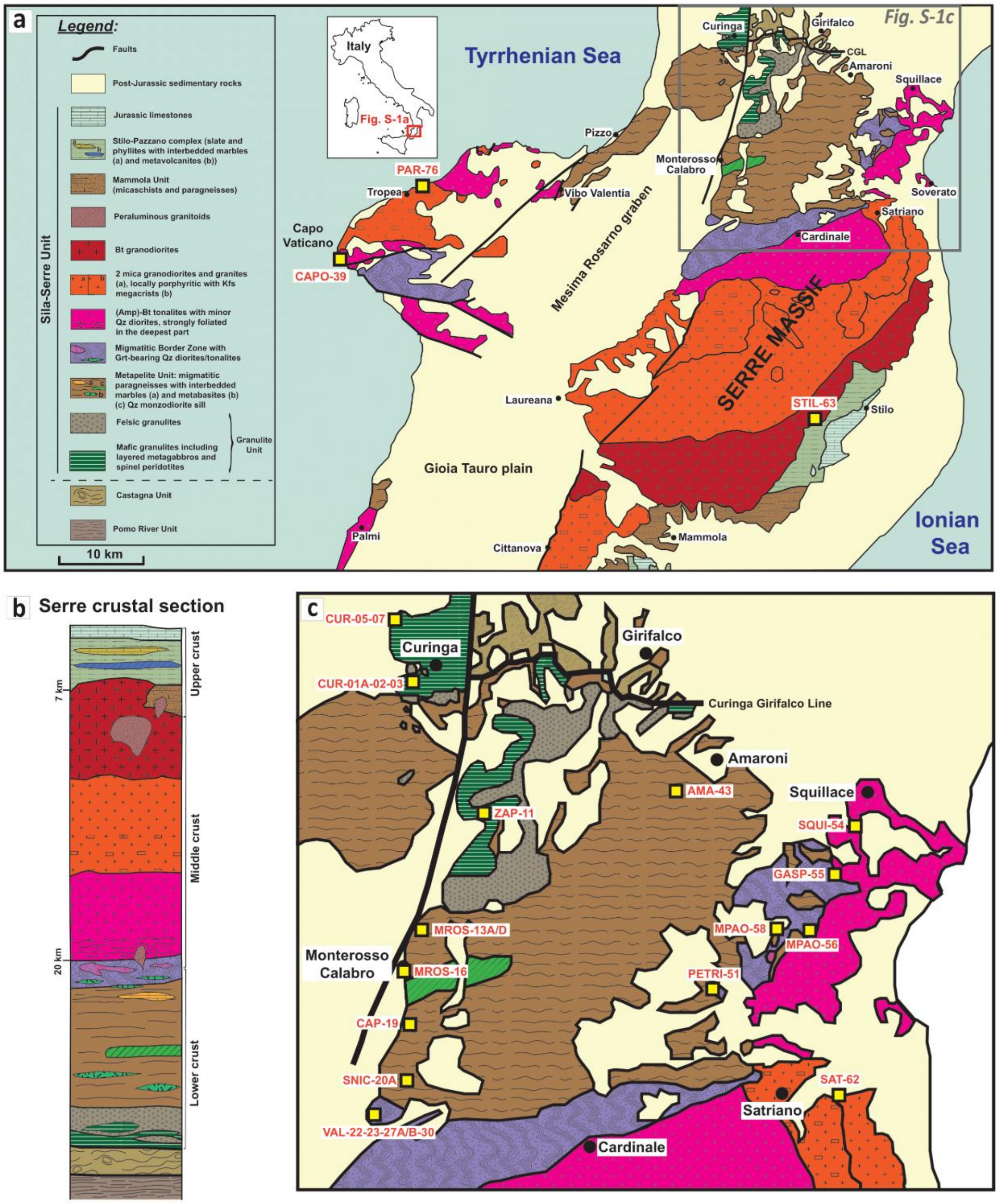

Figure S-1 **(a)** Simplified geological sketch map of the Serre Massif-Capo Vaticano area (modified from Caggianelli *et al.*, 2013 and Fiannacca *et al.*, 2015). **(b)** Schematic lithological column for the Serre Massif (modified from Festa *et al.*, 2004 and Caggianelli *et al.*, 2013). **(c)** Overview of the lower crust with location of the selected samples.

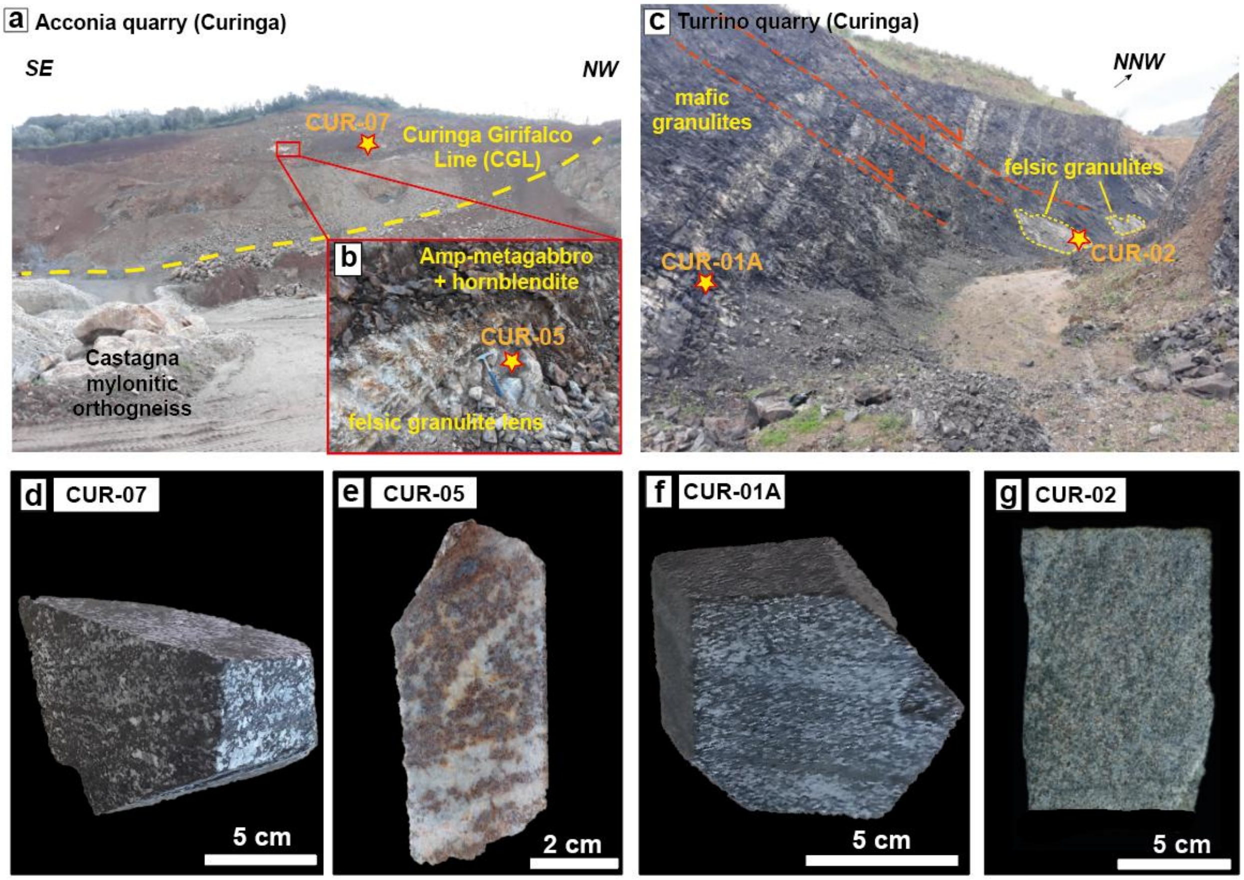

Figure S-2 Outcrop and macroscopic views of some of the selected samples from the Granulite Unit. **(a)** Overview of the Acconia quarry near Curinga, transected by the Curinga-Girifalco Line (CGL) fault (*e.g.*, Brandt and Schenk, 2020; Festa *et al.*, 2020), and showing lenses of felsic granulite (CUR-05) embedded in amphibole metagabbro (CUR-07) and hornblendite **(b)**. **(c)** Overview of the front of the Turrino quarry, cross-cut by normal faults and displaying mafic granulite (CUR-01A) and tectonic boudins of felsic granulite (CUR-02). **(d-g)** Macroscopic view of CUR-07 amphibole metagabbro, CUR-05 felsic granulite, CUR-01A mafic granulite and CUR-02 felsic granulite.

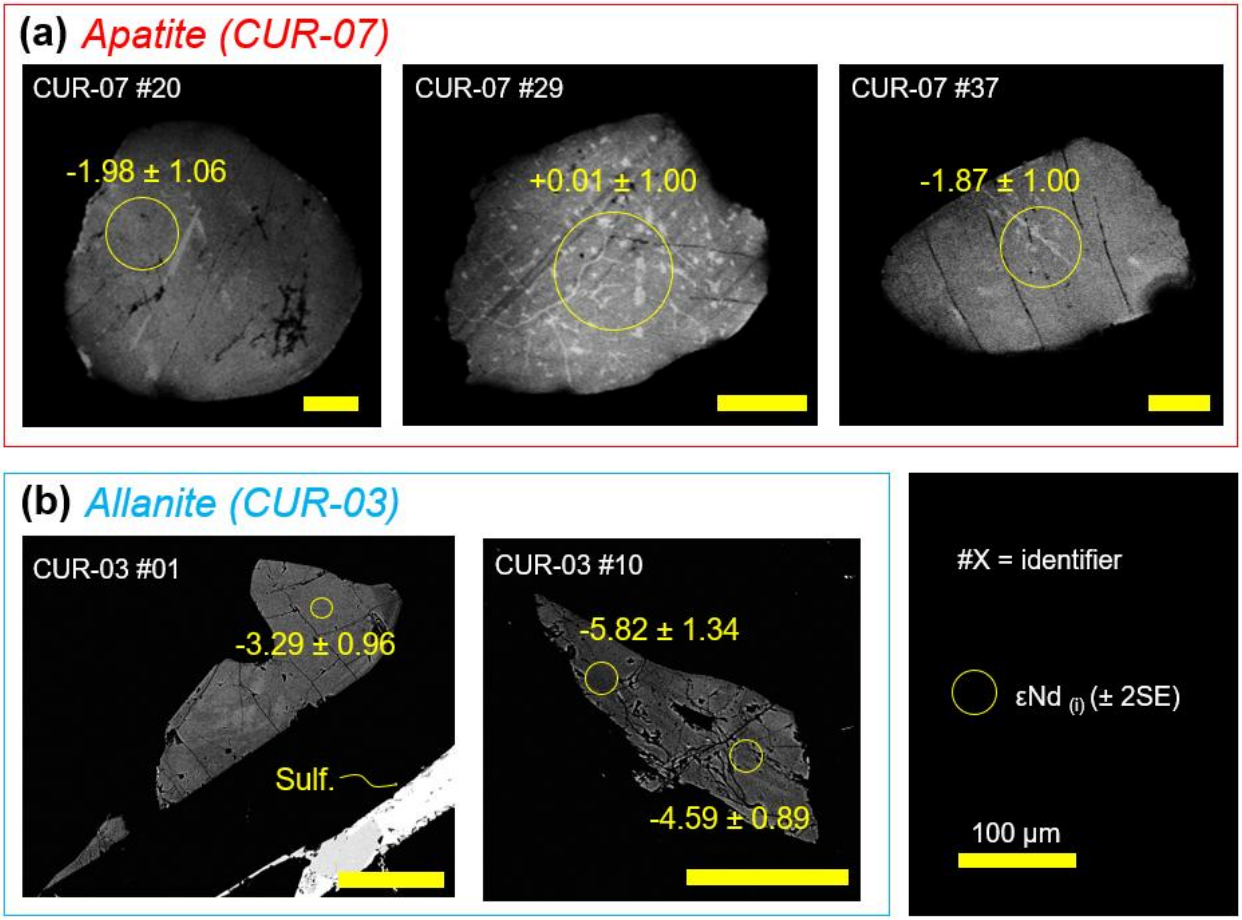

Figure S-3 Representative CL images of apatite from CUR-07 metagabbro **(a)** and BSE images of allanite from CUR-03 mafic granulite **(b)**. The yellow circles indicate the position of the laser spots for Sm-Nd isotopic analyses. εNd were calculated at 290 Ma for CUR-07 apatite and CUR-03 allanite. The yellow scale bar is 100 µm.

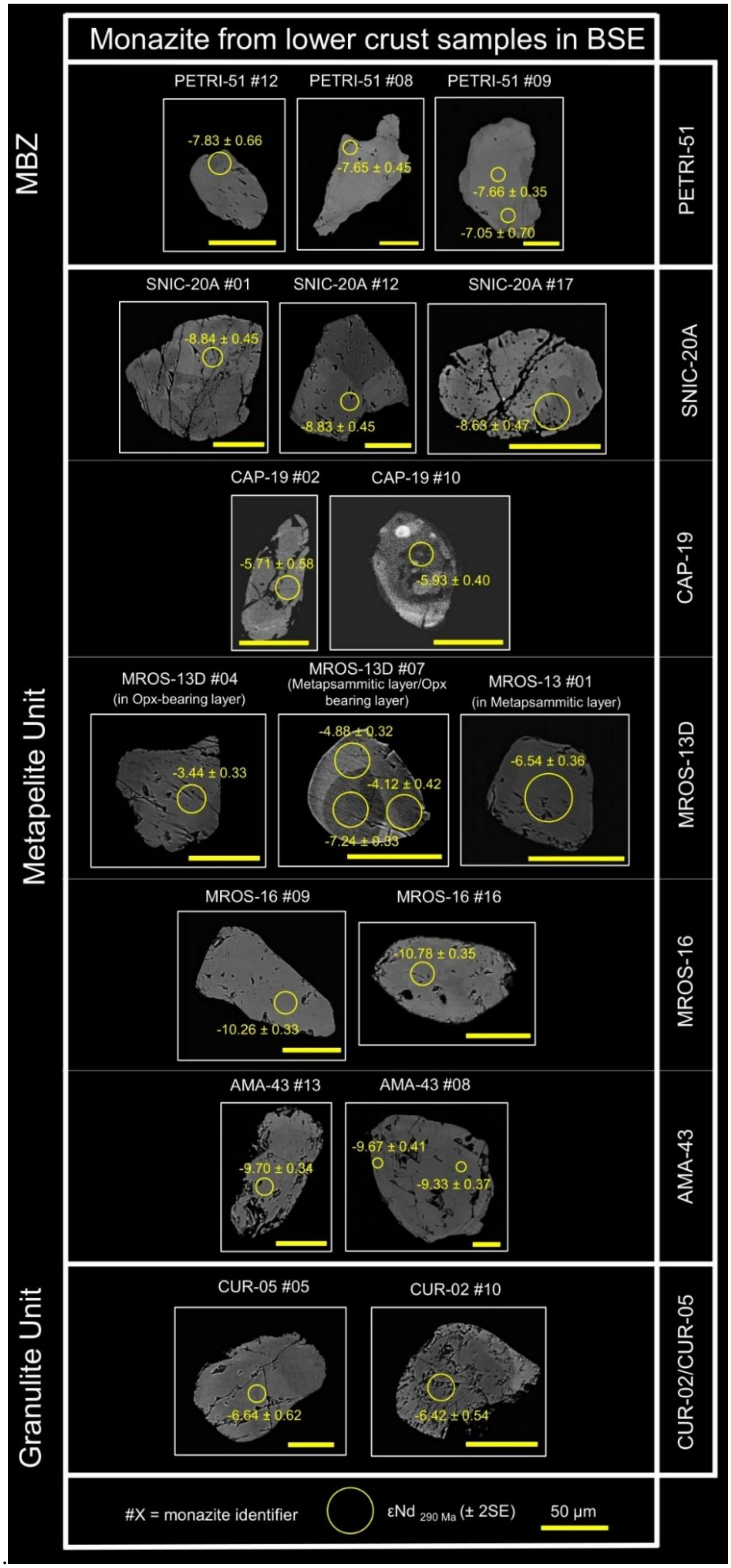

Figure S-4 Representative BSE images of monazite from the samples investigated in this study. The yellow circles indicate the position of the laser spots for Sm-Nd isotopic analyses. εNd were calculated at 290 Ma and uncertainties are ± 2SE. The yellow scale bar is 50 µm.

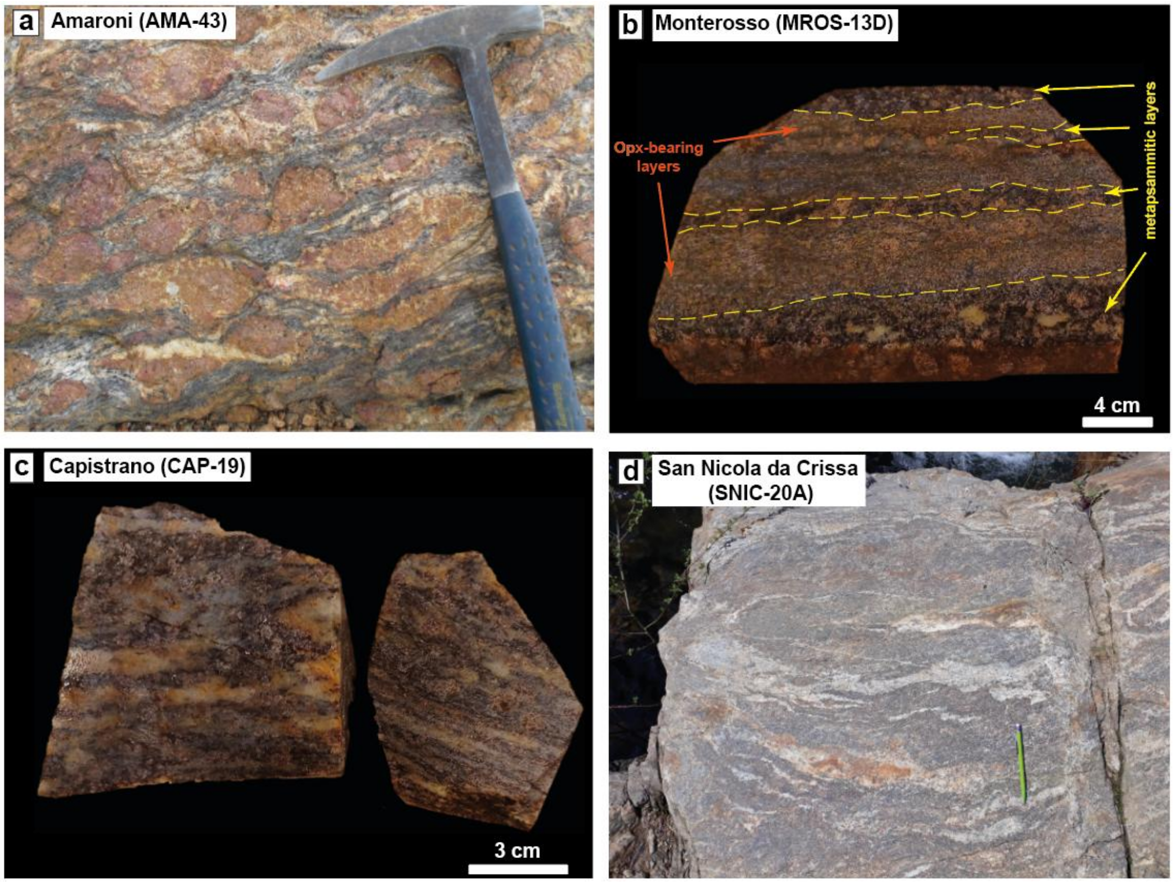

Figure S-5 Outcrop and macroscopic views of representative samples selected from the Metapelite Unit. **(a)** Outcrop of AMA-43 migmatitic paragneiss with giant garnets showing a strong restitic character. **(b)** MROS-13D composite gneiss with alternating metapsammitic and orthopyroxene-bearing layers. **(c)** CAP-19 migmatitic paragneiss. **(d)** SNIC-20A migmatitic paragneiss.

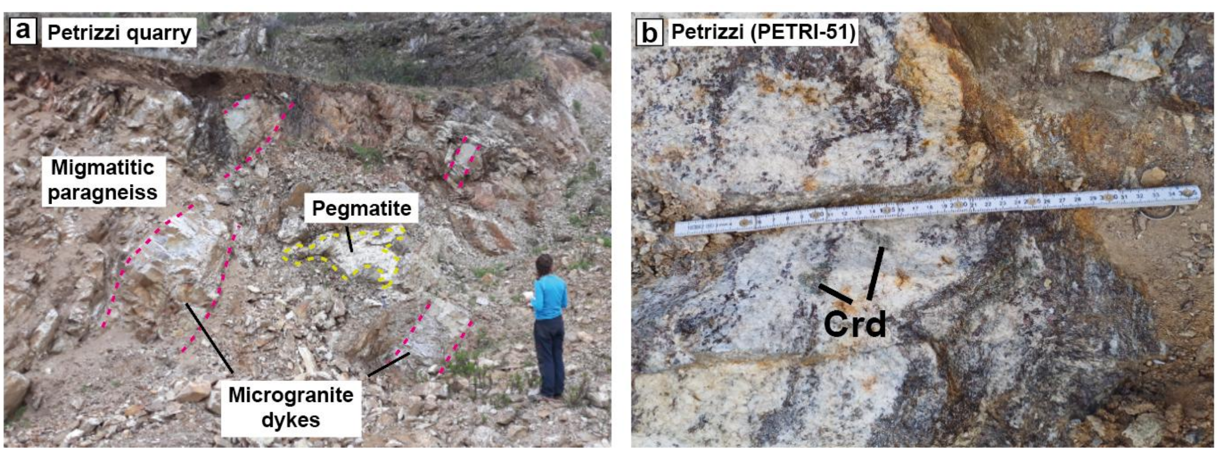

Figure S-6 **(a)** Exposure of the complex outcrops typical of the Migmatitic Border Zone in the Petrizzi quarry, showing migmatitic paragneisses cross-cut by late pegmatite and microgranite dykes. **(b)** Macroscopic view of PETRI-51 migmatitic paragneiss displaying large cordierite crystals.

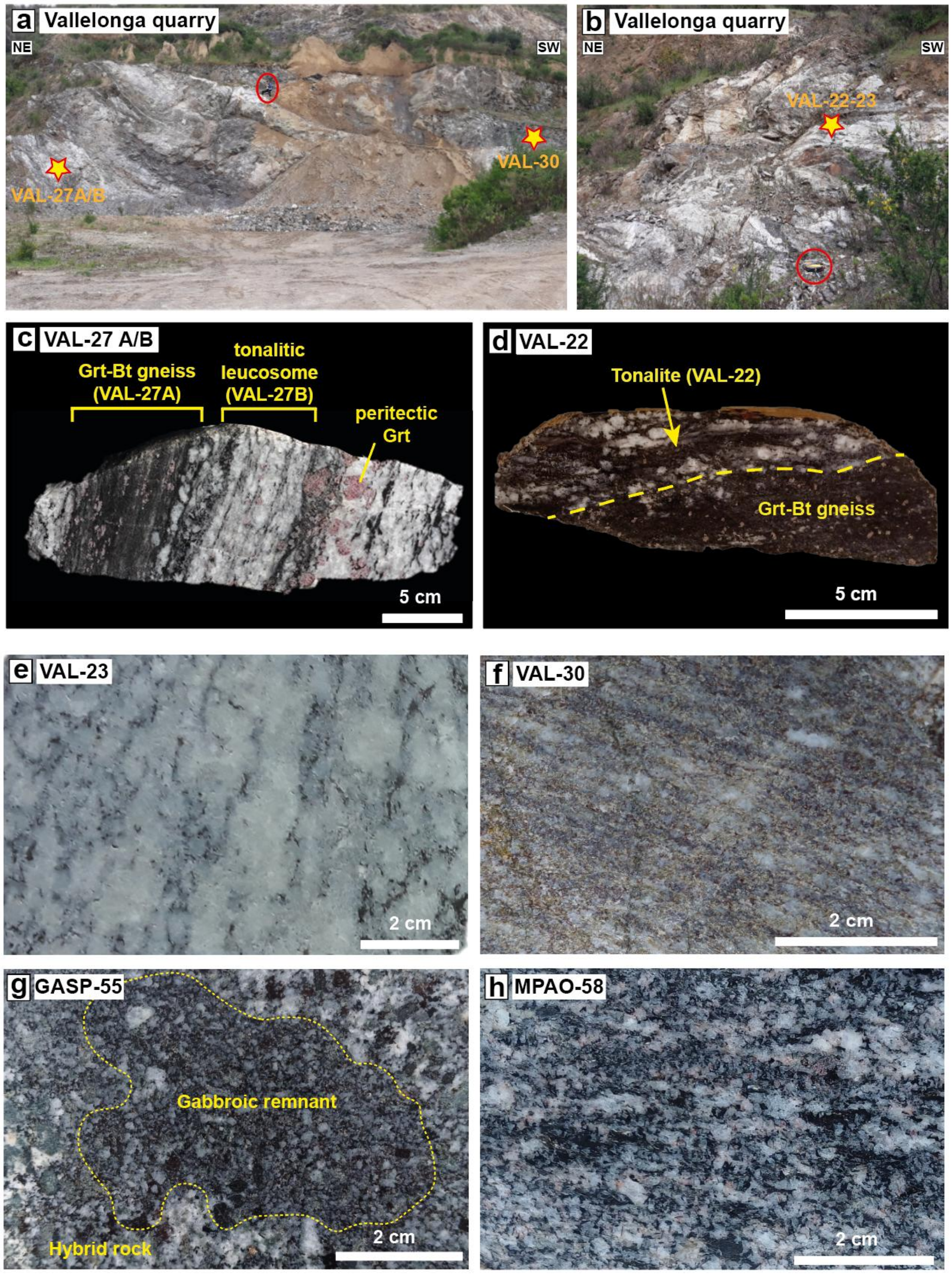

Figure S-7 **(a-b)** Exposure of the complex outcrops typical of the Migmatitic Border Zone in the Vallelonga quarry, showing an anatectic garnet-biotite gneiss interspersed by various igneous rocks including tonalite, monzogranite, and two-mica granite. The circled person in **(a)** and the circled bag in **(b)** give the scale. **(c)** Macroscopic view of VAL-27 diatexite consisting of garnet-biotite gneiss mesosomes (VAL-27A) and tonalitic leucosomes (VAL-27B). **(d)** Foliated amphibole-garnet tonalite (VAL-22) in contact with the garnet-biotite gneiss. **(e)** Sheared monzogranitic intrusion of the Vallelonga quarry (VAL-23). **(f)** Strongly foliated orthopyroxene-cummingtonite mafic rock (VAL-30). **(g)** Hybrid amphibole-bearing mafic rock in Gasperina showing remnants of the original gabbro (GASP-55). **(h)** Foliated garnet-bearing tonalite (MPAO-58).

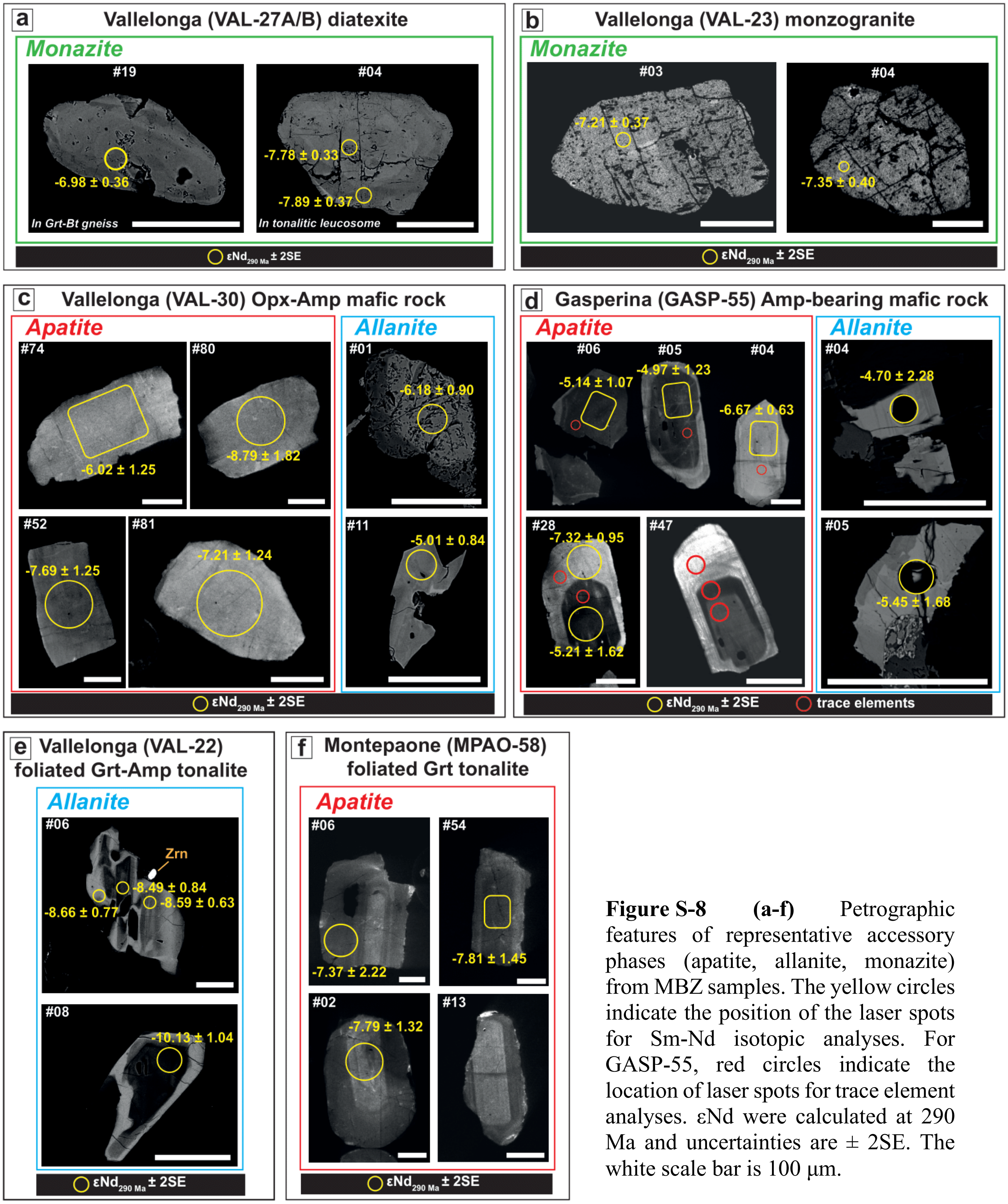

Figure S-8 **(a-f)** Petrographic features of representative accessory phases (apatite, allanite, monazite) from MBZ samples. The yellow circles indicate the position of the laser spots for Sm-Nd isotopic analyses. For GASP-55, red circles indicate the location of laser spots for trace element analyses. εNd were calculated at 290 Ma and uncertainties are ± 2SE. The white scale bar is 100 µm.

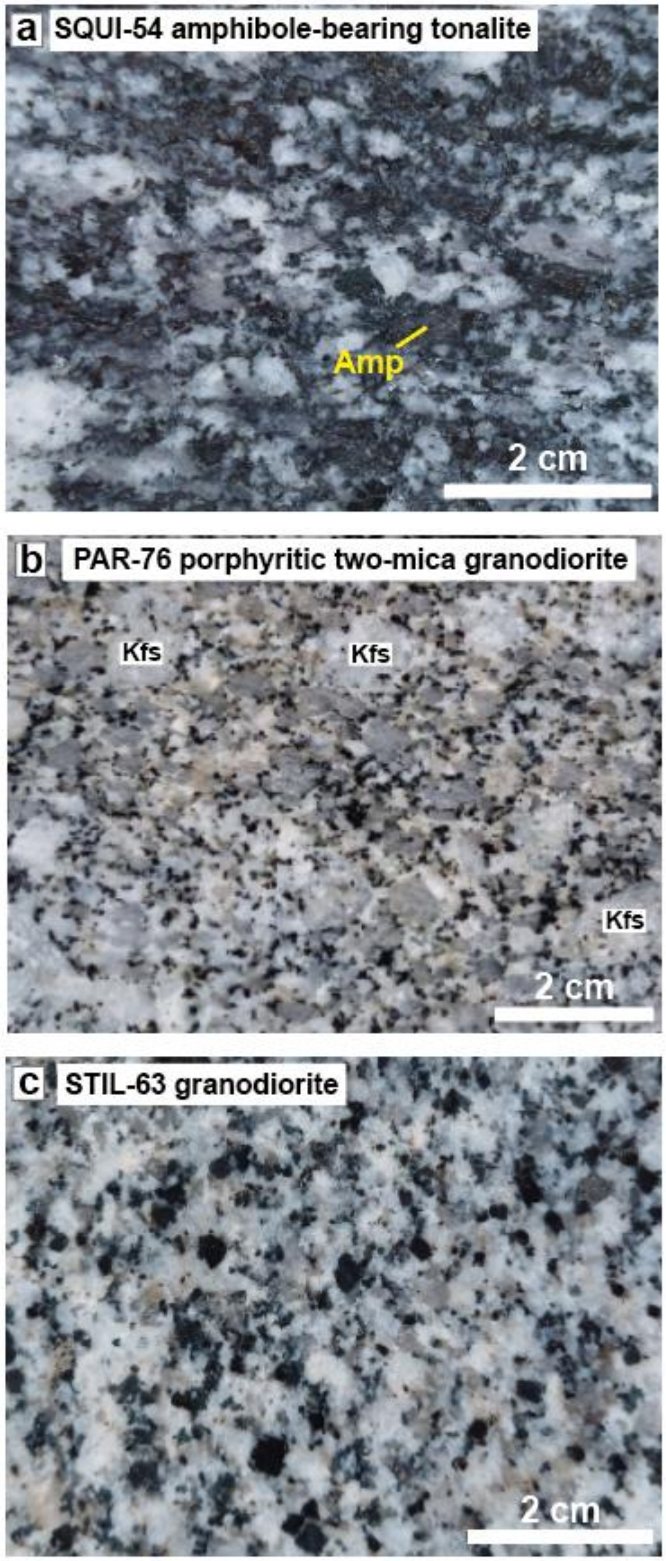

Figure S-9 Mesoscopic appearance of the middle crust granitoids: **(a)** foliated amphibole-bearing tonalite (SQUI-54); **(b)** two-mica granodiorite exhibiting a porphyritic texture with K-feldspar megacrysts (PAR-76) and **(c)** biotite granodiorite (STIL-63).

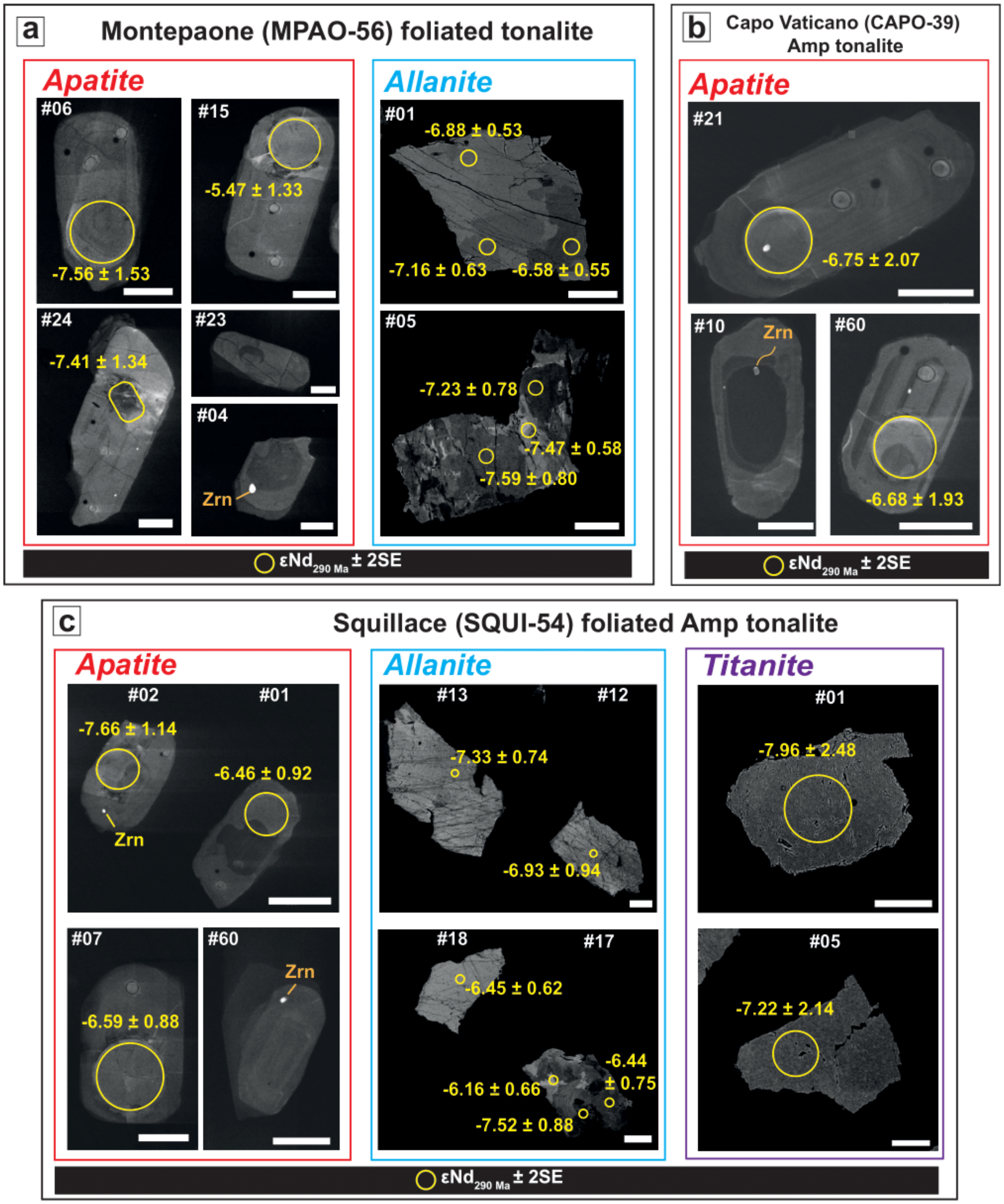

Figure S-10 **(a-c)** Petrographic features of representative accessory phases (apatite, allanite, and titanite) from the selected samples of the tonalite unit. The yellow circles indicate the position of the laser spots for Sm-Nd isotopic analyses. εNd were calculated at 290 Ma and uncertainties are ± 2SE. The white scale bar is 100 µm.

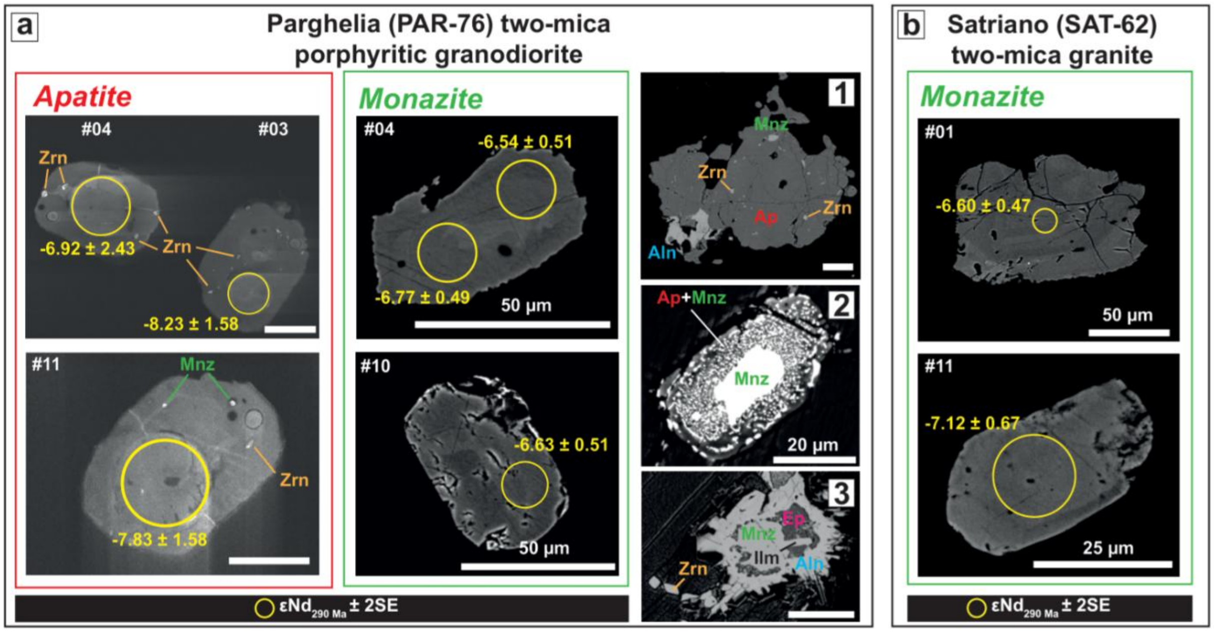

Figure S-11 **(a-b)** Petrographic features of representative accessory phases (apatite and monazite) from the selected samples of the two-mica granite/granodiorite unit. **(a1-3)** Details on the relationships between accessory minerals in PAR-76 two-mica porphyritic granodiorite. The yellow circles indicate the position of the laser spots for Sm-Nd isotopic analyses. εNd were calculated at 290 Ma and uncertainties are ± 2SE. The white scale bar, unless otherwise stated, is 100 µm.

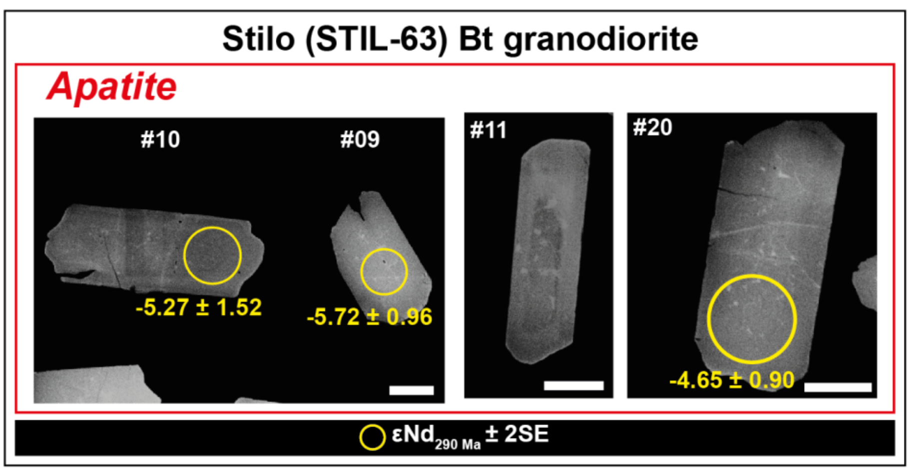

Figure S-12 CL images of apatite from STIL-63 biotite granodiorite. The yellow circles indicate the position of the laser spots for Sm-Nd isotopic analyses. εNd were calculated at 290 Ma and uncertainties are ± 2SE. The white scale bar is 100 µm.

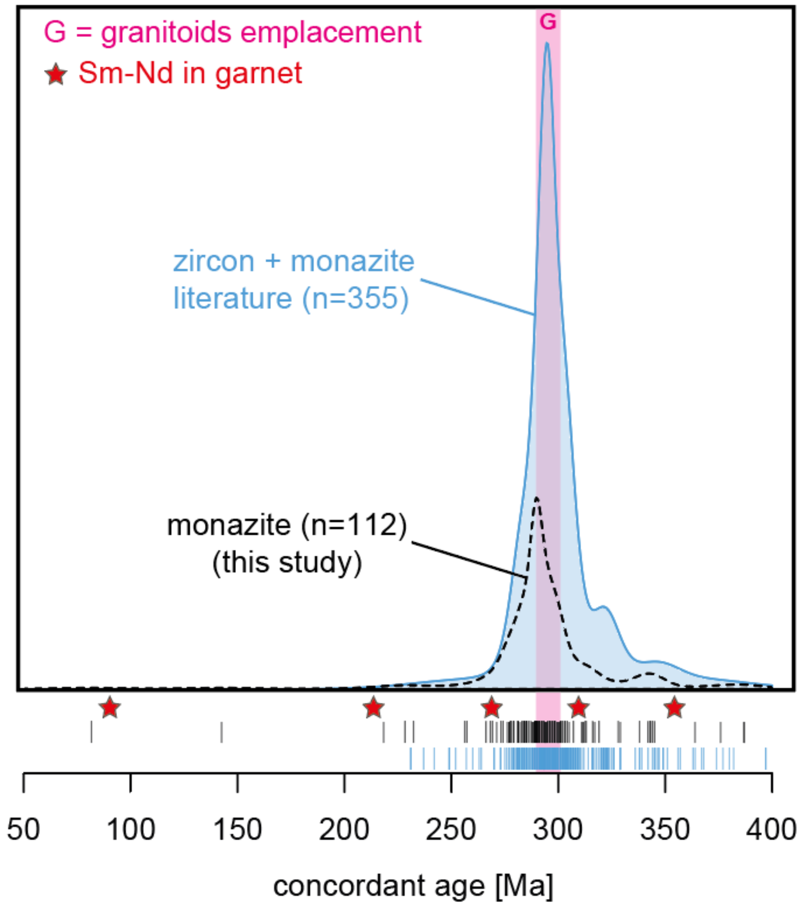

Figure S-13 Kernel Density Estimation (KDE) diagram of concordant monazite U–Pb dates from lower-crustal and mid-crustal igneous samples of the Serre Massif–Capo Vaticano area (black dotted curve; Biget, 2024), compared with concordant zircon and monazite U-Pb dates from granitoids and migmatites reported in the literature (blue curve; Schenk, 1980; Graessner *et al.*, 2000; Micheletti *et al.*, 2008; Fornelli *et al.*, 2011; Langone *et al.*, 2014; Fiannacca *et al.*, 2017). Garnet Sm-Nd dates are also shown (red stars; Duchene *et al.*, 2013) as well as the timing of mid-crustal granitoid emplacement (*e.g.*, Langone *et al.*, 2014; Fiannacca *et al.*, 2017).

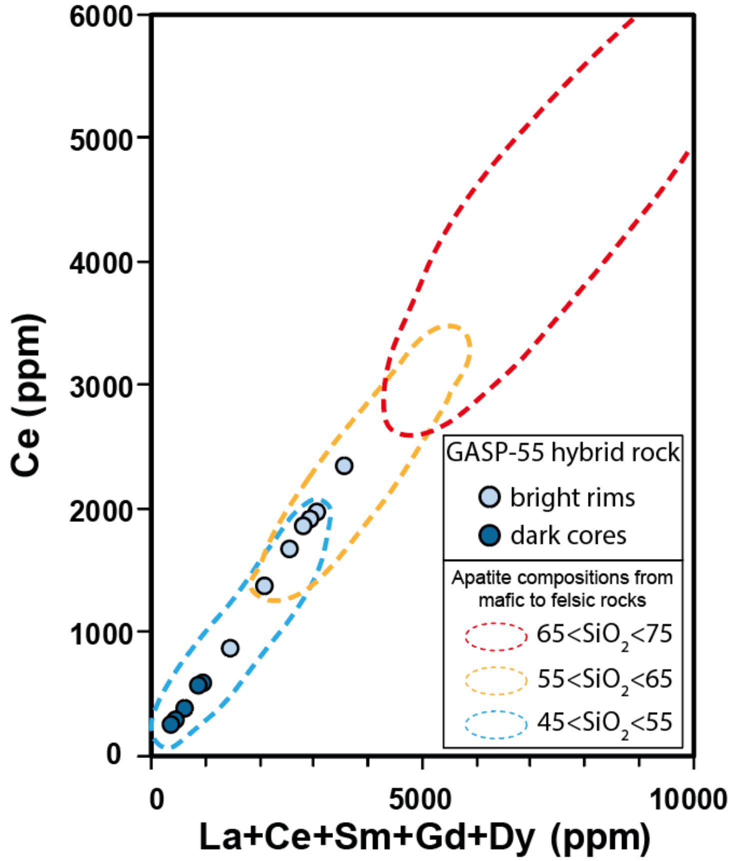

Figure S-14 GASP-55 apatite plotted in the diagram of Xu *et al.* (2024) allowing a comparison with apatite crystallised from mafic to felsic rocks (SiO_2 contents ranging from 45 to 75 wt.%).

4. Supplementary Tables

Table S-1 Summary of the rock-forming minerals and accessory phases for the lower crust samples.

	Unit	Granulite Unit					
	Sample	CUR-07	CUR-01A	CUR-03	ZAP-11	CUR-05A	CUR-02
	Locality	Acconia quarry (Curinga)	Turrino quarry (Curinga)	Turrino quarry (Curinga)	Zappaterra	Acconia quarry (Curinga)	Turrino quarry (Curinga)
	Latitude (°N)	38.8439	38.8218	38.8215	38.7688	38.8439	38.822
	Longitude (°E)	16.2858	16.2955	16.2967	16.333	16.2858	16.2954
	Rock type	Amp (meta)gabbro	Mafic granulite	Mafic granulite	Mafic granulite	Felsic granulite	Felsic granulite
Rock-forming minerals	**Qz**			(X)	(X)	(X)	X
	Pl	X	X	X	X	X	X
	Kfs			X	(X)	X	X
	Bt		X	X	X	X	X
	Grt					X	X
	Sil						
	Crd						
	Hbl	X	X		X		
	Px	Cpx	Cpx	Opx (+Cpx)	Opx+Cpx		
	other					Chl, Ep	
Accessories	**Ap**	X	X	X	X	(X)	X
	Mnz			(X)		X	X
	Zrn	X	X	X	X	X	X
	Aln			X	(X)	(X)	
	Xtm			(X)			
	Ilm	X	X	(X)	X		X
	Rt					X	X
	Ox	X	X		X	X	
	Sulf	X	X	X	X	(X)	X

Table S-1 Continued.

	Unit	Metapelite Unit						Migmatitic Border Zone
	Sample	AMA-43	MROS-13A	MROS-13D	MROS-16	CAP-19	SNIC-20A	PETRI-51
	Locality	Amaroni	Monterosso Calabro	Monterosso Calabro	Monterosso Calabro	Capistrano	San Nicola da Crissa	Petrizzi
	Latitude (°N)	38.7787	38.7250	38.7250	38.7094	38.6869	38.6665	38.7025
	Longitude (°E)	16.4280	16.2987	16.2987	16.2903	16.2951	16.2928	16.4455
	Rock type	migmatitic paragneiss (highly restitic)	migmatitic paragneiss (metapsammite)	Composite gneiss with Opx layers	migmatitic paragneiss	migmatitic paragneiss	migmatitic paragneiss	migmatitic paragneiss
Rock-forming minerals	**Qz**	X	X	X	X	X	X	X
	Pl	X	X	X	X	X	X	X
	Kfs	X			X	X		
	Bt	X	X	X	X	X	X	X
	Grt	X	X	X	X	X	X	X
	Sil	X			X	X	X	X
	Crd					X	(X)	X
	Hbl							
	Px			Opx				
	Others							Cb, And
Accessories	**Ap**			X		(X)	X	X
	Mnz	X	X	X	X	X	X	X
	Zrn	X	X	X	X	X	X	X
	Aln							
	Xtm						(X)	(X)
	Ilm	X	X	X	X	X	X	X
	Rt	X	X	(X)	X	X	(X)	(X)
	Ox	X			X	X	X	X
	Sulf		X	X		X	X	X

Table S-2 Mineralogical content summary (rock-forming and accessory minerals) for the studied igneous sample, ordered according to their approximate structural position within the crustal section. For rock-forming minerals, the number in brackets is the modal proportion (in %) of each phase estimated with images processed on Aztec and ImageJ softwares (Schneider *et al.*, 2012). The two samples highlighted in yellow come from the CVP area. Mineral abbreviations are from Whitney and Evans (2010).

Samples name	Locality	Unit	Coordinates	Type	Rock-forming minerals	Accessory minerals
VAL-22	Vallelonga	MBZ	38.6543 °N 16.2789 °E	Foliated Grt-Amp tonalite	Bt (37), Pl (31), Qz (17), Grt (4), Hbl (2), Cum(1)	Ilm, Ap, Zrn, Aln, Mnz
VAL-23	Vallelonga		38.6543 °N 16.2789 °E	Sheared monzogranite	Kfs (37), Qz (34), Pl (25), Bt (4), Ms (<1%)	Ilm, Mnz, Zrn, Ap
VAL-27A	Vallelonga		38.6543 °N 16.2789 °E	Diatexite: Grt-Bt gneiss mesosome	Pl (41), Qz (29), Bt (28), Grt (2)	Ilm, Mnz, Zrn, (Xtm)
VAL-27B	Vallelonga		38.6543 °N 16.2789 °E	Diatexite: Tonalitic leucosome	Pl (57), Qz (21), Bt (20), Grt(2)	Ilm, Mnz, Zrn
VAL-30	Vallelonga		38.6543 °N 16.2789 °E	Foliated Opx-Cum mafic rock	Pl (57), Cum (19), Bt (14), Opx (8), Qz (2)	Ilm, Ap, Aln, Zrn
GASP-55	Gasperina		38.7447 °N 16.5082 °E	Hbl-Cum mafic rock	Pl (53), Hbl (21), Cum (19), Bt (5), Qz (2)	Ilm, Ap, Zrn, Aln
MPAO-58	Montepaone		38.7260 °N 16.4794 °E	Foliated Grt-bearing tonalite	Pl (50), Qz (26), Bt (22), Grt (2), Chl (<1%)	Ilm, Ap, Zrn
MPAO-56	Montepaone	Middle crust granitoids	38.7228 °N 16.4902 °E	Foliated tonalite	Pl (59), Qz (23), Bt (18), Ep (<1%)	Ilm, Ap, Zrn, Aln, (Ttn)
SQUI-54	Squillace		38.7643 °N 16.5166 °E	Foliated Amp tonalite	Pl (48), Bt (23), Qz (23), Hbl (5)	Ilm, Ap, Zrn, Ttn, Aln
CAPO-39	Capo Vaticano		38.6222 °N 15.8280 °E	Amp tonalite	Pl (47), Qz (34), Bt (11), Kfs (5), Amp (1), Chl (1), Ep (<1%)	Ttn, Ap, Zrn
PAR-76	Parghelia		38.6855 °N 15.9210 °E	Ms-Bt porphyritic granodiorite	Pl (32), Qz (30), Kfs (25), Bt (8), Ms (5)	Zrn, Ilm, Ap, Mnz, Aln, Ttn
SAT-62	Satriano		38.6616 °N 16.5019 °E	Ms-Bt granite	Pl (39), Qz (32), Kfs (20), Ms (7), Bt (2)	Ap, Ilm, Zrn, Aln, Mnz, (Ttn, Xtm)
STIL-63	Stilo		38.4682 °N 16.4090 °E	Bt granodiorite	Pl (46), Qz (31), Bt (11), Kfs (11), Chl (1), Ep (<1%)	Ap, Ttn, Zrn, Ilm, (Aln)

Table S-3 Whole rock Sm-Nd isotopic compositions.

Table S-4 Nd isotopic composition of unknown apatite, allanite, monazite and titanite.

Table S-5 Durango apatite, Connecticut allanite, STK monazite and MKED1 titanite values used for further normalisation on unknowns and to correct from instrumental drift (primary standard).

Table S-6 Tory Hill apatite, Gale allanite and Khan titanite values (secondary standard).

Table S-7 EPMA analytical results for Durango apatite standard.

Table S-8 EPMA and LA-ICP-MS analytical results for GASP-55 apatite.

Table S-9 LA-ICP-MS analytical results for international reference materials (NIST-612, Durango).

Tables S-3 to S-9 *are available for download as a single file (.xlsx) from the online version of this article at https://doi.org/10.7185/geochemlet.2602.* .

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