Geochemical Perspectives Letters EAG

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

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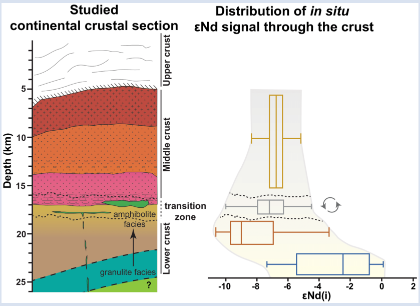
OPEN ACCESS
https://doi.org/10.7185/geochemlet.2602

Abstract



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.

Received 26 June 2025 | Accepted 2 December 2025 | Published 22 January 2026

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

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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

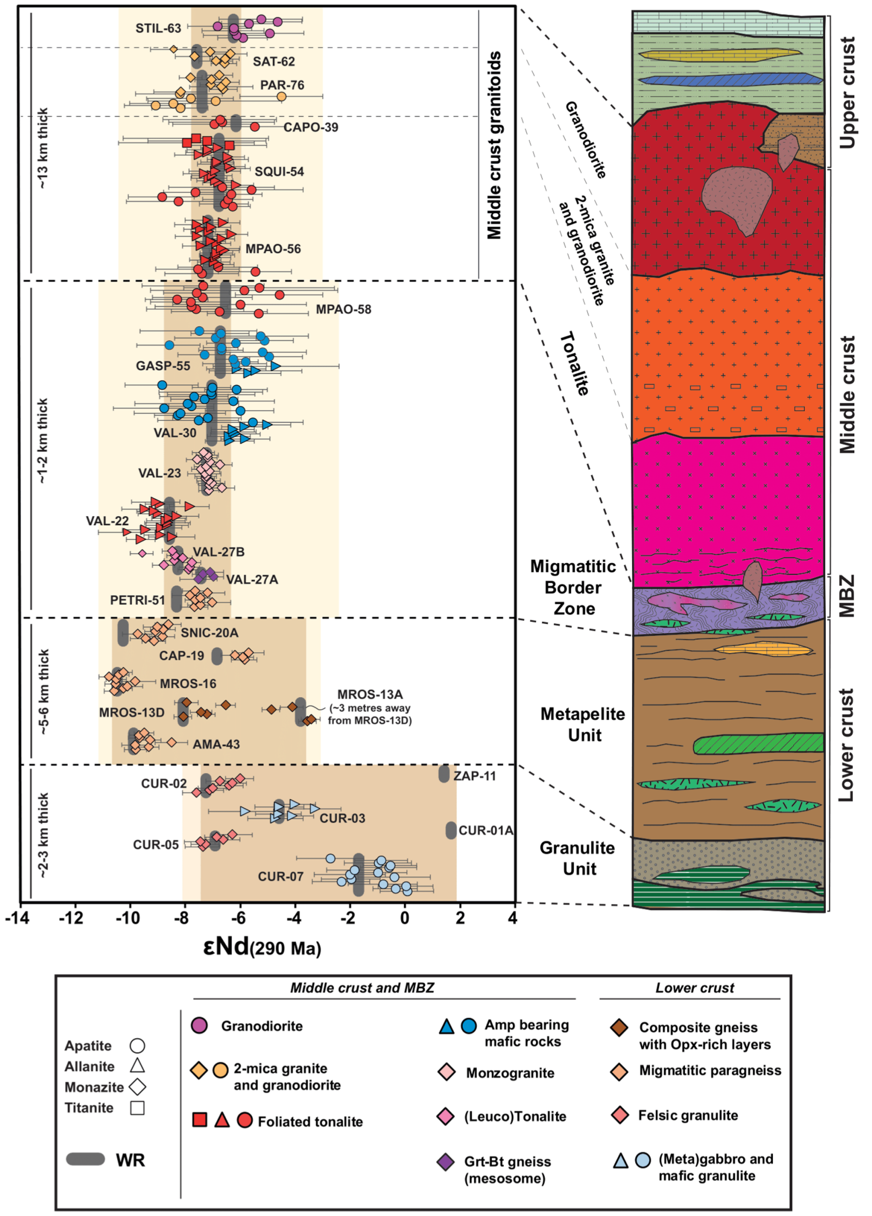

Figure 1 Compilation of whole rock and *in situ* Nd isotopic compositions ($\varepsilon Nd_{290\ Ma}$) for apatite, monazite, allanite, and titanite from the studied lower and mid-crustal samples, ordered by increasing $^{147}Sm/^{144}Nd$ for each mineral. Error bars are ± 2 s.e. Light-brown and light-yellow 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

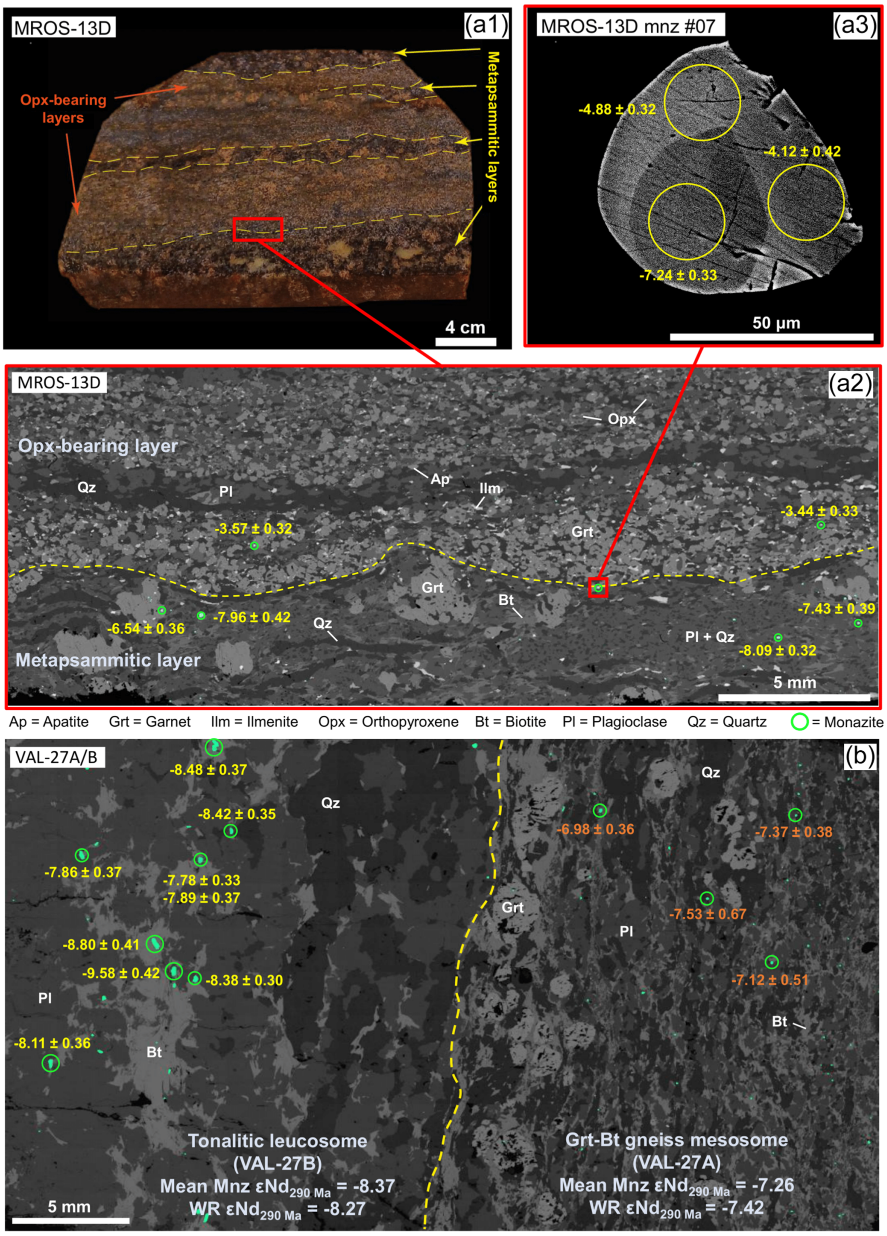

Figure 2 Illustration of the multiscale Nd isotopic heterogeneities of monazite from MROS-13D composite migmatite. **(a1)** Hand specimen, **(a2)** thin section (backscattered electron (BSE) image) and **(a3)** mineral (monazite). **(b)** Thin section scale isotopic variability of monazite between leucosome 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.

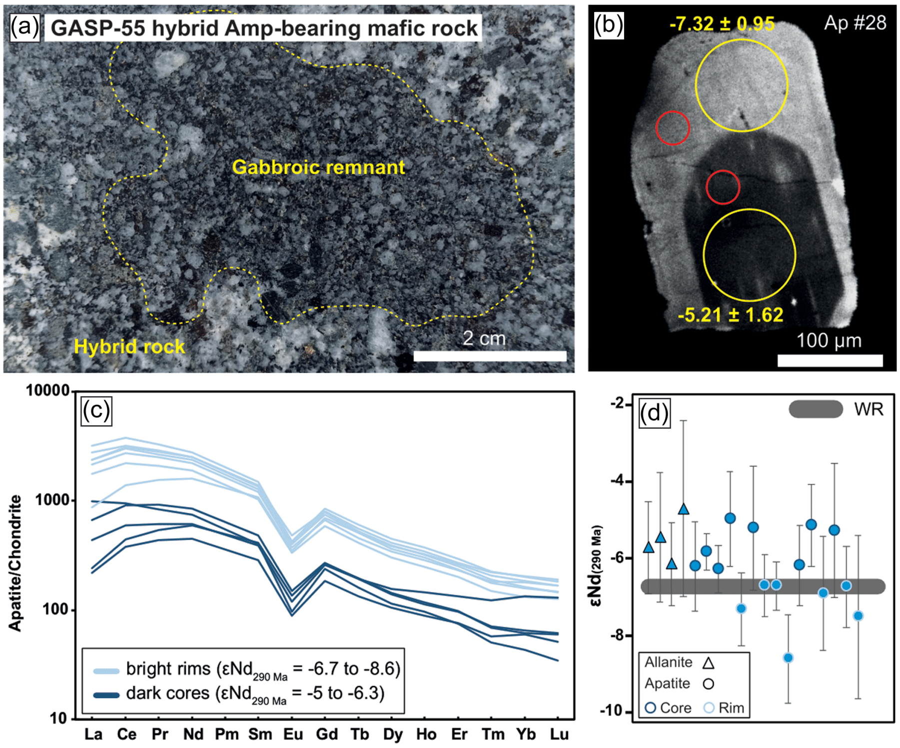

Figure 3 **(a)** Macroscopic view of GASP-55 hybrid mafic rock. **(b)** Representative CL image of apatite showing core–rim zoning with trace element (red circles) and Sm-Nd isotope (yellow circles) analytical spots with ±2 s.e. uncertainties. **(c)** Chondrite normalised (McDonough and Sun, 1995) REE 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.

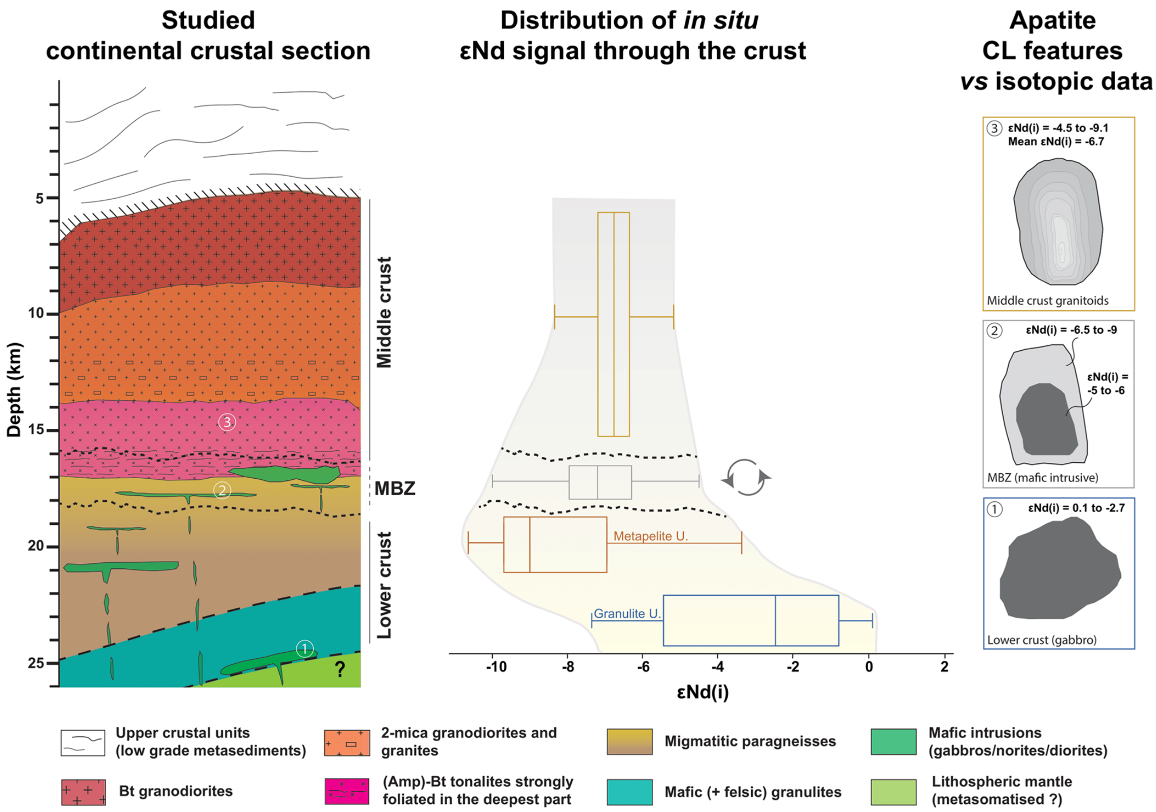

Figure 4 Sm-Nd isotopic scan of the Serre Massif–Capo Vaticano crustal section, illustrated with box plots for the Granulite Unit, Metapelite Unit, MBZ, and middle crust granitoid *in situ* data sets (SI). Box plots display minimum, maximum, median, and 25th–75th percentiles, highlighting isotopic homogenisation 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.

Acknowledgements

This work was supported by the French National Research Agency (grant ANR-21-CE49-0001-01, AMNESIA, PI Emilie Bruand). Two anonymous reviewers and the editor R. Tartèse are thanked for their very constructive and helpful comments.

Editor: Romain Tartèse

Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2602.

Cite this letter as: Biget, T., Bruand, E., Langone, A., Boyet, M., Caggianelli, A., Bonnand, P. (2026) Tracing anatexis and bottom-up crustal homogenisation with *in situ* Sm-Nd isotopes. *Geochem. Persp. Let.* 38, 46–52. https://doi.org/10.7185/geochemlet.2602

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