Architecture and construction mechanisms of post-collisional granitoid complexes: an integrated field, microstructural, AMS and EBSD study of the late Variscan Serre Batholith (southern Calabria)

Damiano Russo
Department of Biological, Geological and Environmental Sciences, University of Catania, Corso Italia 57, 95129, Catania
DOI: 10.19276/plinius.2024.01.008

INTRODUCTION

This work aims to better understand the architecture and construction mechanisms of granitoid batholiths in post-collisional settings, also investigating the relationships between regional tectonics, magma emplacement, and structural evolution of the granitoid bodies from supra- to low-temperature subsolidus conditions.

In this respect, the late Variscan Serre Batholith in southern Italy is an ideal case study because, despite its limited extension (c. 1200 km^2), it is a ca. 13 km-thick composite and zoned batholith, which is exposed with continuity from floor to roof (Fig. 1a, b). Basal tonalites and quartz diorites, emplaced at ca. 20-23 km, pass sequentially upward to porphyritic two-mica granodiorites and granites, equigranular two-mica granodiorites and granites, biotite granodiorites and, finally, shallow fine-grained two-mica granodiorites and granites. As an added value, the Serre Batholith represents the intermediate portion of a nearly complete cross-section of late Variscan continental crust, continuously exposed from deep crustal metagabbros, equilibrated at c. 35 km depth, to upper crustal phyllites. The entire cross-section is exposed in the Serre Massif, but a significant portion of it, comprising the bottom magmatic units of the batholith and their underlying migmatitic host rocks, also crops out in the Capo Vaticano Promontory on the Calabrian Tyrrhenian coast (Cirrincione et al., 2015, and references therein).

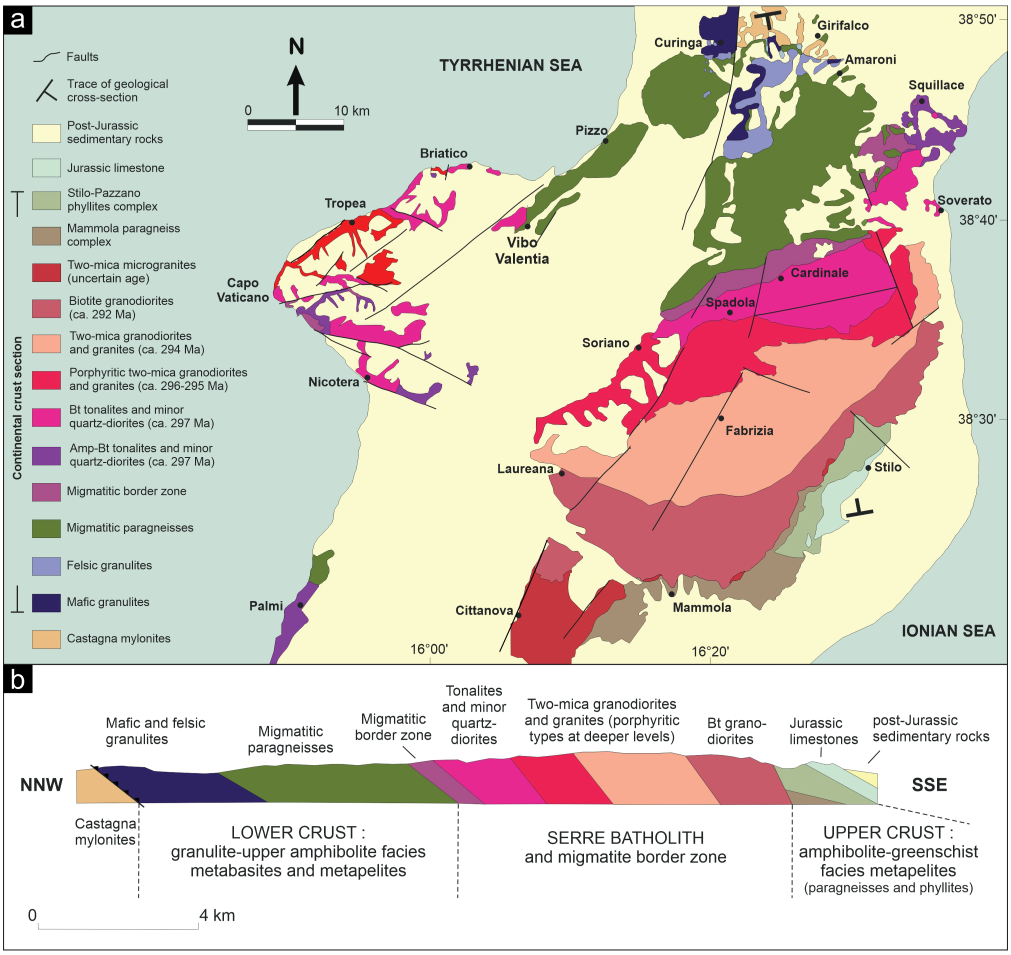

Figure 1 a) *Geological overview map of the Serre Massif and Capo Vaticano Promontory (modified after Fiannacca et al., 2015; Ortolano et al., 2022; Russo et al., 2023). Granitoids ages after Fiannacca et al., 2017 and references therein.* ***b)*** *Simplified lithological cross-section of the Serre Massif (modified after Fiannacca et al., 2015).*

Previous studies on the Serre Batholith have suggested that strongly foliated deep-seated tonalites and quartz diorites emplaced earlier at deep structural levels, whereas weakly foliated to undeformed tonalites, granodiorites, and granites would have emplaced later into higher crustal domains (Rottura et al., 1990; Caggianelli et al., 1997; 2000). In addition, geochronological investigations have helped to define a general over-accretion model for the construction of the Serre Batholith, with younger granitoids being emplaced at progressively shallower depths (Langone et al., 2014; Fiannacca et al., 2017).

Nevertheless, solid constraints for elaborating a detailed model of the architecture and build-up mechanisms of the batholith are still missing. In particular, no structural-geological study aimed at investigating in depth the relationships between all the main magmatic units making up the batholith, as well as the specific field and microstructural features of each single unit, has been attempted so far.

In this framework, field investigations and mapping activities represented the starting point of this research. They helped to define in detail the geological and structural features of the different magmatic units and clarify the relationships between them and the metamorphic basement. From this solid field base, further in-depth multidisciplinary studies have been performed.

More in detail, to investigate the link between magmatism and regional tectonics, thin-section analysis was focused on the deformation microstructures developed in Serre granitoids, outlining the deformation history associated with the construction and cooling of the batholith. Moreover, since most of the studied granitoids have not developed evident planar or linear fabrics, the AMS (Anisotropy of Magnetic Susceptibility) technique was employed, allowing the detection of an internal magnetic fabric also in the apparently isotropic granitoids. The obtained three-axis ellipsoid of magnetic susceptibility provided valuable information on the intensity and orientation of the deformation experienced by both the foliated and unfoliated rocks.

In particular, after a preliminary AMS study carried out

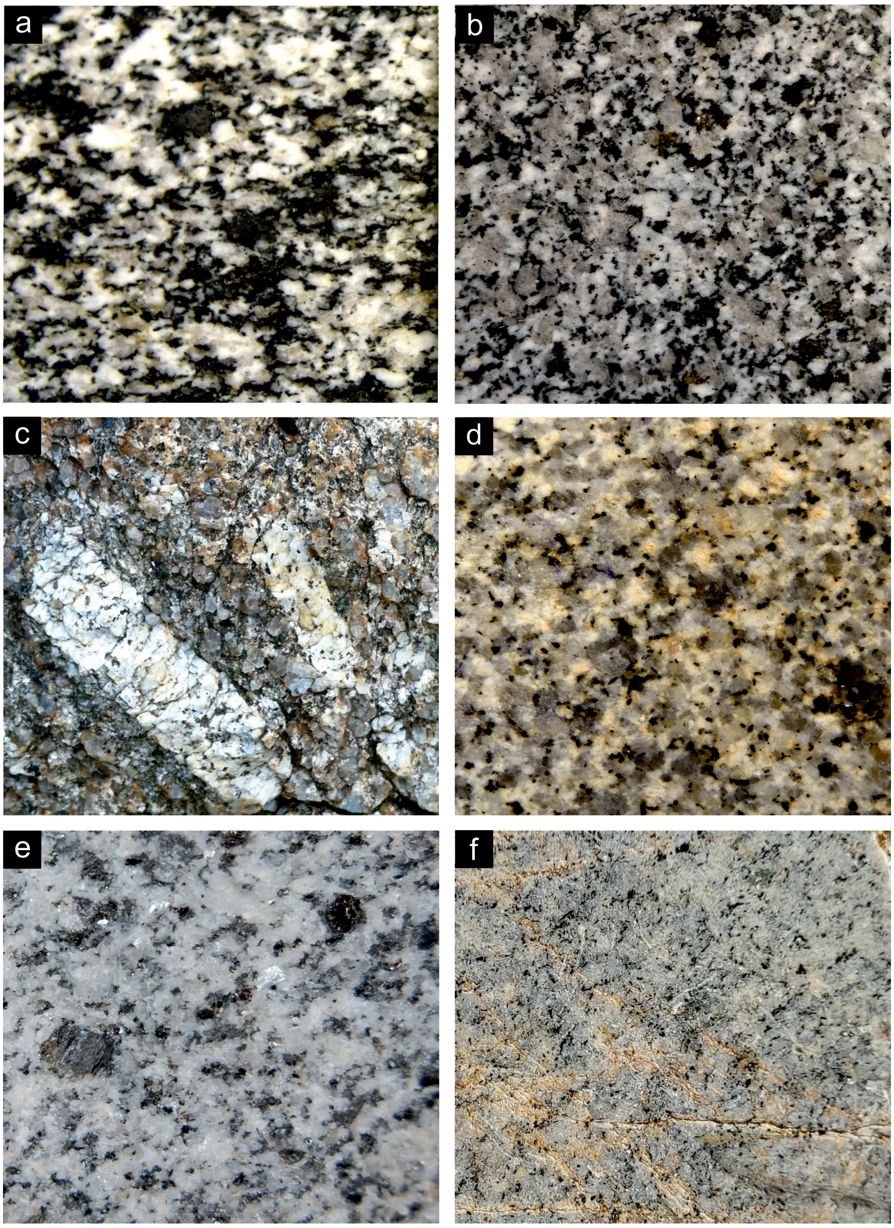

Figure 2 Mesoscopic comparison of floor (a) to roof (f) granitoids from the Serre Batholith. ***a)*** *Moderately foliated ABT.* ***b)*** *Weakly foliated BT.* ***c)*** *Slightly oriented K-feldspar megacrysts in PMBG.* ***d)*** *Unfoliated MBG.* ***e)*** *Weakly foliated BG.* ***f)*** *Moderately foliated MBM. The long side measures 6 cm in all photos.*

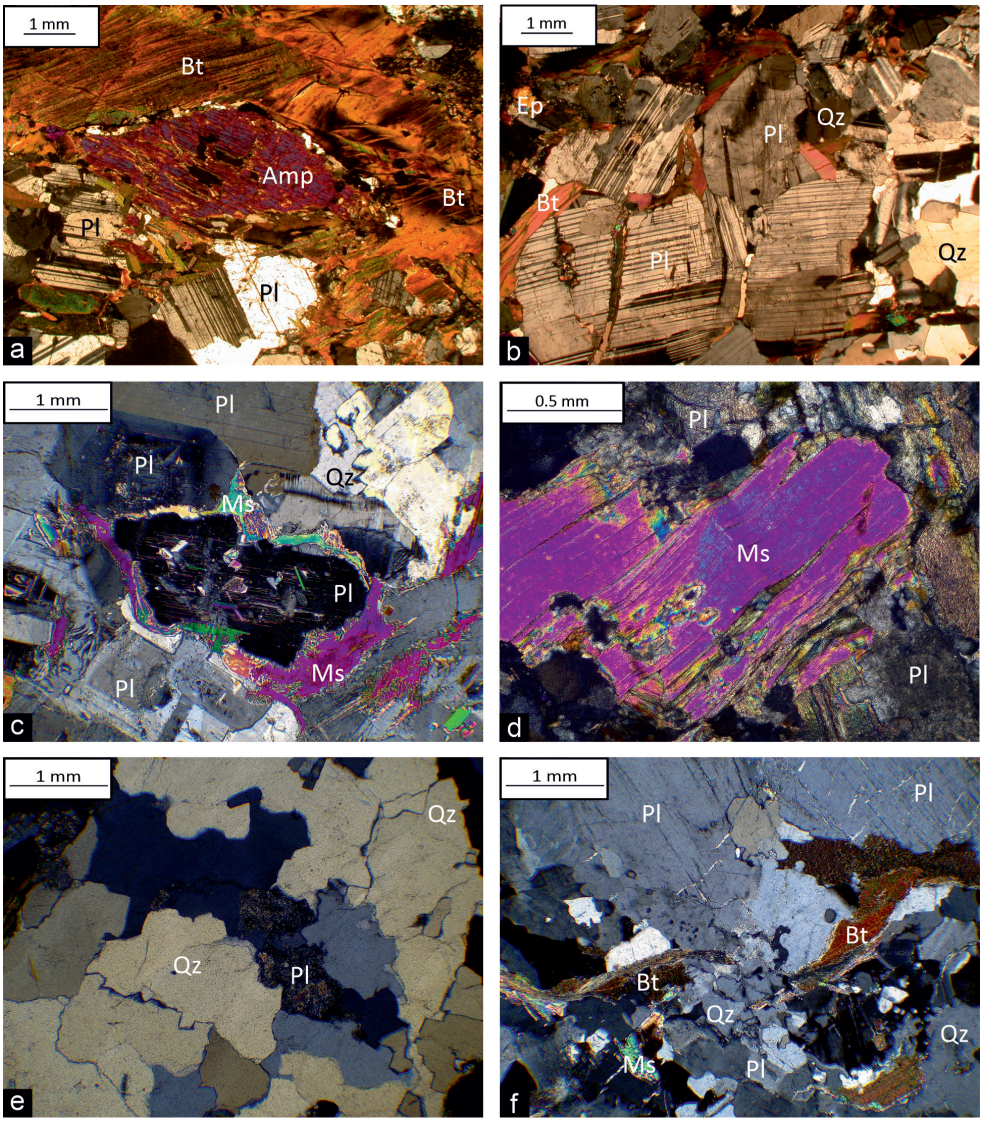

Figure 3 *Deformation microstructures from submagmatic to solid-state regime in the granitoids from the Serre Batholith.* ***a)*** *Sigmoid amphibole, mantled by deformed biotite platelets and recovered quartz ribbons, suggests deformation at T > 650°C in ABT rocks.* ***b)*** *Several submagmatic microfractures, filled by subhedral biotite and epidote grains, in a large plagioclase crystal from BT rocks.* ***c)*** *Plagioclase bordered by asymmetrically anastomosing muscovite folia consistent with sub-simple shear deformation experienced by PMBG rocks. Myrmekites are also visible.* ***d)*** *Kinked muscovite in MBG rocks partly broken in smaller individuals with fish-like appearances.* ***e)*** *Well-displayed evidence of dominant GBM recrystallisation in a quartz domain from BG rocks.* ***f)*** *Well-developed oriented fabric marked by isoriented mica fishes in a strongly recrystallised micro-domain from MBM rocks. Large plagioclase crystals at the top exhibit muscovite-filled fractures oriented parallel to the mica fishes and subgrains testifying SGR recrystallisation in the crystal to the left.*

by Fiannacca et al. (2021) on two magmatic units from the intermediate-upper crustal level of the Serre Batholith, the AMS investigations were here performed for the first time on all six magmatic units that represent the different growth stages of the batholith, from the deepest and oldest tonalites/quartz diorites to the shallowest and youngest two-mica microgranitoids.

Finally, the EBSD (Electron BackScattered Diffraction) technique has been additionally employed on selected samples from all the studied magmatic units, obtaining the first quartz Crystallographic Preferred Orientation (CPO) data for the Serre Batholith, aimed to: a) infer the intracrystalline deformation mechanisms and related slip-systems activation temperatures; b) reveal the deformation regime, i.e. coaxial vs non-coaxial; c) obtain possible kinematic constraints.

FIELD OBSERVATIONS

A robust field mapping, supported by petrographic investigations, revealed the relationships between all the main magmatic units making up the batholith, never mapped in such detail before this work. Strongly to moderately foliated amphibole-biotite tonalites (ABT; Fig. 2a) and strongly to weakly foliated biotite tonalites (BT; Fig. 2b) represent the oldest and deepest granitoids. The BT have been further distinguished into strongly to moderately foliated (BTs) and weakly foliated to unfoliated (BTw), the latter typically occurring at the top levels of the BT unit. They transition upward to weakly foliated to unfoliated porphyritic muscovite-biotite granodiorites and granites (PMBG; Fig. 2c) by clear intrusive contacts, which are locally exposed. These observations refer to both the Serre Massif and Capo Vaticano Promontory sectors of the Serre Batholith. In particular, in the latter sector, where only the deep-intermediate portion of the batholith crops out, field activity and petrographic studies allowed to separate the promontory into a northern sector characterized by continuous exposure of the deep-intermediate granitoids and a southern sector with a more chaotic arrangement due to a stronger tectonic reworking.
The relationships between all the overlying magmatic units have been mapped and studied in the Serre Massif, where the whole cross section from floor to roof of the batholith is exposed.

The contact between PMBG and overlying unfoliated muscovite-biotite equigranular granodiorites and gran-

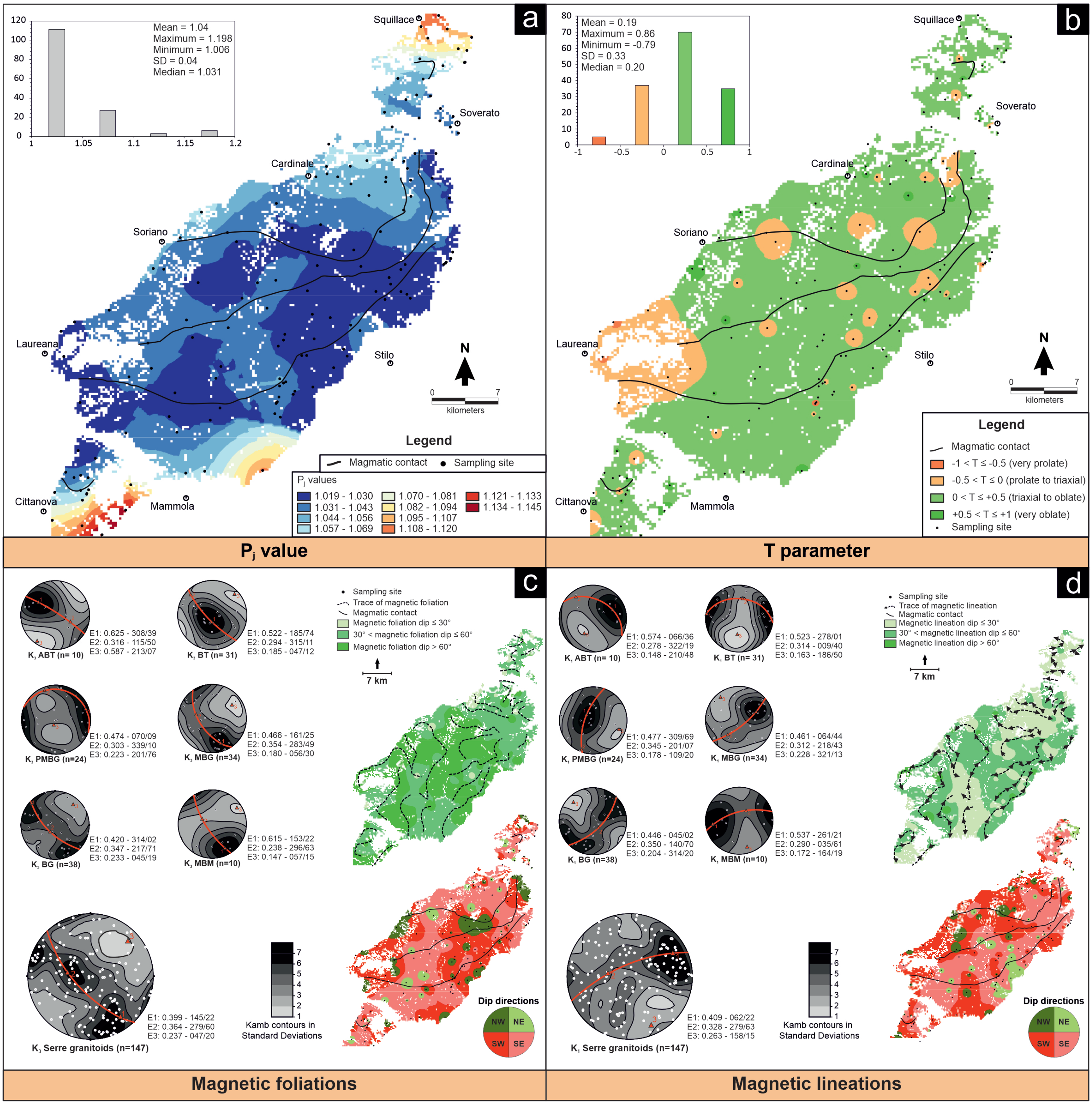

Figure 4 *Representative histograms and contoured maps of **a)** the magnetic anisotropy and **b)** shape factor for the study area. Kriging and IDW interpolation methods have been employed in **a)** and **b)** contoured maps, respectively. **c)** Magnetic foliations and **d)** lineations data displayed using lower hemisphere equal area projections for the single magmatic units and the whole study area (on the left) and IDW-based interpolation maps (on the right). On the top right, **c)** magnetic foliation and **d)** lineation dip map with mean trajectories; on the bottom right, **c)** magnetic foliation and **d)** lineation dip direction map.*

ites (MBG; Fig. 2d), as well as between the MBG and the overlying unfoliated to weakly foliated biotite granodiorites (BG; Fig. 2e), making up most of the batholith roof, is gradational, suggesting interaction of the newly emplaced granitoid magma with the largely solidified underlying unit. In addition, the BG unit is sharply intruded in its southwestern sector by fine-grained weakly to moderately foliated two-mica granodiorites and granites (MBM; Fig. 2f), which form the batholith roof in this sector.

DEFORMATION MICROSTRUCTURES

Microstructural investigations performed in all the CVP and Serre Massif magmatic units indicate deformation under active tectonic stress, with varying intensity recorded in the different units, from at least submagmatic conditions (Fig. 3a-f). However, a well-developed mineral preferred orientation in ABT-BTs and local weaker fabric in BTw-bottom PMBG, as well as in the BG and MBM from the southwestern sector of the Serre Massif, would indicate that the tectonic stress was already active at magmatic conditions. Suprasolidus deformation was followed by continuous subsolidus deformation at pro-

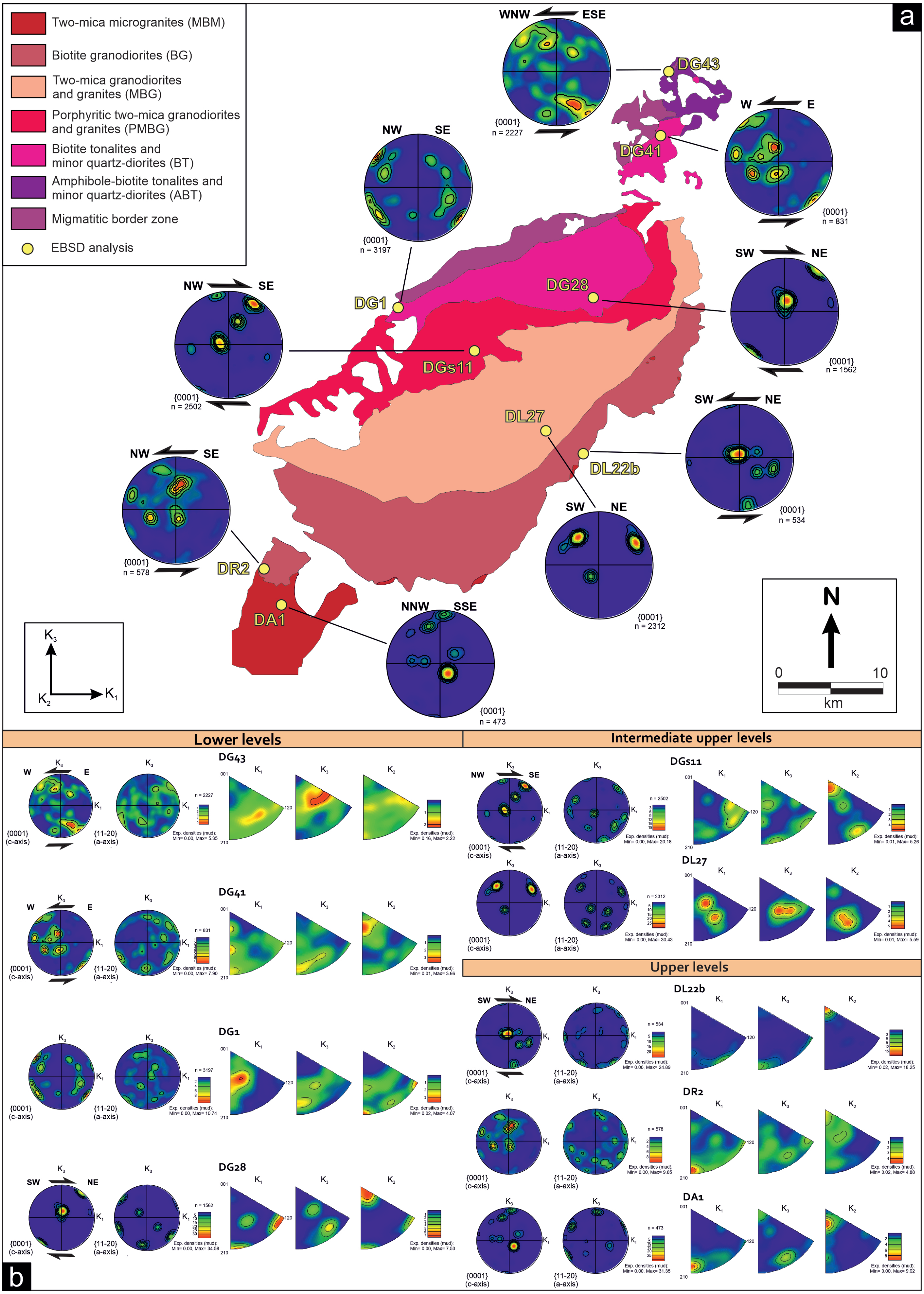

Figure 5 a) *Distribution and mean orientation of quartz CPO fabrics in the Serre Batholith. For each oriented sample, quartz CPO was determined in thin sections cut parallel to K1K3 (parallel to magnetic lineation and orthogonal to the magnetic foliation).* ***b)*** *Graphical representation of EBSD data from the studied oriented samples of the Serre Batholith. The pole figures are plotted in the lower hemisphere, equal area, one point per grain of {0001} i.e., c-axis, and {1120} i.e., a-axis of the quartz grains. N=number of quartz grains. The inverse pole figures are plotted in the upper hemisphere with a half width of 15° and a cluster size of 5° for each. Contour lines are multiples of uniform distribution (mud). EBSD analysis was carried out on thin sections parallel to the K1K3 plane of the AMS ellipsoid. The reference frame in all the diagrams is K1 (horizontal) and K3 vertical.*

gressively lower temperatures during cooling of all the sequentially emplaced magmatic units, indicating uninterrupted tectonic activity during the batholith's lifetime. Stages of tectonic quiescence are, nevertheless, documented by static recrystallization microstructures (i.e., foam texture in quartz aggregates) showing evidence of tectonic reactivation (i.e., GBM and BLG dynamic recrystallization, stretched foam aggregates). Finally, kinematic indicators, more common in the ABT-BTs and top MBM (Fig. 3a, f), suggest deformation under a sub-simple shear regime.

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

Since many granitoids did not develop meso- and microscopic fabrics, AMS investigations were essential to identify an internal fabric also in the apparently isotropic granitoids. Granitoids are dominantly paramagnetic, with main magnetic carriers represented by biotite and local amphibole. The magnetic anisotropy (P_j; Fig. 4a) increases in the deepest and shallowest units, suggesting possible magma emplacement along higher strain zones; lower P_j values in the intermediate-upper units are in accordance with a weaker tectonic activity during emplacement-to-cooling of these magmatic units. Similar low P_j values are nevertheless not rare in syn-tectonic granites. Prevailing oblate AMS ellipsoids are considered to reflect flattening of the emplacing plutons between the pre-existing underlying magmatic unit and overlying metamorphic host rocks, while minor prolate shapes, associated with sub-vertical lineations and foliations, might provide an indication of possible feeder zones (Fig. 4b). Magnetic foliations and lineations (Fig. 4c, d) reveal an extensional tectonic phase associated with emplacement of the oldest and deepest ABT unit and a dominant NW-SE compression direction for all the other units, consistent with tectonic stress mostly operating in a regional compressive regime during the construction of the batholith.

CRYSTALLOGRAPHIC PREFERRED ORIENTATION

Quartz CPO indicates deformation at medium to low temperatures, as suggested by dominant activation of basal <a>, rhomb <a> and prism <a> slip systems (Fig. 5a, b). The absence of the c-slip system is here considered the result of superimposed lower temperature deformation. CPO asymmetric patterns recorded in most of the studied granitoid samples provide solid evidence for sub-simple shear deformation. Contrasting senses of shear obtained for rocks from different, or even the same, magmatic units might reflect minor conjugate shear planes associated with major shear zones activated during cooling of the granitoids or, alternatively, the effect of superimposed post-Variscan deformation.

CONCLUDING REMARKS

This study, based on a multidisciplinary approach integrating field, microstructural, AMS and CPO data, allowed adding new significant constraints on the architecture of the late Variscan Serre Batholith and the link between batholith construction and activation of regional-scale shear zones. Dominant compression revealed by the AMS, coupled with the indication for shear-related deformation from kinematic indicators and CPO asymmetric patterns, is consistent with an active transpressional regime. Together with continuous supra- to subsolidus deformation of varying intensity, these results indicate syn-tectonic magma emplacement of the studied granitoids, along a progressively waning shear zone.

This work proposes a multistage model to illustrate the architecture and the build-up mechanisms of the Serre Batholith (Fig. 6).

In such model, the magmatic units emplaced sequentially by incremental over-accretion along a shear zone. In particular, in the first construction stage, deepest ABT magmas emplaced syn-tectonically in a transtensional tectonic regime. On the other hand, the emplacement of the overlying units occurred in a transpressional regime, which operated throughout the build-up history of the batholith, triggering the nucleation of a crustal-scale shear zone, here named Lower Mammola Shear Zone (LMSZ), which detached the bottom of the Mammola Paragneiss Complex from the lower crustal metapelitic host rocks of the batholith.

From the top of the lower crust, the LMSZ started its rise to higher crustal levels, accommodating the newly emplacing magmatic units that were progressively sandwiched between the previously emplaced underlying granitoids and the overlying Mammola paragneisses, which acted as the continuously uplifted lid of the batholith. The LMSZ concluded its upward journey through the Calabrian crust at shallow crustal levels, in direct contact with the BG and MBM, representing the final stages of the Serre Batholith construction.

REFERENCES

Caggianelli, A., Prosser, G., Di Battista P. (1997) - Textural features and strain of granitoids emplaced at different depths: the example of the Hercynian tonalites and granodiorites from Calabria. Mineral. Petro. Acta, 40, 11-26.

Caggianelli, A., Prosser, G., Rottura, A. (2000) - Thermal history vs. fabric anisotropy in granitoids emplaced at different crustal levels: An example from Calabria, southern Italy. Terra Nova, 12, 109–116.

Cirrincione, R., Fazio, E., Fiannacca, P., Ortolano, G., Pezzino, A., Punturo, R. (2015) - The Calabria-Peloritani

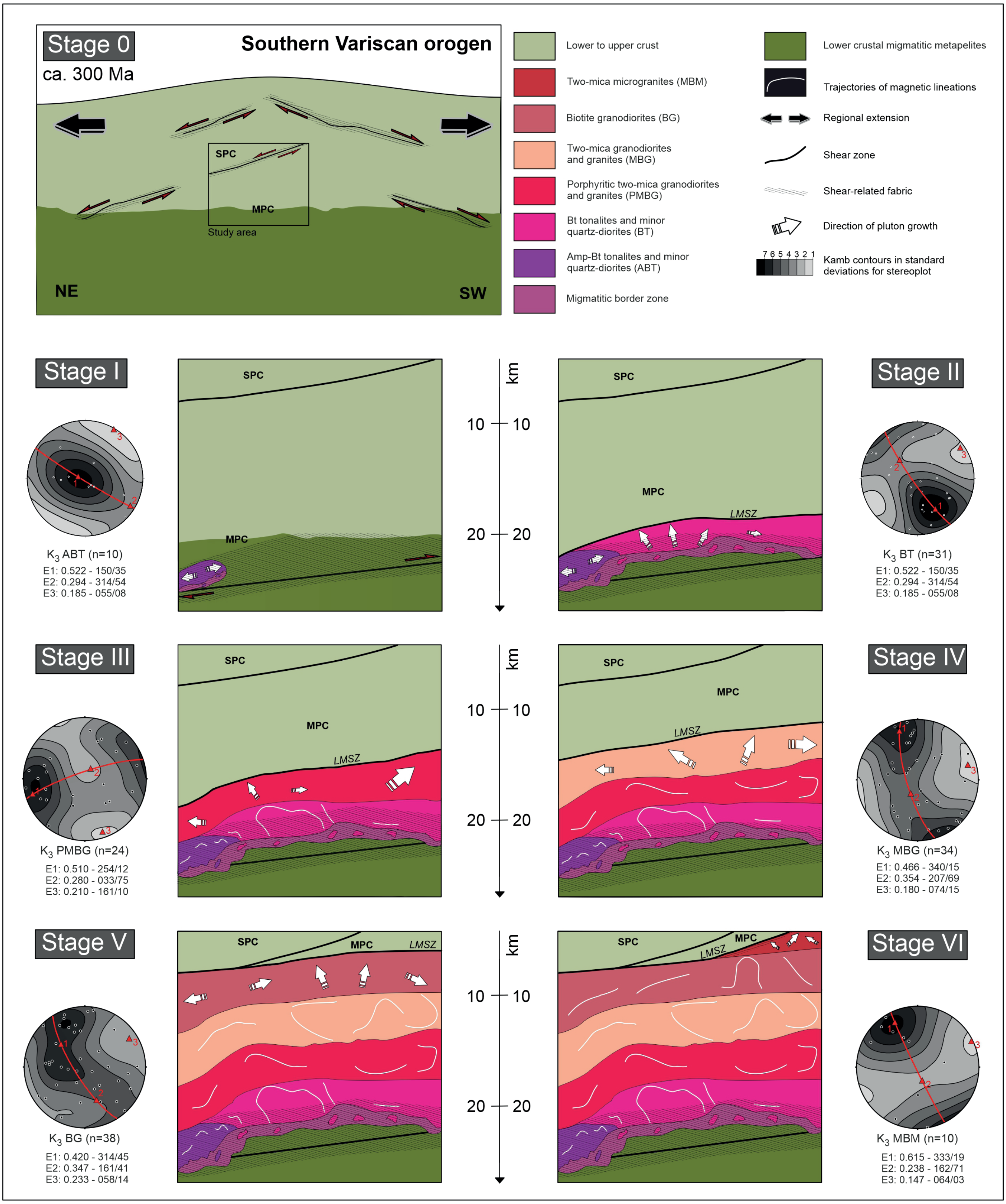

Figure 6 *Simplified cartoon model illustrating the sequential stages of construction of the Serre Batholith in conjunction with stereoplots reporting poles of magnetic back-tilted foliations for each stage. Stage 0 represents the pre-emplacement scenario of the Serre Massif in the framework of the southern Variscan orogen. Stage I to Stage VI illustrate the sequential emplacement of the Serre magmatic units. See text for further details. SPC = Stilo Pazzano Complex; MPC = Mammola Paragneiss Complex; LMSZ = Lower Mammola Shear Zone. Hatched lines represent the inferred LMSZ in a progressively waning stage. Shown poles to magnetic foliations are tilted according to the original setting of the study area (i.e., 43° counterclockwise tilting looking in the direction of a N45° horizontal rotation axis; Festa et al., 2003). E1 corresponds to the far field principal stress axis; E2 equals to K2 axis of the magnetic ellipsoid; E3 is the magnetic lineation K1.*

Orogen, a composite terrane in Central Mediterranean; its overall architecture and geodynamic significance for a pre-Alpine scenario around the Tethyan basin. Period. Mineral., 84, 701-749.

Festa, V., Di Battista, P., Caggianelli, A., Liotta, D. (2003) - Exhumation and tilting of the late Herchynian continental crust in the Serre Massif (Southern Calabria, Italy). Boll. Soc. Geol. Ital., 2, 79-88.

Fiannacca, P., Cirrincione, R., Bonanno, F., Carciotto, M.M. (2015) - Source-inherited compositional diversity in granite batholiths: the geochemical message of Late Paleozoic intrusive magmatism in central Calabria (southern Italy). Lithos, 236, 123-140.

Fiannacca, P., Williams, I.S., Cirrincione, R. (2017) - Timescales and mechanisms of batholith construction: Constraints from zircon oxygen isotopes and geochronology of the late Variscan Serre Batholith (Calabria, southern Italy). Lithos, 277, 302-314.

Fiannacca, P., Russo, D., Fazio, E., Cirrincione, R., Mamtani, M.A. (2021) - Fabric analysis in upper crustal post-collisional granitoids from the Serre Batholith (Southern Italy): Results from microstructural and AMS investigations. Geosci., 11, 414.

Langone, A., Caggianelli, A., Festa, V., Prosser, G. (2014) - Time constraints on the building of the Serre Batholith: consequences for the thermal evolution of the Hercynian continental crust exposed in Calabria (southern Italy). The J. Geol., 122, 183-199.

Ortolano, G., Pagano, M., Visalli, R., Angì, G., D'Agostino, A., Muto, F., Tripodi, V., Critelli, S., Cirrincione, R. (2022) - Geology and structure of the Serre Massif upper crust: a look in to the late-Variscan strike–slip kinematics of the Southern European Variscan chain. J. Maps, 18, 314-330.

Rottura, A., Bargossi, G.M., Caironi, V., Del Moro, A., Maccarrone, E., Macera, P., Paglionico, A., Petrini, R., Piccareta, G., Poli, G. (1990) - Petrogenesis of contrasting Hercynian granitoids from the Calabrian Arc, southern Italy. Lithos, 24, 97-119.

Russo, D., Fiannacca, P., Fazio, E., Cirrincione, R., Mamtani, M.A. (2023) - From floor to roof of a batholith: Geology and petrography of the north-eastern Serre Batholith (Calabria, southern Italy). J. Maps, 19, 2149358.