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# Multiple crustal and mantle inputs in post-collisional magmatism: evidence from late-Variscan Sàrrabus pluton (SE Sardinia, Italy) --Manuscript Draft--

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Abstract:	The Sàrrabus pluton is formed by multiple short-lived intrusions emplaced at about 286 Ma at shallow crustal levels within the external part of the South Variscan Orogenic Belt. A chemical and Sr and Nd isotopic study on the Variscan post-collisional magmatism from the Sàrrabus pluton reveals the repeated bimodal character of the intrusions, in which heterogeneous crustal sources and mantle-derived calcalkaline magmas are involved. Products of this magmatic activity occur as intrusive units and mafic/felsic dykes intruded in post-collisional regime along extensional faults during tectonic exhumation. Pluton growth started with an early stage of emplacement of broadly granodioritic magma with subordinate mafic magma batches (stage 1) followed by large intrusions of metaluminous to subaluminous and subordinately peraluminous granites (stage 2). In stage 1, the occurrence of remnants of stratified olivine-bearing gabbroic rocks indicates the intrusion of mafic magmas which experienced low-pressure crystal/liquid fractionation. Mafic magmas may represent an external heat supply for melting of different crustal materials belonging to an inferred Precambrian crystalline basement underlying the Paleozoic rocks of the Variscan nappe pile. Strong evidence for heterogeneous crustal sources is constrained by isotope data. Peraluminous granites and felsic dikes display initial 875r/86Sr in the range of 0.7140+0.7215 and a roughly constant ɛNd286 (-7.4 to -7.5). Conversely, a peculiar less radiogenic character, in the range of 0.7030+0.7067/–5.5+-6.2, is observed for metaluminous to subaluminous varieties. Calculated Neodymium Crustal Index (NCI) confirmed a progressive increase in crustal magmas generation during the pluton growth, from stage 1, recording minor mixing processes between mantle- and crustal-derived peraluminous and peraluminous granites. Possible crustal sources for metaluminous to subaluminous granites. Possible crustal sources for metaluminous/subaluminous and peraluminous granites, respectively, well comp

	Sàrrabus mafic products, compared to coeval Variscan mafic rocks of Corsica and northern Sardinia, may be indicative of previous fractionation and mixing processes, possibly related to magmatic underplating of the lower crust. The Sàrrabus pluton is formed by multiple short-lived intrusions emplaced at about 286 Ma at shallow crustal levels within the external part of the South Variscan Orogenic Belt. A chemical and Sr and Nd isotopic study on the Variscan post-collisional magmatism from the Sàrrabus pluton reveals the repeated bimodal character of the intrusions, in which heterogeneous crustal sources and mantle-derived calcalkaline magmas are involved. Products of this magmatic activity occur as intrusive units and mafic/felsic dykes intruded in post-collisional regime along extensional faults during tectonic exhumation. Pluton growth started with an early stage of emplacement of broadly granodioritic magma with subordinate mafic magma batches (stage 1) followed by large intrusions of metaluminous to subaluminous and subordinately peraluminous granite (stage 2). In stage 1, the occurrence of remants of stratified olivine-bearing gabbroic rocks indicates the intrusion of mafic magmas which experienced low-pressure crystal/liquid fractionation. Mafic magmas may represent an external heat supply for meting of different crustal materials belonging to an inferred Precambrian crystalline basement underlying the Paleozoic rocks of the Variscan nappe pile. Strong evidence for heterogeneous crustal sources is constrained by isotope data. Peraluminous granites and felsic dikes display initial 87Sr/86Sr in the range of 0.7140+0.7215 and a roughly constant tNd286 (-7.4 to -7.5). Conversely, a peculiar less radiogenic character, in the range of 0.7030+0.7067/-5.5+-6.2, is observed for metaluminous metts, to stage 2, where extensive crustal melting occurred, originating metaluminous and peraluminous granites are (Pan-African) amphibolites and metaled reved peraluminous subaluminous granites are (Pan-African) amphibolites a
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Highlights

- The Sàrrabus pluton is formed by multiple short-lived intrusions at ca. 286 Ma;
- Pluton growth started with an early stage of broadly granodioritic composition;
- Large intrusions of metaluminous to subaluminous granites follow the granodiorites;
- During the pluton growth, a progressive increase in crustal magmas generation occurred;
- Last magmatics are subalkaline mafic/felsic dikes with major intrusions signature;

#### 1 Multiple crustal and mantle inputs in post-collisional magmatism: evidence from late-Variscan Sàrrabus pluton (SE Sardinia, Italy) 2 3 4 Secchi, F.<sup>1,2</sup>, Giovanardi, T.<sup>3\*</sup>, Naitza, S.<sup>4</sup>, Casalini, M.<sup>5</sup>, Kohút, M.<sup>6</sup>, Conte A.M.<sup>7</sup>, Oggiano G.<sup>1</sup> 5 (1) Dipartimento Chimica e Farmacia, Via Piandanna 4, I-07100 Sassari (Italy). Università degli Studi di Sassari, Sassari 6 7 (Italv). 8 (2) CNR-Istituto di Geologia Ambientale e Geoingegneria, Sede Secondaria di Cagliari, Via Marengo 2, 09123 Cagliari, 9 Italy. 10 (3) Dipartimento Scienze Chimiche e Geologiche, Via G. Campi 103, I-41125 Modena. Università degli Studi di Modena 11 e Reggio Emilia, Modena (Italy). 12 (4) Dipartimento Scienze Chimiche e Geologiche, Cittadella Universitaria S. S. 554 bivio per Sestu, I-09042 Monserrato 13 (CA). Università degli Studi di Cagliari, Cagliari (Italy). (5) Dipartimento Scienze della Terra, Via LA Pira 4, I-50121 Firenze. Università degli Studi di Firenze, Firenze (Italy) 14 15 (6) Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia. 16 (7) CNR-IGAG, Sede di Roma, c/o DST Sapienza Università di Roma, P.<sup>le</sup> Aldo Moro 5, I-00185, Roma, Italy. 17 18 \*Corresponding author. E-mail address: tommaso.giovanardi@unimore.it; https://orcid.org/0000-0002-9953-6707. 19 20 Keywords: (Late-Variscan magmatism, bimodal magmatism, dilatant shear zones, crustal sources, Sr-Nd isotopes, 21 Neodymium crustal index) 22 23 Abstract 24 The Sàrrabus pluton is formed by multiple short-lived intrusions emplaced at about 286 Ma at shallow 25 crustal levels within the external part of the South Variscan Orogenic Belt. A chemical and Sr and 26 Nd isotopic study on the Variscan post-collisional magmatism from the Sàrrabus pluton reveals the 27 repeated bimodal character of the intrusions, in which heterogeneous crustal sources and mantle-28 derived calcalkaline magmas are involved. Products of this magmatic activity occur as intrusive units 29 and mafic/felsic dykes intruded in post-collisional regime along extensional faults during tectonic 30 exhumation. Pluton growth started with an early stage of emplacement of broadly granodioritic 31 magma with subordinate mafic magma batches (stage 1) followed by large intrusions of 32 metaluminous to subaluminous and subordinately peraluminous granites (stage 2). In stage 1, the 33 occurrence of remnants of stratified olivine-bearing gabbroic rocks indicates the intrusion of mafic 34 35 magmas which experienced low-pressure crystal/liquid fractionation. Mafic magmas may represent an external heat supply for melting of different crustal materials belonging to an inferred Precambrian 36 crystalline basement underlying the Paleozoic rocks of the Variscan nappe pile. Strong evidence for 37 heterogeneous crustal sources is constrained by isotope data. Peraluminous granites and felsic dikes 38 display initial ${}^{87}$ Sr/ ${}^{86}$ Sr in the range of 0.7140 $\div$ 0.7215 and a roughly constant $\varepsilon$ Nd<sub>286</sub> (-7.4 to -7.5). 39 Conversely, a peculiar less radiogenic character, in the range of 0.7030÷0.7067/-5.5÷-6.2, is 40

observed for metaluminous to subaluminous varieties. Calculated Neodymium Crustal Index (NCI)
confirmed a progressive increase in crustal magmas generation during the pluton growth, from stage
1, recording minor mixing processes between mantle- and crustal-derived peraluminous melts, to
stage 2, where extensive crustal melting occurred, originating metaluminous to subaluminous

granites. Possible crustal sources for metaluminous/subaluminous and peraluminous granites are 45 (Pan-African) amphibolites and metasedimentary rocks, respectively. Two-stage depleted-mantle Nd 46 model ages cluster at 1.4 and 1.6 Ga for metaluminous/subaluminous and peraluminous granites, 47 respectively, well comparable with other segments of the European Variscan belt. Remarkably, last 48 49 magmatic pulses resulted in widespread subalkaline bimodal mafic/felsic dykes that overlapped the Sr-Nd signature recorded by major intrusions. This similar geochemical affinity between late dykes 50 and the first intrusives may be related to decreasing temperature in the crust, which inhibited 51 extensive mixing processes with the upwelling melts. At the same time, the presence of felsic 52 intrusions in the shallow crust would have prevented the rise of more primitive basic magmas, which 53 would have consolidated at depth. Finally, the high radiogenic character of Sàrrabus mafic products, 54 55 compared to coeval Variscan mafic rocks of Corsica and northern Sardinia, may be indicative of previous fractionation and mixing processes, possibly related to magmatic underplating of the lower 56 57 crust.

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#### 60 Introduction

The Corsica-Sardinia Batholith (CSB) belongs to the southern Variscan belt of Europe and 61 represents a key area for studies on post-collisional evolution of this orogenic chain (Ferrè and Leake, 62 2001; Paquette et al., 2003; Cocherie et al., 2005; Rossi et al., 2009, 2015; Edel et al., 2014; Casini 63 et al., 2015a, b; Conte et al., 2017) (Fig. 1). The CSB was-emplaced through a complex succession of 64 discontinuous short-lived tectonic and magmatic episodes from the late collisional stages to the post-65 collisional collapse and exhumation of the orogenic roots. At present, a general agreement exists in 66 literature in considering the control of lithospheric shear zones on the emplacement of major intrusive 67 complexes of the CSB (Edel et al., 2014; Casini et al., 2012; 2015; Cuccuru et al., 2016), and the 68 involvement of metaigneous and metasedimentary crustal sources with subordinate mantle 69 contribution (Poli et al., 1989; Cocherie et al., 1994; Tommasini et al., 1995; Macera et al., 2011; 70 Rossi et al., 2015; Conte et al., 2017). Also, the heat source necessary to generate the large volumes 71 of crustal-derived intrusive magma in the post-collisional regime of SCB was related to lithospheric 72 delamination and asthenospheric upwelling promoting partial melting of lower crust (Gaggero et al., 73 2007; Rossi et al., 2015). As a result, a wide range of crustal melts and hybrid varieties, mainly of 74 broadly granodioritic composition, produced by mafic/felsic magma interactions, contributed to the 75 76 architecture of the entire batholith. Common effect of mafic/felsic magma interaction was documented by igneous dark enclaves dispersed in granodiorites and subordinately in monzogranites 77 (Poli et al., 1989; Zorpi et al., 1991; Barbey et al., 2008; Casini et al., 2015b). Mantle-derived 78 magmas, commonly intruding in the final stages of the CSB growth, are represented by gabbroic 79

magma batches and mafic dikes. The tholeiitic and calcalkaline mafic dikes spread over the whole
batholith, and partly within the host metamorphic basement. Even if recent radiometric ages point to
a substantial contemporaneity among the main intrusive events and the subalkaline mafic dike swarms
(Rossi et al., 2015; Conte et al., 2017), the genetic linkage between this hypabyssal activity and the
plutons making the batholith was never taken into consideration.

The Sàrrabus pluton (south-eastern Sardinia), is formed by multiple intrusions emplaced within 85 the shallow crustal levels of a fold and thrust belt along the Gondwana foreland; it shows peculiar 86 characteristics compared to the rest of the CSB due to the different geochemical affinities of the 87 88 magma intrusions and their coeval ages. Previous studies performed on the Sàrrabus pluton (Brotzu et al., 1981, 1993; Poli and Tommasini, 1999; Ronca et al., 1999; Conte et al., 2017; Franciosi et al., 89 90 2019) focused on single aspects of the pluton without proposing a global genetic model. In a recent study, Secchi et al. (2021) firstly recognized the substantial contemporaneity of a wide spectrum of 91 92 magma pulses concentrated in a short time span, forming a relatively small pluton (400 km<sup>2</sup>), which differentiate the Sàrrabus pluton with respect to others in CSB. 93

In this work, field evidence and chemical and isotopic data (Sr and Nd bulk rock and Hf in zircons) are presented and discussed with data from previous studies, to constrain the petrogenesis of the entire Sàrrabus pluton. We will focus on the nature of involved crustal sources which originated the granitic units of the pluton and their interactions with mantle derived melts. We will propose a genetic model of growth of the Sàrrabus pluton by magma ascending through lithospheric-scale shear zones active in an extensional post-collisional setting which could be applied to other shallow crustal magmatic complexes rooted on lithospheric shear zones.

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#### 103 Geological setting

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#### 105 *The Variscan orogenic wedge*

The Variscan collisional frame of Sardinia and Corsica results in a high-grade, inner, anatectic 106 complex retaining remnants of eclogite and high-pressure mafic granulite well exposed in Corsica 107 and northern Sardinia (Cruciani et al., 2015), which overthrusts a complex pile of nappes showing 108 low- to medium- grade metamorphic imprint (Fig. 1). The nappe pile in turn overrides, with general 109 110 top- to- southwest transport, a non-metamorphic foreland located in southern Sardinia (Carmignani et al., 1994), which is commonly interpreted as a Gondwana foreland (Edel et al., 2014; Rossi et al., 111 2015 and reference therein). This frame is the result of the early Carboniferous collision between the 112 northern Gondwana margin, and the ribbon-like collage of terranes interposed between Gondwana 113 and Laurussia after the (present time) north-directed subduction of an oceanic domain, namely the 114

Paleo-Tethys or South-Armorican Ocean (Stampfli et al., 2003; Oggiano et al., 2010; Gaggero et al., 115 2012). The Variscan crust was thus highly heterogeneous, consisting of several assembled terranes 116 and syn-collisional plutonic intrusions. During the post-collisional evolution of the chain, the 117 Variscan crust was widely reworked in the general context of a strike slip dextral mega shear zone 118 119 (Casini and Funedda, 2014; Rossi et al., 2015; Edel et al., 2016). This reworking was coeval with the collapse (Ruben Diez and Preira, 2016) of the previously thickened crust and by heating related to 120 slab breakoff of the north-directed subducting oceanic lithosphere as well as to shear heating (Casini 121 et al., 2012). This post collisional frame in Sardinia, similarly to the entire Variscides, went on with 122 HT/LP metamorphism (Kröner and Willner, 1998; Casini and Oggiano, 2008) and was accompanied 123 by intensive magmatic activity giving rise to the CSB. The magmatic activity is coeval with 124 125 lithospheric-scale shear zones and anatexis in the 320÷305 Ma wide interval, as well as to extension and to the clockwise rotation of Corsica-Sardinia microplate (Rossi et al., 2009, 2015; Edel et al., 126 127 2014).

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#### 129 *The Corsica-Sardinia Batholith*

The CSB resulted from the succession of discrete, short-lived plutonic and volcanic events of broadly calcalkaline affinity, which may be grouped into three main magmatic peaks based on geographic, geochronological and magmatic criteria as follows:

(1) late-collisional magmatic peak, only documented in western and northwestern Corsica within a
short time span of 344 ÷ 335 Ma (Cocherie et al., 2005);

135 (2) older post-collisional magmatic peak (hereafter OMP, *sensu* Conte et al., 2017), poorly 136 represented in southern Sardinia lasting from  $322 \pm 8$  Ma (northern Sardinia; Casini et al., 2015a) to

137  $299 \pm 3$  Ma (central Sardinia; Meloni et al., 2017);

(3) younger post-collisional magmatic peak (hereafter YMP, *sensu* Conte et al., 2017) widespread in
Sardinia and Corsica and referred to the short time span of 291÷286 Ma (Cocherie et al., 2005; Casini
et al., 2015a).

The igneous activity belonging to the syn-collisional peak resulted in a rock-association made up of quartz monzonites to syenogranites with enclaves of ultrapotassic mafic rocks (the so-called Mg-K rock-suite; Cocherie et al., 1994 and reference therein), emplaced from deep crustal levels up to shallow conditions.

The architecture of CSB is instead closely related to the post-collisional stages of the Variscan orogen. With the exception of the earlier andalusite-bearing foliated granodiorites and leucogranites occurring in northernmost of Sardinia (i.e., Barrabisa and Santa Maria Island:  $321 \pm 8 \div 313 \pm 6$  Ma; Oggiano et al., 2007; Casini et al., 2012), the OMP is characterized by repeated sequences of monzogranitic and granodioritic pulses with subordinate mafic rocks, which represent the dominant intrusive activity in the internal nappe zone of northern-central Sardinia. Overall, magma pulses
emplaced almost constantly at shallow crustal levels (about 2–4 kbar; Casini et al., 2012; Conte et al.,
2017; Bosi et al., 2019). Shallow conditions are constrained by the common development of narrow
contact aureoles with andalusite-cordierite hornfelses around the plutons, as well as by geobarometric
results (Conte et al., 2017; Bosi et al., 2019 and reference therein); in addition, andalusite and
cordierite may occur as fundamental phases in peraluminous varieties (e.g., Barrabisa and
Gennargentu, Fig. 1; Casini et al., 2012; Gaeta et al., 2013).

In the external nappe zone and in the Gondwanan foreland of southern Sardinia, the OMP is only represented by small plutons with inverse zonation belonging to an ilmenite rock-*series* and ranging from granodiorites to peraluminous cordierite-bearing granites (e.g., Arbus and Grighini) with local small amounts of olivine-bearing monzo-gabbronorites (Arbus, Capo Pecora and Burcèi) (Secchi et al., 1991; Brotzu et al., 1993; Musumeci et al., 2014) (Fig. 1).

The intrusive bodies belonging to YMP are dominated by voluminous (mainly NE-trending) 162 peraluminous to subaluminous felsic and minor mafic intrusions emplaced at the shallowest crustal 163 levels (about 1 kbar; Gaggero et al., 2007; Conte et al., 2017 and reference therein). Granodioritic 164 sequences associated to mafic bodies cover a restricted time span of  $286 \pm 1 \div 279 \pm 1$  Ma (Paquette 165 et al., 2003; Casini et al., 2015a). The age of these late intrusions overlaps that of peralkaline granites 166 which are only exposed in northern Corsica (Cocherie et al., 2005). In southern Sardinia, 167 metaluminous to sub-aluminous granites are dominant over peraluminous granites. They mainly 168 belong to ilmenite rock-series and show a F-rich ferroan character as well as a peculiar metallogenic 169 signature as testified by Sn-W-Mo and F ores (Naitza et al., 2017). 170

Exposed rock-types are dominantly felsic (over 90% granodiorites and granites), with only minor 171 amounts of gabbroic rocks commonly associated with tonalites mingled with host granodiorites 172 173 (Zorpi et al., 1991). The production of magmas in the CSB is largely interpreted as related to contemporaneous partial melting of crustal materials and interactions of felsic melts with mafic 174 magmas at several levels in the crust (Secchi et al., 1991; Zorpi et al., 1991; Tommasini and Poli 175 1992; Cocherie et al., 1994; Tommasini et al., 1995; Di Vincenzo et al. 1996; Poli and Tommasini, 176 1999; Renna et al., 2006; Barbey et al., 2008). According to Rossi et al. (2015), the voluminous felsic 177 activity marking the end of YMP in the entire CSB reflects a phase of intense crustal heating triggered 178 179 by lithospheric delamination and intrusion of mafic magmas in the lower crust. Heating contribution in this phase has also been related to intense shearing (Casini et al., 2012; 2015b) and radiogenic 180 heating (Puccini et al., 2013). 181

The  $291\div286$  Ma emplacement age interval identified for YMP overlaps with U/Pb data determined for *HT-LP* granulites from the Variscan deep crust exhumed along the "European" margin

of the thinned Tethys margin from Corsica and Calabria, which are in the range of 285÷280 Ma (Rossi 184 et al., 2015). 185

Furthermore, the early Permian intrusive magmatism is coeval with calcalkaline felsic/intermediate 186 volcanism associated to the onset of continental basins in an extensional/transtensional regime 187 (Cortesogno et al., 1998; Gaggero et al., 2017). 188

Based on SHRIMP analyses on zircons, the late calcalkaline mafic dykes from Corsica provided age 189 values of  $279 \pm 1$  Ma (Cocherie et al., 2005). 190

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#### 192 The Sàrrabus pluton

The Sàrrabus pluton -exposed for over 400 km<sup>2</sup>- is formed by multiple, short-lived pulses 193 emplaced at shallow crustal levels within an anchi-metamorphosed Cambro-Ordovician volcano-194 sedimentary sequence in the frontal part of the orogenic wedge of the SE Sardinia (Fig. 1). Its original 195 196 extension and shape are unknown, as the contact with the host rocks is limited to its northern boundary (Fig. 2) even if small roof pendants of metamorphic basement are locally exposed along the southern 197 Sardinian coastline. The pluton may be framed in a dilatant extensional/transtensional shear zone 198 bordering the Sardinia-Corsica tectonic microplate to the E (Secchi et al., 2021). It consists of 199 200 different generations of granodiorites, associated to gabbroic rocks and tonalites, and of metaluminous, subaluminous and subordinately peraluminous granites, all referable to the YMP. The 201 202 pluton shows abundant mafic and felsic dikes crosscutting the main intrusions, thus representing the later igneous activities. 203

The available geochronological data support a restricted time interval of emplacement for the 204 whole pluton, with ages clustered around 286 Ma (Secchi et al., 2021). In detail, U/Pb data on single 205 zircons yielded overlapping ages at  $287 \pm 1$  Ma for the S. Vito leucogranite satellite intrusion (Dack, 206 2009) and at  $286 \pm 9$  Ma for the Cala Regina granodiorites (Secchi et al., 2021). These ages are in 207 good agreement with Ar-Ar and Rb/Sr data available for S. Vito leucogranite and Cala Regina 208 granodiorites yielding  $285 \pm 1$  and  $292 \pm 17$  Ma, respectively (Dini et al., 2005; Secchi et al., 2021). 209 The geology of the pluton has been recently outlined by Secchi et al. (2021; Fig.2). The intrusive 210 sequence may be schematized as follows. The older part of Sarrabus pluton (hereafter the stage 1) is 211 an intrusive sequence of EW/ENE trending pulses of granodiorites and coeval mafic batches, well 212 exposed along the southern Sardinian coastline (Fig. 2). The granodioritic pulses have been defined 213 by Secchi et al. (2021) as Cala Regina, Monte Cresia and Monte Nai units; in this study they are 214

215 hereafter reported together as the Cala Regina Group. In the field, size and abundance of

microgranular dark enclaves and frequency of mafic bodies in granodiorite increase from N to S. In 216

their southernmost outcrops, where they are intruded by the NE trending, peraluminous granite of 217 218

Monte Maria-Unit, granodiorites contain in addition hololeucocratic felsic enclaves (Fig. 3a).

The Cala Regina Group granodiorites locally grade into foliated quartz-diorite and tonalite with 219 highly stretched hybrid enclaves (Fig. 3b), dismembered syn-plutonic dikes and decametric bodies of 220 elongated two pyroxene-bearing hornblende-gabbroic rocks with local remnants of olivine-bearing 221 layers (i.e., cumulitic rocks of Solànas Complex; SO in Fig. 2). The magmatic foliation trends roughly 222 E-W and is sub-vertical or steeply dipping to the south. It is defined by the preferred orientation of 223 dark mica, feldspar and stretched microgranular mafic enclaves. The magmatic lineation, where 224 observed, plunges down dip and is defined mostly by alignment of dark mica, feldspars as well as the 225 long axis of mafic enclaves (Fig. 3b). Close to the coast, along a 2 km wide belt roughly trending E-226 W, extremely stretched enclaves occur in large proportion along banded mafic-felsic domains (Fig. 227 3c), these features have been related to mingling processes (Poli and Tommasini 1989) enhanced by 228 229 a normal, syn-plutonic shear zone, namely the South Sarrabus Shear zone (SSSZ; Secchi et al 2021; Fig. 2). The coeval intrusion of mafic and felsic magmas favored localized magma mixing, which 230 231 resulted in the local production of heterogeneous magmas of broadly tonalitic composition. This 232 magma emplaced by lateral expansion in a NS direction that is common to the other pulses (Secchi et al., 2021). 233

The younger part of Sàrrabus pluton is dominated by a group of at least three different pulses of F-rich ferroan granites (hereafter as *stage 2*), which intrude the granodiorites and range from biotite granites (Bruncu Nicola Bove Unit and San Priamo Unit) to hastingsite granites (Monte Sette Fratelli Unit). The first two granitic intrusions were emplaced along an E-W trend while the Monte Sette Fratelli Unit overlaps the others emplaced as a large sub-vertical stock. Contacts of the three are parallel to the contact of stage 1 Monte Cresia unit with the surrounding Paleozoic metasediments.

This general frame is complicated by the occurrence of a bimodal subalkaline rock-association 240 made up of a several generations of NNW trending mafic and (metaluminous to subaluminous) felsic 241 242 dykes crosscutting an earlier generation of NE trending peraluminous felsic dikes dated at  $293 \pm 3$ Ma (Ronca et al., 1999; Fig. 3e; f). Remarkably, mafic dikes consist of spessartites to hornblende-243 244 bearing granular rocks and is prevalently outcropping in Cala Regina Group granodiorites exposed in southern portion of the pluton. The end of Sàrrabus igneous activity is represented by a generation of 245 olivine plagioclase-phyric mafic dikes with tholeiitic signature (Ronca et al., 1999) that crosscuts 246 granite intrusions with a dominant NS trend. 247

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#### 250 Analytical methods

Whole-rock major and trace element concentrations of twelve samples representing the different
Sàrrabus lithologies were determined at Activation Laboratories, Ancaster, Ontario, Canada.
Powdered samples were previously fused using lithium metaborate or tetraborate, and then rapidly

- digested in weak nitric acid solutions. Resulting solutions were analyzed by inductively coupled plasma–optical emission spectroscopy (ICP–OES) and ICP–mass spectrometry (ICP–MS) techniques. The uncertainties in major element concentrations are generally between 1% and 3%, except for MnO (5%–10%) and P<sub>2</sub>O<sub>5</sub> (>10%); most trace elements concentrations have uncertainties of <5%. Major element concentrations usually have detection limits of 0.01 wt%. Loss on ignition (L.O.I.) and FeO contents were measured using standards gravimetric techniques and titration with 10N KMnO<sub>4</sub> techniques, respectively. Data are reported in Supplementary Material Table 1.
- Additional samples were analysed for major and trace elements by XRF spectrometry using 261 powder pellets, at the University of Cagliari laboratories, Italy. X-ray analyses were performed on an 262 automatic Philips spectrometer (PW1400). Data were corrected for drift and background effects. 263 264 Major elements were reduced for matrix effects according to Franzini et al. (1972). Trace elements were reduced for matrix effects using the method of fundamental parameters according to Criss and 265 266 Birks (1968). Thirty reference rock standards were used for calibration. Analytical accuracy is within  $\pm 1\%$  for SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, CaO, K<sub>2</sub>O and MnO, and  $\pm 4\%$  for MgO, Na<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub>. The 267 accuracy of trace element analyses is  $\pm 2$  to 3% at 1000 ppm,  $\pm 5$  to 10% at 100 ppm, and  $\pm 10$  to 268 20% at 10 ppm level. Rh and W X-ray tubes were used, and detection limits were around 3 ppm for 269 most trace elements. Data are reported in Supplementary Material Table 2. 270
- Eleven selected samples, representing all the Sàrrabus lithologies were analyzed for Sr and Nd 271 isotopic compositions at the laboratories of Dipartimento Scienze della Terra (Università degli Studi 272 di Firenze, Italy). Sr and Nd measurements were obtained by a Thermofisher Triton Plus multi-273 collector mass-spectrometer, running in a static mode, following separation of Sr and Nd using 274 conventional ion-exchange procedures as reported in Avanzinelli et al. (2005). Measured <sup>87</sup>Sr/<sup>86</sup>Sr 275 ratios were normalized to  ${}^{88}$ Sr/ ${}^{86}$ Sr = 8.375209,  ${}^{143}$ Nd/ ${}^{144}$ Nd ratios to  ${}^{146}$ Nd/ ${}^{144}$ Nd = 0.7219. During 276 277 collection of isotopic data, replicate analyses of the Sr NIST SRM 987 (SrCO<sub>3</sub>) isotopic standards gave an average  ${}^{87}$ Sr/ ${}^{86}$ Sr value of 0.710251 ± 20 (2 $\sigma_m$ , N = 100) well in agreement with the reference 278 279 value of Thirwall, (1991). The in-house Nd isotopic standard NdFi (Nd oxide) was used to test reproducibility. Data are reported in Supplementary Material Table 3. 280
- 281 Lu-Hf analyses were performed on the same zircon crystals previously U-Pb dated by Secchi et al. (2021) on SSP2 sample from Cala Regina granodiorite (Capo Carbonara, Fig. 2). Analyses were 282 283 done in the same dated domains and were carried out using a double focusing MC-ICP-MS with a forward Nier-Johnson geometry (Thermo Fisher Scientific, Neptune<sup>™</sup>), coupled to a 213 nm 284 Nd:YAG laser ablation system (New Wave Research<sup>™</sup>) at the laboratory of Centro 285 Interdipartimentale Grandi Strumenti of the Università di Modena e Reggio Emilia. Isotopic ratios 286 were acquired in static mode with a block of 250 cycles (including laser warm-up, ~50-80 cycles of 287 analysis and washout), an integration time of 0.5 s, a laser spot of 55  $\mu$ m and a fluence of ~10 J/cm2. 288

A low laser frequency (~10 Hz) was used to achieve better signal stability with a He flux of ~0.5 L/min. Details of the method are reported in Giovanardi et al. (2018). Data reduction was performed using the Hf-INATOR software (Giovanardi and Lugli, 2017). During the analytical session, reference material zircon TEMORA-2 was used to check accuracy and precision. TEMORA-2 provides <sup>176</sup>Hf/<sup>177</sup>Hf ratios of 0.282686 ± 0.000075 ( $2\sigma$ , *n*=6), identical within error to the reference value of 0.282686 (Woodhead and Hergt, 2005). Data are reported in Supplementary Material Table 4.

296 297

#### 298 **Results**

Representative samples from the intrusive units of Sàrrabus pluton have been analyzed for major, trace elements and Sr and Nd systematics to integrate whole-rock data available in the literature for gabbroic rocks and granodiorites (Poli and Tommasini, 1999; Franciosi et al., 2019), granitic units (Conte et al., 2017), as well as for mafic and acidic dikes (Ronca et al., 1999).

Overall, this expanded dataset supports a new and broader petrological and evolutionary pictureof the pluton.

According to Miller (1985), in this paper granites with ASI > 1 (ASI = (mol. Al/(Ca+Na+K-1.67\*P) < 1.0) coupled with the occurrence of a more aluminous mineral phase than dark mica will be classified as peraluminous.

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#### 309 Essential petrographic features

The main petrographic and mineralogical features of Sàrrabus igneous units are outlined in Conte et al. (2017; 2018*a*; *b* and reference therein) and summarized in Fig. 4 and Tab. 1. Rocks were classified according to IUGS's recommendations, using modal compositions obtained by mass balance calculations (Stormer and Nicholls, 1978). In this paragraph we will briefly describe the principal features of the different lithotypes, summarizing information from D'Angelo (1998), Poli and Tommasini (1999), Conte et al. (2017) and Franciosi et al. (2019).

Petrographic differences observed in the Cala Regina granodiorites mainly consist of an increase 316 southward in (a) size and amount of dark enclaves, which compositionally range from tonalites to 317 hornblende quartz-gabbros, (b) color index (from 14% to 20%), as well as (c) abundance of primary 318 Fe-hornblende (1%-4%; Mg#<sub>0.40-0.36</sub>), respectively. Typical plagioclase feldspar is a light-coloured, 319 slightly zoned andesine (An<sub>45-41</sub>), even if patchy zoned plagioclases with relic of calcic cores (An<sub>63-</sub> 320 39; Fig. 4f) are locally observed especially in biotite granodiorites. Common accessory phases are 321 well-developed euhedral allanite, associated with mafic minerals, zircon, monazite, and minor apatite 322 + ilmenite as inclusion on brownish dark mica. 323

Dismembered mafic masses in granodiorites (Solanas Complex of Cala Regina Group 324 granodiorites) are hornblende gabbroic rocks with relics of ortho- and clinopyroxene, grading to 325 hornblende quartz gabbros. These latter represent the typical composition of dark enclaves (Fig. 4a), 326 and usually show panidiomorphic and fluidal textures characterized by calcic plagioclase (An<sub>84-45</sub>) 327 328 with cotectic relationships with Fe-hornblende (Mg#0.55-0.48), dark mica (Mg#0.48-0.45) and interstitial quartz (Fig. 4b). The mafic masses also include olivine-bearing gabbronorites and leuco-gabbros with 329 cumulate textures (Conte et al., 2018b; Secchi et al., 2021), which document a dismembered formerly 330 stratified sequence. Cumulitic rocks show commonly poikilitic textures; the dominant mineral 331 assemblage is homogeneous olivine (Fo74) with peritectic relationships with orthopyroxene 332 (Wo<sub>2</sub>En<sub>77</sub>Fs<sub>21</sub>) followed by calcic plagioclase (An<sub>89-92</sub>) and clinopyroxene (Wo<sub>47-42</sub>En<sub>45-49</sub>Fs<sub>8-9</sub>) set in 333 334 a dominant mass of amphibole of pargasitic composition (Fig. 4c).

Strong petrographic variations are observed within felsic rock-types in terms of mafic mineralogy, feldspar composition as well as typical accessory phases. In detail, granites at the core of Sàrrabus pluton (i.e., Bruncu Nicola Bove Unit -BNB in Fig. 2) range from biotite monzogranite to leucogranite with normal oligo-albitic plagioclase (An<sub>30-15</sub>). Conversely, the San Priamo granite is made up of coarse-grained pinkish biotite leucogranite showing a slightly less sodic plagioclase feldspar (An<sub>40-26</sub>), large allanite grains and magnetite as typical accessory phases; additional interstitial dark or, less frequently, white micas are often observed (Fig. 4*g*).

The Monte Maria granite is a garnet-bearing (Alm<sub>65-69</sub>Sp<sub>22-27</sub>Py<sub>5</sub>Gr<sub>3</sub>) two-mica variety, locally 342 containing altered cordierite (Fig. 4h), whereas the Monte Sette Fratelli Unit consist of leucogranite 343 grading to monzogranite containing oligo-albitic plagioclase (An<sub>20-15</sub>), large euhedral Fe-hastingsite 344 and red-brown dark micas as early crystallized phases. Main accessory phases are large allanite + 345 magnetite + ilmenite, mostly included in amphiboles, abundant zircons included in quartz and K-346 347 feldspars and anhedral fluorite grains as interstitial phases. In these rocks, dark mica of annitic composition, also occurs as interstitial phase, or as discontinuous coronas on interstitial and altered 348 349 fayalite grains (Conte et al., 2017).

Main petrographic information on mafic and felsic rocks in dike swarms is outlined by Ronca et 350 al. (1999). Overall, dike swarms recorded similar features observed for compositionally-equivalent 351 intrusive rocks. Generally, the NE trending peraluminous felsic dikes, which predate the other dike 352 swarms, resemble the Monte Maria peraluminous granites: they are characterized by oligo-albitic 353 plagioclase and perthitic orthoclase with minor amounts of dark and white mica and/or spessartine-354 rich garnet. Remarkably, rare corroded andalusite with continuous coronas of white mica are 355 356 occasionally observed. Apatite, zircon, monazite, magnetite and locally tourmaline are the typical accessory phases. 357

Mafic dikes include rocks of dominant basaltic andesite to andesite composition, with minor amounts of basalts. Overall, an orthopyroxene + clinopyroxene succession replaced by amphibole, is frequently observed in the spessartitic mafic dikes (Fig. 4d); when observed, olivine occurs as completely altered phenocrysts. Locally basaltic rock-types display glomero-porphyritic which may be evidence of cumulitic character.

The final generation of basaltic dikes (tholeiitic basalt *sensu* Ronca et al., 1999) are commonly characterized by labradoritic plagioclase feldspar, altered olivine and augite set in a fine-grained matrix of augite, plagioclase, and minor amount of amphibole.

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#### 367 *Whole rock chemistry*

Major and trace-element chemical compositions of selected samples are reported in Supplementary material Tables 1 and 2. Supplementary material Table 1 reports ICP-MS data for 9 specimens from main intrusive units and 3 representative samples from mafic dikes emplaced in granodiorites. Supplementary Material Table 2 refers to additional unpublished *XRF* data while Supplementary Material Table 5 reports average *XRF* analyses of intrusive units calculated on both our analyses and literature data (Pirinu 1994, D'Angelo. 1998).

Gabbroic and mafic dikes rocks have medium-K character while medium- to high-K character is 374 observed for quartz-gabbroic varieties (Fig. 5a). Gabbroic rocks and analyzed mafic dikes 375 (Supplementary Material Table 1) may be defined as high alumina basalts (Fig. 5b) and show in 376 addition the prevalence of Na<sub>2</sub>O over K<sub>2</sub>O as a common feature: Na<sub>2</sub>O/K<sub>2</sub>O ratio decreases from 2.45 377 to 1.48 in olivine-bearing gabbros to quartz-gabbros, respectively, and from 2.95 to 1.90 in mafic 378 dikes. In addition, gabbroic rocks show an abrupt increase of FeO/(FeO + MgO) and Na<sub>2</sub>O + K<sub>2</sub>O -379 CaO (modified alkali index) with SiO<sub>2</sub> from olivine-bearing gabbroic rocks to quartz gabbroic 380 varieties (Fig. 5d). 381

Conversely, granodiorites and granites are plotted at the end of a high-K rock-series (Fig. 5a) and 382 show a general increase of peraluminous character with SiO<sub>2</sub> evidenced by ASI in the range of 0.73 383  $\div$  0.98 (in granodiorites) with a higher value of 1.05 in garnet-bearing granite (Supplementary 384 Material Table 1). A prevalence of K with respect to Na is displayed in granodiorites and garnet-385 bearing granite in the restricted range of  $0.72 \div 0.74$  and 0.61, respectively (Supplementary Material 386 Tables 1 and 5). In the Frost's and Frost (2001) discrimination diagrams, granodiorites display a 387 magnesian/calc-alkalic signature while granites straddle along the ferroan/alkali-calcic fields (Fig. 388 389 5*c*; *d*).

REE normalized contents of different rock-*lithotypes* show a similar LREE enriched pattern and are poorly fractionated in MREE and HREE (Supplementary Material Table 1; Fig. 6). However, some differences could be noticed. Rocks from gabbroic association show a slight decrease of the Eu

- negative anomalies from two pyroxene-bearing gabbros (Eu/Eu\* 0.79 ÷ 0.81) to quartz gabbros
- 394 (Eu/Eu\* 0.63 ÷ 0.74, Supplementary Material Figure 1). Quartz gabbros and two-pyroxenes gabbros
- display less LREE fractionation (La<sub>N</sub>/Sm<sub>N</sub> ( $1.42 \div 2.00$  in quartz gabbros and 1.6-2.2 in two pyroxene

bearing-gabbros) with respect to other gabbroic rocks (Fig. 6). Generally, a direct correlation is found

between the Eu anomaly and the  $La_N/Yb_N$  ratio, while this latter is inversely correlated to the  $Gd_N/Yb_N$ 

- 398 (Supplementary Material Figure 1). Cumulate rocks show Eu/Eu\* values around 1 and La<sub>N</sub>/Sm<sub>N</sub> in
- the range of  $1.9 \div 2.9$ .
- Trace elements normalized patterns for gabbroic rocks show negative anomalies for Nb, Ta, P, Ti and Sr and enrichments in more incompatible elements (i.e., Rb, Ba, Th and U; Fig. 7a).

Granodioritic rocks show fractionated LREE ( $La_N/Sm_N$  between 2.90 and 4.33) and higher La<sub>N</sub>/Yb<sub>N</sub> (between 8.02 and 13.53) than mafic rocks, with slightly more pronounced Eu anomalies (Eu/Eu\* average of 0.67) (Fig. 6b). In addition, trace elements show depletion for Nb, Ta, Sr and P, and high fractionation for the more incompatible elements (Rb, Ba, Th and U), along with peaks in Sr (Fig. 7b).

- Granitic rocks display fractionated LREE, relatively flat HREE patterns with Gd<sub>N</sub>/Yb<sub>N</sub> values range 407 from 0.95 to 1.45 (Supplementary Material Table 1). Eu/Eu\* decrease from 0.33 in Monte Sette 408 Fratelli and San Priamo metaluminous/subaluminous granites to 0.18 in Monte Maria Unit 409 peraluminous granite (Fig. 6b). In detail, granites from Monte Sette Fratelli Unit are more enriched 410 in REE and show a slight fractionation in HREE. Conversely, granites from San Priamo Unit are less 411 enriched in REE and show a convex pattern for M-HREE (Fig. 6d). The picture is complicated by the 412 peraluminous granite (Monte Maria), which shows fractionated enrichment for LREE from La to Nd 413 and almost flat trend from Sm to Lu (except for the Eu negative anomaly), showing LREE contents 414 lower than other granites but HREE almost comparable with those observed for Monte Sette Fratelli 415 416 granites (Fig. 6d). It is also the only lithology displaying Ba depletion while it also shows Nb, Sr and P negative anomalies (Fig. 7b). 417
- 418 Mafic dykes (basalts to andesite-basalt in composition) show fractionated REE patterns with 419 LREE enrichments ( $La_N/Yb_N$  between 5.94 and 8.35) and weak or none Eu anomaly (Eu/Eu\* between 420 1.05 and 0.83). Trace elements are depleted in Nb, Ta and P, and the more primitive dykes have a 421 positive Sr anomaly which became negative in the more evolved ones (Fig. 7a).
- With respect to the studied samples, the late felsic dykes show the most heterogeneous REE contents
  (Fig. 6d). Different REE compositions, which basically overlap both metaluminous and peraluminous
  granites, point out to several different sources of the parent melts.
- 425

426 Isotope data

Sr and Nd isotopic ratios (Supplementary Material Table 3) have been calculated back to 286 Ma the likely age for intrusive rocks and mafic to felsic dykes (Secchi et al., 2021) assuming a substantially rapid emplacement of magmatic pulses based on the field evidence on the intrusion sequence, as well as on geochronological data.

When schematizing the Sàrrabus pluton as composed by an older *stage 1* and by a younger *stage*2, the isotope composition may be discussed as follows.

Granodiorites and associated gabbroic rocks show no correlation between 1/Nd and <sup>143</sup>Nd/<sup>144</sup>Nd 433 initial values (Supplementary Material Figure 2), as well as between SiO<sub>2</sub> and <sup>87</sup>Sr/<sup>86</sup>Sr<sub>t</sub> and εNd<sub>(t)</sub> 434 (not shown). In addition, in the <sup>87</sup>Sr/<sup>86</sup>Srt vs. ɛNd<sub>(t)</sub> diagram (Fig. 8) granodiorites plot in a restricted 435 field, ranging from 0.7088 to 0.7097 and from -5.5 to -6.3, respectively. Remarkably, gabbroic rocks 436 437 commonly show more radiogenic values for Nd and range in composition from 0.7081/-5.9 to 0.7099/-6.8; overall, a similar behavior is observed in the 1000/Sr vs. <sup>87</sup>Sr/<sup>86</sup>Srt diagram 438 439 (Supplementary Material Figure 2). A partial overlap in isotopic data between these groups of rocks 440 is represented by tonalites, confirming field observations of mingling relationships with gabbroic rocks. 441

In the Rb-Sr and Nd-Sm isochron plot (Supplementary Material Figure 3), only the granodioritic
rocks and microgranular quartz-gabbros cluster on a 286 Ma reference line (according to published
Pb/Pb chronological data: Secchi et al., 2021), whereas gabbroic rocks show scattered values.

Peraluminous granites belonging to Monte Maria and peraluminous rhyolitic dikes show constant  $\epsilon Nd_{(t)}$  (-7.5) and extremely high  ${}^{87}Sr/{}^{86}Sr_t$  in the range of 0.7154÷0.724, respectively, which approach to a supracrustal endmember.

448 Metaluminous to sub-aluminous granite rock-types belonging to *stage 2* (i.e., Monte Sette Fratelli 449 and San Priamo), which occupy the northern side of the pluton, form an independent group showing 450 a flat trend in the Sr–Nd diagram (barred symbols in Fig. 8; Conte et al., 2017). They exhibit a wide 451 Sr isotopic composition, from 0.703 to 0.7095 and, conversely, a quite homogeneous  $\varepsilon Nd_{(t)}$  value of 452 about –7.5 that does not differ from the field of metaluminous felsic dikes reported in Ronca et al. 453 (1999).

In general, in the  ${}^{87}$ Sr/ ${}^{86}$ Sr<sub>t</sub> vs.  $\epsilon$ Nd<sub>(t)</sub> diagram (Fig. 8), mafic dikes overlap the trend described by the entire *stage 1* ranging from 0.7068/–2.9 to 0.7097/–6.2. Is to be noticed that lesser and roughly constant radiogenic compositions (0.7053/–1.35) are recorded for late mafic (tholeiitic) dikes hosted in leucogranites.

Further petrogenetic information may be provided by the Nd crustal residence ages for granites and basaltic dikes, on account of a crustal origin proposed in literature (Ronca et al., 1999; Conte et al., 2017) and of mafic/felsic magma interactions described in the previous geological section, respectively. Given the observed linear correlation between Sm/Nd and two-stage Nd crustal residence age, a two-stage model is here preferred. Overall, calculated model ages are in the 1.4 - 1.6Ga range reported for European Variscan chain (Janoušek et al., 1995; Downes et al., 1997; Villaseca et al., 1998). In detail, two-stage Nd crustal residence ages calculated for basaltic dikes are in the range of 1.25 - 1.61 Ga and decrease to 1.11 in olivin-phyric tholeiitic basalts. Metaluminous/subaluminous granites and dikes are in the range of  $1.44 \div 1.50$  Ga; higher values clustered to 1.59 Ga have been obtained for peraluminous granites and dikes.

468 On the granodiorite sample dated by U-Pb zircon ages by Secchi et al. (2021), Lu-Hf analyses on 469 dated zircons were performed (Supplementary Material Table 4 and Figure 4).  $^{176}$ Hf/ $^{177}$ Hf ratios for 470 Cala Regina granodiorite (sample SPP2) are between 0.282441 and 0.282621.  $\epsilon$ Hf<sub>(t)</sub> recalculated back 471 at 286 Ma (Secchi et al. 2021) provided negative values, between -5.6 and -1.0, but a single positive 472 value was also found at 0.5.

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- 474

#### 475 **Discussion**

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### 477 *Geological constraints for Sarrabus magmatism*

The emplacement of Sàrrabus pluton occurred in a crustal segment likely made up of an ancient (Proterozoic) basement belonging to northern Gondwana margin overthrusted by Paleozoic nappes dominated by Cambro-Ordovician anchimetamorphic sedimentary rocks (Carmignani et al., 1994; Edel et al., 2014).

482 Field (Secchi et al., 2021) and geochronological data discussed in the previous geological section provide evidence of rapid emplacement at shallow crustal levels (1-2 kb: Conte et al., 2017; Secchi 483 et al., 2021) of a wide variety of compositionally different magma pulses: (a) mafic/granodiorite 484 485 mingling relationships, the lack of contact metamorphic aureole and syn-magmatic deformation; (b) granitic pulses that unconformably crosscut granodiorite flat intrusions with steep contacts; (c)486 undistinguishable ages, clustered at 286 Ma, based on several isotopic systematics on stage 1 and 487 stage 2 units (Nicoletti et al., 1982; Di Vincenzo et al., 2005; Dack, 2009; Secchi et al., 2021); (d) 488 489 occurrence of substantially coeval bimodal basaltic/rhyolitic dikes.

490 Stage 1 melt ascending is controlled by a dilatant roughly EW trending shear zone (the SSSZ) that 491 acted as a feeder for magmas and records mingling relationships between granodiorites and gabbroic 492 magmas. Indeed, the dilatant style of the SSSZ channelized the migration of large volumes of mantle-493 derived magmas up to upper crustal levels. Moreover, a close field association with peraluminous 494 granites is observed (i.e., Monte Maria Unit; Fig. 2). Conversely, a succession of independent granitic 495 magma pulses that share a common F-rich ferroan character marks the *stage 2* (Fig. 5d). In this stage, 496 mantle-derived magmas are only represented by few mafic dike swarms, representing a late
497 generation of olivine-plagioclase phyric basalts with tholeiitic affinity (Ronca et al., 1999; Conte et
498 al., 2017).

499

### 500 Petrogenetic constraints for Sàrrabus magmatism

501 Several lines of evidence support for the Sàrrabus pluton an early involvement of mantle-derived 502 magmas and a progressive more relevant production of crustal-derived magmas. Overall, each rock-503 types shows distinctive petrographic and chemical characters which suggest independent evolution 504 paths.

Petrographic data allow to constrain the evolution of different magma pulses to upper crustal levels. Evidence in favor of a general low-pressure evolution for mafic magmas hosted in Cala Regina Group (<5 kbar) is the early appearance of orthopyroxene followed by calcic plagioclase and clinopyroxene; in addition, olivine shows peritectic relationships with orthopyroxene (Conte et al., 2018a). The increase of water content in melts, testified by amphibole + dark mica segregation, characterizes the quartz gabbroic varieties; moreover, amphibole (Fe-hornblende) and dark mica of similar composition become the only mafic minerals within the assemblage of granodiorites.

512 Generation of different granitic magmas is constrained by the occurrence of garnet, muscovite and 513 rare cordierite in Monte Maria Unit peraluminous rocks and, conversely, by the early appearance of 514 hastingsite in metaluminous granites (Monte Sette Fratelli Unit). An upper limit of 5 kb for magma 515 evolution (e.g., Green, 1977; Dahlquist et al., 2007 and references therein) is further confirmed for 516 Monte Maria granite by homogeneous garnet compositions (spessartine contents > 10%), coexisting 517 with cordierite.

Isotopic data constrain a general model for Sàrrabus magmatism. Sr-Nd systematics well 518 document the contrasting behavior between two different groups of crustal-derived (peraluminous 519 520 and metaluminous/subaluminous) granitic magmas and a small homogenous granodiorite field unrelated to the higher variation of the trend displayed by gabbroic magmas (Fig. 8). In addition, 521 further evidence in favor of an independent origin between the mafic and granodioritic suites forming 522 the Cala Regina Group is provided by serial affinity (Fig. 5c) and REE normalized patterns (Fig. 6a). 523 In detail, the gabbroic rocks are generally LREE-enriched with respect to granodiorites; conversely, 524 525 cumulitic varieties suggest that the segregation process for gabbroic parent melts produced a decrease in the LREE content. Granodiorites are more fractionated in LREE with respect to gabbroic rocks, 526 527 but also show a more pronounced negative Eu anomaly, thus indicating that plagioclase fractionation in granodiorites has differently affected the REE compositions. The dual signature of gabbroic rocks 528 pointing to none, or small segregation of plagioclase indicates different *P*-*T* conditions for the parental 529 melts during fractionation, thus suggesting a vertically zoned magmatic reservoir. 530

In a general extensional setting, the ascent of gabbroic magmas at middle/upper crustal levels may provide the necessary heat input to cause dehydration melting of biotite and muscovite in metasedimentary rocks and promotes the generation of peraluminous granitic melts belonging to the *stage 1*. In this scheme, evidence in favour of a source located in the middle crust is the general lowpressure (<5 kbar) evolution indicated for gabbroic magmas by textural relationships. In addition, generally flat REE patterns lead to exclude a garnet-bearing source.

As expected by geological relationships and petrographic characters, mafic and felsic dike swarms
overlap the trends observed for rocks belonging to *stage 1* and *stage 2*, respectively.

A genetic model involving contamination and crystal/liquid fractionation process has been already 539 proposed to explain the magmatic evolution observed for gabbroic magmas of Scala Carbonara body 540 541 (SC in Fig. 2) contaminated by granodioritic magma (Poli and Tommasini, 1999). The different behavior of gabbroic and granodioritic magmas point to different compositions and evolutions of the 542 parent melts. Overall, an enriched mantle source is inferred from Ta/Yb-Th/Yb plot for gabbroic 543 magmas and for selected mafic dikes from Sàrrabus pluton, in agreement with data reported by 544 Gaggero et al. (2007) for lamprophyric dikes from northern Sardinia (Supplementary Material Figure 545 5). In addition, mafic rocks of the Sàrrabus pluton shows several degrees of crustal assimilation as 546 revealed by Rb, Ba, Th and U concentrations which are relatively high and negative ENd also in 547 cumulate gabbroic rocks (Fig. 7). This implies consequences with regard to isotope ratios: Nd model 548 ages for these rocks are actually meaningless, being calculated on mixed isotopic composition derived 549 by several sources. Moreover, different isotopic trends displayed by gabbroic rocks and granodiorites 550 suggest that the mantle-derived melts interacted with different crustal components and could be re-551 equilibrated at different crustal levels. 552

According to Conte et al. (2017), metaluminous to sub-aluminous granitic magmas require processes of partial melting involving lower crustal level of mostly intermediate/mafic composition, as confirmed by whole-rock initial Pb isotopic compositions of metaluminous to subaluminous granites (i. e., San Priamo and Monte Sette Fratelli units which plot in the lower crust field in the <sup>206</sup>Pb/<sup>204</sup>Pb–<sup>208</sup>Pb/<sup>204</sup>Pb plot in Conte et al., 2017).

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#### 559 Evaluating the involvement of crustal materials

560 An essential assumption of our models of magma genesis and the relation to Nd isotopes is the 561 involvement of pre-existing continental crustal material (with low  $\varepsilon$ Nd and relatively high Nd 562 concentration) and/or contribution from sub-continental lithospheric mantle (SCLM) (with high  $\varepsilon$ Nd 563 and moderate Nd concentration) in the generation of mafic and granitic magmas. The <sup>147</sup>Sm/<sup>144</sup>Nd 564 ratio in a reservoir is expressed as the enrichment factor relative to CHUR as  $f_{\rm Sm/Nd} =$ 

(<sup>147</sup>Sm/<sup>144</sup>Nd<sub>sample</sub>)/(<sup>147</sup>Sm/<sup>144</sup>Nd<sub>CHUR</sub>) – 1 after De Paolo and Wasserburg (1976). According to De 565 Paolo et al. (1992) the fractional isotopic shift from mantle (MC) to crustal (CC) ENd values can be 566 described by the Neodymium Crustal Index (NCI): NCI =  $[\epsilon Nd(rock) - \epsilon Nd(MC)]/[\epsilon Nd(CC) - \epsilon Nd(MC)]/[\epsilon Nd(CC$ 567 ɛNd(MC)]. NCI thus describes the fraction of crustal Nd in a rock. NCI is 0 when the rock has no 568 569 crustal Nd (the ENd value is equal to the mantle MC source value) and 1 when all Nd in a rock has a crustal origin (the ENd value is equal to the crustal CC value). Surveying local data, we have 570 considered MC = +8 and CC = -15 for NCI calculation, representing MC – an average composition 571 of the YMP mafic rocks from Sardinia (Gaggero et al., 2007), and CC - composition of the most 572 crustal metasedimentary schist from the Sardinia basement (Di Vincenzo et al., 1996). Nd isotopic 573 compositions of mafic/felsic rocks from Sàrrabus pluton and available data from entire Sardinia range 574 from near model mantle values to near model crustal values (Fig. 9a). Moreover, collected data show 575 slightly negative correlation in the  $f_{Sm/Nd}$  vs. NCI plot, and partial coincidence of mafic rocks with 576 granitic rocks. The abnormally high NCI = 0.62 - 0.75 for the mafic rocks was likely caused by fluid-577 metasomatism of pre-existing SCLM or related to contamination with (amphibolitic) lower crust. 578 This enrichment is obvious from  $f_{\text{Sm/Nd}}$  vs.  $\epsilon \text{Nd}_{(286)}$  plot (Shirey and Hanson, 1986; Fig. 9b) where 579 both mafic and felsic rocks from Sàrrabus pluton lie in the quadrant characterized by crustal 580 enrichment (i. e. negative  $f_{\text{Sm/Nd}}$  and  $\varepsilon \text{Nd}_{(i)}$  values; Fig. 9b). 581

582 Such mafic/felsic intrusions, that have initial Nd isotope ratios below to the chondritic value (ENd < 0), indicate possible SCLM sources that are chemically enriched/metasomatized, and thus different 583 from the MORB or volcanic-arc basalt sources. Although the Sr-Nd isotopic characteristics of 584 particularly mafic components are quite atypical, nevertheless it is possible to model the mixing 585 586 between the mafic component (sample SSP6b from a mafic dike) and the crustal ones (sample SSP59, from peraluminous granite: Fig. 10). Obviously, from the presented model, the crustal source is 587 dominant (80–85%) in the genesis of granodioritic magmas, as also supported by negative  $\varepsilon Hf(t)$ 588 values, while the concomitant mafic components with unusually high negative ENd(286) over -4 (Fig.s 589 8 and 10) show considerable crustal enrichment or fluid-metasomatism. 590

591 This large involvement of crustal materials is coherent with negative EHf values of granodiorites zircons and the large compositional gap emerging from Sr-Nd systematics for Corsica and northern 592 Sardinia granitoids with respect to Sàrrabus pluton (Fig. 8), that was inherited from deep sources of 593 granite magmas and related to the thermal structure of different lithospheric fragments assembled 594 during the Variscan collision in the Sardinia-Corsica massif. The more radiogenic signature and the 595 value of  $\delta^{18}O_{SMOW}$  = +8.4 ‰ (Brotzu et al., 1981) observed for mafic suites and associated 596 granodiorites from Sàrrabus pluton does not conflict with an earlier contamination stage and different 597 598 residence times at lower crustal levels with respect to the northern Sardinia/Corsica suites.

#### 600 Mantle-crust interactions and nature of involved crustal materials

601 When considering the genesis and emplacement of Sàrrabus magmas, which belong to a reworked crust of the northern Gondwana margin thinned during the collapse and exhumation of the Variscan 602 603 chain (Casini and Oggiano, 2008; Rossi et al., 2015), a complex petrological model can be depicted. Schematically, in a commonly accepted regime of lithospheric mantle delamination (Edel et al., 2014; 604 Rossi et al., 2015), extensional shear zones, as the SSSZ, favoured the repeated ascents of mantle-605 derived magmas which experienced crystal/liquid fractionation (Poli and Tommasini, 1999; Conte et 606 al., 2018; Franciosi et al., 2019) and likely served as a heat source for melting of metasedimentary 607 crustal levels, producing peraluminous granite magmas in stage 1. 608

609 Tommasini et al. (1995) pointed out that the main geochemical characters of the Sardinian high-K and I-type calcalkaline granitoids suggest a dominant derivation from partial melting of 610 metaigneous and igneous-derived materials belonging to a volcanic arc linked to an Ordovician 611 612 subduction. Remarkably, this group of granites and rhyolitic dikes overlaps the field of felsic granulites belonging to the Central Spanish Variscan System (Villaseca et al., 1998); an overlap with 613 lower crustal sources was also inferred by Pb isotopic data obtained for SPU leucogranites. According 614 to Conte et al. (2017), granitic rocks like MSFU, which plot in the III quadrant of <sup>87</sup>Sr/<sup>86</sup>Srt vs. εNd<sub>(t)</sub> 615 diagram, have isotopic values which are rather uncommon at the scale of entire European Variscides. 616 Accordingly, the two-stage T<sub>DM</sub> crustal residence ages calculated for Sàrrabus granites overlap 617 those calculated for Cambro-Ordovician orthogneisses from northern Sardinia and central Iberia (Di 618 Vincenzo and Ghezzo, 1996; Villaseca et al., 1998). On the other hand, the geochemical/metallogenic 619 and lead isotopic signatures of the F-rich, ferroan granites indicates the derivation from meta-igneous 620 sources in the lower crust (Conte et al., 2017). This provenience from a deep source for the 621 622 metaluminous/subaluminous products of the Sàrrabus pluton stage 2 may also assume the significance of a possible derivation from an inferred and more ancient (Proterozoic) volcanic arc, 623 624 rooted in a crystalline basement under the cover of Paleozoic nappes.

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#### 627 Conclusions

The Sàrrabus pluton documents a sequence of magmatic events which record a repeated bimodal character in which different mantle-derived and crustal-related magmas, whose ascent was controlled by dilatant extensional faults, are recognized. Several lines of evidence suggest a complex frame of mafic magmas promoting partial melting of continental crust, as well as continuous mafic/felsic magma interactions decreasing in time at different crustal levels. In the general late orogenic context of the frontal zone of the Variscan wedge, it is possible to hypothesize different scenarios capable of

explaining thermal anomalies and magma production. Radiogenic heating of previous thickened crust 634 and shear heating are mechanisms that can account for the heat supply consistent with generation of 635 large volume of crustal melts. LID delamination is a further mechanism that from syn- to post-636 collisional settings can transfer large amount of heat from the mantle into the crust of evolving 637 638 orogenic belts. Delamination models may be applied to the Variscan granitic provinces even in absence or scarcity of mantle magmas. Indeed, mixing processes, assimilation and mingled zones are 639 clues for mantle contributes to the building of the Variscan batholiths, including the Corsica-Sardinia 640 Batholith. The Sàrrabus pluton intruded at 286 Ma in a slightly thickened frontal portion of the 641 orogenic wedge, where low levels of radiogenic heating are expected and syn-intrusive shear heating 642 is not documented. Therefore, these two heat sources can hardly account for the melting of the crust 643 644 in this part of the Variscan chain. Conversely, the progressive migration of delamination away from the suture zone located in Northern Sardinia, down to Central-Southern Sardinia and Sàrrabus, could 645 646 have heated the crust up to temperatures close to 1000 °C, which might lead to crustal melting at different crustal levels. A further hypothesis may consider the high heat flux produced by a possible 647 lithosphere necking triggered by pre-existing weak zones in the mantle, determining astenospheric 648 uplift to the crust base; the far field stress able to initiate necking in an already stiffed Variscan crust 649 could be envisaged in the plate reorganization the led to the Pangaea. 650

Whatever was the actual large-scale heating mechanism, stretching conditions of Sàrrabus crust favored the partial melting of different crustal levels by a heat input from mantle-derived gabbroic magmas. In this context, a regime of decreasing temperature of the crust may account for the marked bimodality of diking activity, which inhibits the production of voluminous granodioritic magmas by mixing processes.

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Fig. 1: simplified geological map of Sardinia-Corsica batholith (after Casini et al., 2012). 1-4:
metamorphic basement. (1) Pan-African schists. (2) Unmetamorphosed Foreland. (3) Low- to
medium-grade metamorphic units (nappe zone). (4) High grade metamorphic complex. 5-6 SardiniaCorsica batholith. (5) Syn-collisional Variscan magmatism (Mg-K rock-series). (6) Late-Variscan
post-collisional magmatism. (7) Post-Variscan covers. Other symbols: main Variscan faults (8). From
north to south, Arg, SM, Arz, Br, Gn, Gh, Arb and SV refer to localities cited in the text (Santa Maria
Island, Arzachena, Barrabisa, Gennargentu, Grighini, Arburèse and San Vito, respectively).

Fig. 2: Geological sketch map of late-Variscan Sàrrabus pluton (SE Sardinia, Italy). (1) 907 Undifferentiated epimetamorphic complex: metasandstones, metapelites and metalimestones 908 (Cambrian-early Carboniferous). (2-8) Late-Variscan igneous units of Sàrrabus pluton: (2) Two-909 pyroxene biotite gabbro tonalites (Burcèi Unit). (3) biotite to biotite hornblende granodiorites (Cala 910 Regina Group) with syn-plutonic stocks and dismembered dikes of two pyroxene-bearing hornblende 911 gabbroic varieties (Solànas complex; SO). (4) Garnet-bearing two mica granites (Monte Maria Unit). 912 (5) biotite monzogranites grading to leucogranites (Bruncu Nicola Bove Unit). (6) F-rich biotite 913 leucogranite (San Priamo Unit). (7) F-rich hastingsite granite stocks (Monte Sette Fratelli Unit). (8) 914 Mafic and acidic dike swarms. (9) Post-Mesozoic sedimentary and volcanic covers and recent 915 continental and transitional sedimentary deposits. Other symbols (10-12). Late-Variscan southern 916 917 Sàrrabus shear zone (SSSZ) (10). Main extensional faults, certain (11) and inferred/buried (12). CR, Ge, TF, So, SC, Vs, Ca, S.P., Bu, S.G. and M. SF refer to Cala Regina, Geremèas, Torre de su Fenugu, 918 919 Solànas, Scala Carbonara, Villasimius, Castiadas, San Priamo, Burcei, San Gregorio and Monte Sette Fratelli localities cited in the text, respectively. 920

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Fig. 3: Field relationships of Sàrrabus igneous rocks. (a) Sub-horizontal magmatic foliation of 922 hornblende granodiorites evidenced by dark and felsic enclaves (FE; Capo Carbonara). (b) strongly 923 foliated quartz diorites with large mafic enclaves of quartz gabbroic composition (Porto Murròni); (c) 924 densely interdigitation between gabbroic rocks and quartz diorites (western slope of Torre de su 925 Fenùgu); (d) disrupted large syn-magmatic mafic dikes into granodiorite (western slope of Torre de 926 su Fenùgu); (e) contact relationships between different dike generation: composite dikes predate 927 metaluminous acidic dikes (Cala Regina); (f) fine-grained centimetric rounded dark enclaves in acidic 928 dike (Porto Murròni). 929

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Fig. 4: Petrographical characters of magmatic rocks from Sàrrabus igneous massif. (a) two pyroxenebearing equigranular gabbroic rocks from inner part of Scala Carbonara body (crossed polars; Scala Carbonara, sample SSP16,); (b) panidiomorphic textures of quartz microgabbros (crossed polars; sample SSP17; Capo Carbonara); (c) cumulophyric texture of olivine-bearing dark layers from stratified septa (crossed polars; Cabu Oi, sample SSP29); (d) clinopyroxene/brown amphibole relationships in equigranular varieties of mafic dike (crossed polars; north of Olia Speciosa, sample ESP10); (e) local plagioclase enriched zones in hornblende quartz diorites (crossed polars; sample SSP8, Porto Murroni; (f) large patchy-zoned plagioclase lath on Cala Regina granodiorites (crossed polars; Monte Nai, sample ESP1); (g) interstitial white mica in San Priamo leucogranites of (plane polarized light; Monte Gruttas, sample SPP9); (h) Almandine garnet associated to pinitized cordierite in peraluminous granites of Monte Maria Unit (plane polarized light; Porto Carbonara, sample LPC).

- Fig. 5: Discrimination diagrams for the igneous rocks from Sàrrabus pluton. (a) Boundaries according
  to Peccerillo and Taylor (1976); (b) discrimination diagram for basaltic rocks. HAB and HMB refer
  to high alumina and high Mg basalts, respectively; boundaries according to Miyashiro (1974). (c) and
  (d) Frost's and Frost (2001) discrimination diagrams. C, CA, AC and A refer calcic, calc-alkalic,
  alkali-calcic and alkaline rock-series, respectively. Pale and smaller symbols refer to literature data.
  Literature after Poli and Tommasini (1999) and Franciosi et al. (2019) is reported for comparison.
  Fields refer to mafic and acidic dike swarms (data after Ronca et al., 1999).
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Fig. 6: REE normalized patterns for Sàrrabus magmatism: (a) syn-plutonic gabbroic suite; solid, 951 952 double and dashed lines refer to olivine-bearing cumulate, two pyroxene-bearing gabbros and 953 hornblende Qz-gabbros, respectively. Light and pale blue fields refer to data for olivine-bearing cumulates and hornblende Qz-gabbros (Franciosi et al., 2019), respectively. (b) Granodiorite rock-954 association; solid, double and dashed lines refer to Qz-diorite, tonalitic granodiorite and foliated 955 granodiorite, respectively. The solid field refers to data for granodiorites after Franciosi et al. (2019); 956 (c) mafic dikes; solid field refers to data for basalts from Ronca et al. (1999); (d) granites and felsic 957 dikes; solid, dashed and dotted lines refer to peraluminous granite, metaluminous dikes and 958 peraluminous dike (data after Ronca et al., 1999), resepctively. Dark and pale yellow solid fields refer 959 to San Priamo and Monte Sette Fratelli granites, respectively (data after Conte et al. (2017). Data are 960 normalized to CI (Mc Donough and Sun, 1995). Labels in (c) as in Supplementary Material Table 1. 961 962

Fig. 7: Spider diagrams for syn-plutonic mafic (a) and granodiorite (b) rock-associations from
Sàrrabus pluton normalized to primitive mantle (McDonough and Sun, 1995). Peraluminous granite
is reported for comparison.

Fig. 8: ɛNd(t) vs. <sup>87</sup>Sr/<sup>86</sup>Sr(t) for late-Variscan rocks from Sàrrabus pluton (south-eastern Sardinia, 967 Italy) calculated for an age of 286 Ma (see text). Red, orange, and blue colors refer to Corsica, Gallura 968 969 (northern Sardinia) and Sàrrabus pluton, respectively. Circle refer to peraluminous garnet-bearing granite from Monte Maria Unit. Barred circles refer to metaluminous to sub-aluminous granites of 970 San Priamo and Monte Sette Fratelli units (data after Conte et al., 2017). Dike trend refers to mafic 971 to intermediate dikes from Sarrabus pluton (data after Ronca et al., 1999). Data for Corsica mafic 972 suites after Cocherie et al. (1994); data for Gallura mafic suites after Tommasini et al., 1995 (Punta 973 Falcone) and Casini (Bortigiadas and La Etica), still unpublished data; mafic (subalkaline and 974 975 transitional) dikes after Gaggero et al., 2007). Dark blue arrow refers to gabbros to hornblende quartz micro gabbros evolutive line (with olivin-cumulites at left hand). Note the position of granodiorites 976 outside of evolutive sequence and the intermediate position of tonalites for which a hybrid origin is 977 required. Note also that less evolved granodiorites (i.e., Scala Carbonara and Capo Carbonara) show 978 a more radiogenic character with respect of Solànas granodiorites (Porto Murroni). 979

980 Fig. 9: a) f(Sm/Nd) vs. NCI plot for the Sàrrabus pluton and other available Sardinia samples. fSm/Nd 981 =  $(^{147}\text{Sm}/^{144}\text{Ndsample})/(^{147}\text{Sm}/^{144}\text{NdCHUR}) - 1$  (DePaolo and Wasserburg, 1976); NCI = [ $\epsilon$ Nd(rock) 982  $- \epsilon Nd(MC)$ ] / [ $\epsilon Nd(CC) - \epsilon Nd(MC)$ ] according DePaolo et al. (1992). Field refer to metasediments 983 from central-eastern Sardinia (data after Di Vincenzo et al., 1996). b) f(Sm/Nd) vs. ɛNd(286) plot for 984 the Sàrrabus pluton and other available Sardinia sample. DM, EM and CC are according to Hodkinson 985 et al. (1995). Field refer to orthogneisses and migmatites from central-eastern Sardinia (data after Di 986 Vincenzo et al., 1996). Other symbols as in Fig. 5. 987 988

Fig. 10: Mixing binary plot of <sup>87</sup>Sr/<sup>86</sup>Sr<sub>(286)</sub> vs. εNd<sub>(286)</sub> showing variability of rocks from Sàrrabus
pluton. Symbols as in Fig. 5 and 10; numbers refer to SSP samples reported in Supplementary
Material Table 3. Dashed lines refer to possible mixing hyperbolas obtained by reverse least-squares
method (Janoušek et al., 2016) using SSP6b (mafic dike) and SSP59 (peraluminous granite) samples
as mantle- and crustal-derived endmembers, respectively to model the observed granodiorite rockassociation. Pale field refer to data for granodiorite rock-association after Poli and Tommasini (1999)
and Franciosi et al. (2019).

















Figure 8







# TABLES

Bt + Ms + Fe-ChlActin+Cumm Actin+Cumm Actin+Prgs Late-stage FI + AnnTc + CcCumm Turm Turm Tum I Zrn + Ap + All + Mnz + Ilm + MtTab. 1 -Summary of petrographic features for late-Variscan intrusives and dikes from Sàrrabus igneous massif (south-eastern Sardinia, Italy)  $Ti-Mt + Ilm + Sulf + Ap \pm All$  $IIm + Ap + Aln + Mon \pm Tit$ Ti-Mt + Ilm + Sulf + Ap $Ilm + Zrn + Ap \pm Mnz$  $Ilm + Zrn + Ap \pm Mnz$ IIm + Ap + Zrn + SulfAln + Mt + Zrn + ApTit + Mt + Ap + IlmAccessory phases llm+Tit+All+Zrn Aln + Mt + ZmIIm + Zrn + ApIIm + Ap + ZirMt + Ap $PI + Opx + Cpx \pm HbI \rightarrow PI + Bt + Kfs + Qz$  $Qz+Kfs+Pl+Bt+Gt+Ms\pm Chrd$  $Mg-Hbl + Pl + Bt + Qz \pm Opx \pm Cpx$  $PI + Mg-HbI + Bt + Qz \pm Kfs \pm Opx$  $Pl + Hbl + Qz \pm Bt \pm Opx \pm Cpx$ Pl + Qz + Kfs + Bt + Opx + Cpx $Qz+Kfs+Pl+Bt\pm Ms\pm And$ PI + Kfs + Qz + Fe-HbI + Bt $Qz + Kfs + Pl + Bt \pm Fe-Hbl$ SF: Qz + Kfs + Pl + Hs + AnnOI + Opx + Cpx + PI + Qz $OI + PI \rightarrow Cpx + PI \pm HbI$ Fundamental phases  $Pl+Cpx\pm Ol+Qz$ BNB: Qz + Kfs + Pl + BtQz + Kfs + Pl + BtSP: Qz + Kfs + Pl + BtPanhydiomorphic/Hypidiomorphic Porphyritic to hypidiomorphic Microgranular to granophyric Microgranular/porphyritic Leucogranites to monzogranites Hypidiomorphic Hypidiomorphic Hypidiomorphic Hypidiomorphic Hypidiomorphic Hypidiomorphic Rock-textures Pecilophytic Porphyritic Sub ophitic Porphyritic Peraluminous granite (MM) Peraluminous felsic dikes Gabbrotonalites (BU) (basalts to andesites) Gabbroic rocks (CR) Granodiorites (CR)) Latest mafic dikes (tholeiitic basalts) (BNB, SP and SF) Mafic dikes Felsic dikes Rock-types 7 9801S I Stage 1

Gt = garnet; Ms = white mica; And = andalusite; Chrd = cordierite; Ol = olivine; Ilm = ilmenite; Ap = apatite; Mon = monazite; Aln = allanite; Zrn = zircon; Sulph = sulphides; Mt = magnetite; Alb = albite: Fl = fluorite; Ann = annite; Actin = actinolite; Cumm = cummingtonite; Prgs = pargasite; Fe-Chl = Fe-chlorite; Tc = talc. Talc observed in mafic dikes formed at the expense of olivine phenocrysts. Ortho- and clinopyroxene observed in Burcei gabbrotonalites and gabbroic rocks belonging to Stage 1 show commonly a hypersthene CR, BU, MM, BNB, SP and SF refer to, Cala Regina Group and Burcei, Monte Maria, Bruncu Nicola Bove, San Priamo and Monte Sette Fratelli rock-units reported in Fig. 2. Abbreviations list for mineral phases: Pl = plagioclase; Qz = quartz; Kfs = K-feldspar; Bt = biotite; Hbl = hornblende; Opx = orthopyroxene; Cpx = clinopyroxene; Hs = hastingsite; and augitic composition, respectively; they are often replaced by actinolite and cummingtonite.

Table 1