BUILDING THE MONTE CAPANNE PLUTON (ELBA ISLAND, ITALY) BY MULTIPLE MAGMA BATCHES

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INTRODUCTION

Field observations, geophysical and geochronological data indicate that many igneous bodies grow by amalgamation of successive magma sheets (Glazner *et al.*, 2004). This observation has the crucial consequence of depicting the feeding of a pluton as a process characterized by the injection, over time, of a number of discrete pulses of magma(s) opening a series of questions regarding the entire evolution of granitic systems, from magma genesis to emplacement. The discrete growth stages of an intrusion, can be marked by internal contacts that are mappable at the plutonic scale. However, only rarely are internal contacts mappable in a traditional way. Most commonly, these contacts are cryptic, and the detection of internal magma batches relies on detailed studies using a combination of different techniques.

An integrated field and geochemical approach has been applied to the Monte Capanne pluton in order to recognize and map the different magma pulses forming the intrusion. A quantitative method, based on megacryst amount per unit area (area %) has been proposed. Compared to a classification based on qualitative field observations, the proposed method allows the definition of numerical limits (percentage amount of K-feldspar megacrysts) among intrusive facies that can be used with appropriate software to automatically build a contour map of facies distribution. The petrographic intrusive facies defined by this method will be verified and strengthened using additional petrographic and geochemical data in order to decipher the origin of different facies and their relationship to build the pluton.

GEOLOGICAL BACKGROUND

In late Miocene time, as extensional processes affected the area of Elba Island, an intrusive complex was progressively emplaced. The igneous sequence started in western Elba with the construction of a nested laccolith that was intruded by the Monte Capanne pluton and its associated late leucogranite-pegmatite dikes. The monzogranitic pluton is roughly circular, and with its 10 km diameter, represents the largest pluton exposed in the Tuscan Magmatic Province. It is bordered along two-thirds of its perimeter by contact metamorphosed rocks, whose mineral assemblages, coupled with stratigraphic measurement of the overburden, indicate an emplacement depth of around 6 km. The Monte Capanne pluton is characterised by the widespread occurrence of K-feldpar megacrysts whose content is strongly variable across the intrusion (Marinelli, 1959; Dini *et al.*, 2002).

K-FELDSPAR MEGACRYSTS: A MAPPING MARKER

The distribution of K-feldspar megacrysts (MKx) has been used to define intrusive facies as well as to determine their spatial distribution and map their exposure in the field. In order to determine the numerical limits of facies, megacrysts have been defined in terms of their size, and counting criteria were established that best expressed the variability observed in the field.

K-feldspar megacrysts definition

Recognizing MKx in the field means being able to define their lower size limit, *i.e.* define a grain size separating megacrysts and "groundmass". The minimum threshold grain size for a crystal to be defined a megacryst has been obtained through Crystal Size Distribution (CSD) analysis carried out in two areas representing the granite types that are most and least enriched in large K-feldspars. Data obtained from the study of outcrops and slabs were converted to three-dimensional data using the program "CSDCorrection" (Higgins, 2000) and the results were plotted on a diagram of population density (n(L)) versus crystal size (L). The CSDs for the two areas show a major break in slope occurring between 15 and 22 mm (corresponding to crystals of about 2 cm^2), thus identifying two populations of K-feldspar crystals. The first population defined by steep slopes mainly represents the anhedral crystals of the matrix, while the second population is characterised by more gentle slopes and includes exclusively euhedral, prismatic K-feldspar crystals. The lower size threshold of megacrysts can thus be put at an area of 2 cm^2 (L = 20 mm; Fig. 1). This size threshold has been used in the fieldwork to determine MKx distribution throughout the pluton.

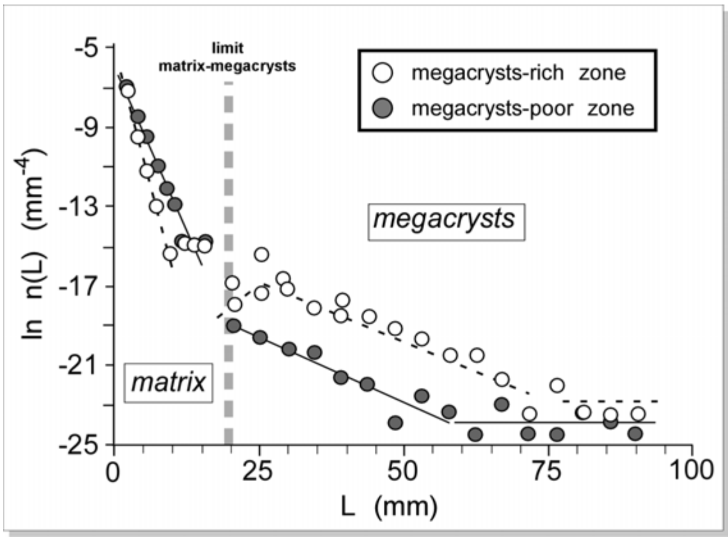

Fig. 1 – K-feldspars Crystal Size Distribution for zones most and least enriched in large K-feldspar. L(mm) is the crystal size defined as the maximum crystal length on outcrop/slab surface; n(L) is the number density.

K-feldspar megacrysts distribution

The megacryst abundance parameter have been collected at 351 stations over the whole Monte Capanne pluton (about 7 stations/km^2). In order to establish the best discriminating features the following parameters have been analysed for each station: i) the number of MKx for unit area; ii) the area of each MKx; iii) the percentage of area occupied by MKx in the rock (area %).

The resulting megacryst modal abundance (area %) is reported in Fig. 2a , that shows ill-defined minima of frequency at 0.7-0.8 and at 2.2-2.4%. These minima separate three zones of the plot: low-abundance, high-frequencies to the left, medium-abundance, medium-frequencies in the central part, and high-abundance, low frequencies to the right. This can be taken as indicative of the occurrence in the pluton of three different facies with distinctive megacryst frequency distribution.

On the basis of these starting observations, we performed a detailed study on the areas most enriched (close to Sant'Andrea village) and depleted (close to San Piero village) in megacrysts (Fig. 2b). Both data sets have a normal distribution, with strongly different average MKx contents: in the San Piero zone the area % is 0.26±0.21 (1σ), corresponding to about 4 megacryst/m^2; in the Sant'Andrea zone the area % is 3.37±0.56 (1σ), corresponding to about about 57 megacryst/m^2. Reporting these normal distributions on the whole-pluton frequency diagram of Fig. 2a, it is worth noting that the San Piero average values (±2σ) overlaps the low-abundance, high-frequencies interval, and the Sant'Andrea average values (±2σ) overlaps the high-abundance, low-frequencies interval. On the basis of these observations, we define: (i) a facies named San Piero when their area % is lower than 0.7; (ii) a facies named Sant'Andrea when their area % exceed 2.3%; iii) a facies named San Francesco when area % is between 0.7 and 2.3%.

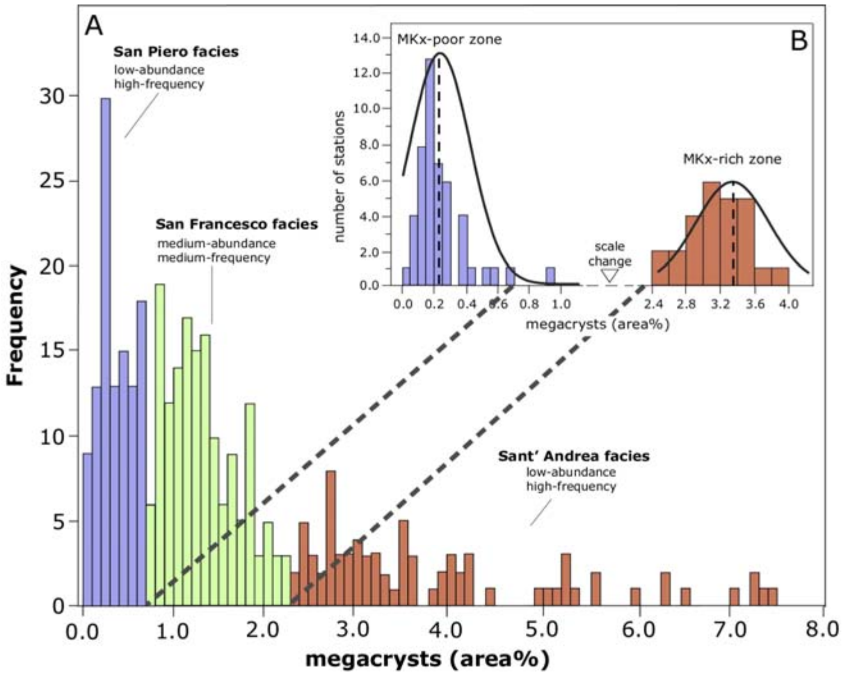

Fig. 2 – Definition of intrusive facies: A) Frequency histogram of eMKx modal content (area %) for the whole pluton based on the 351 station measured across the pluton; B) Frequency histograms of eMKx modal content at most and least MKx enriched type localities.

The map of intrusive facies

All the data obtained from the 351 counting stations were used to produce a detailed contour map of megacryst distribution in the Monte Capanne pluton (Fig. 3). For this purpose we used the Kriging Gridding Method of the Surfer 8™ code. The resulting map evidenced that:

- The Sant'Andrea facies crops out discontinuously as the external shell of the pluton, along the boundary with the country rock and on the morphologic highs.

- The San Piero facies crops out primarily in the eastern part of the pluton forming a continuous NNE-SSW belt, and generally in the morphologic lows where the deepest portions of the pluton are exposed by erosion.

- The San Francesco facies shows a variable extent between the San Piero and Sant'Andrea facies, from a few tens of metres width in an eastern zone, up to a couple of km in the central and north-western areas of the pluton.

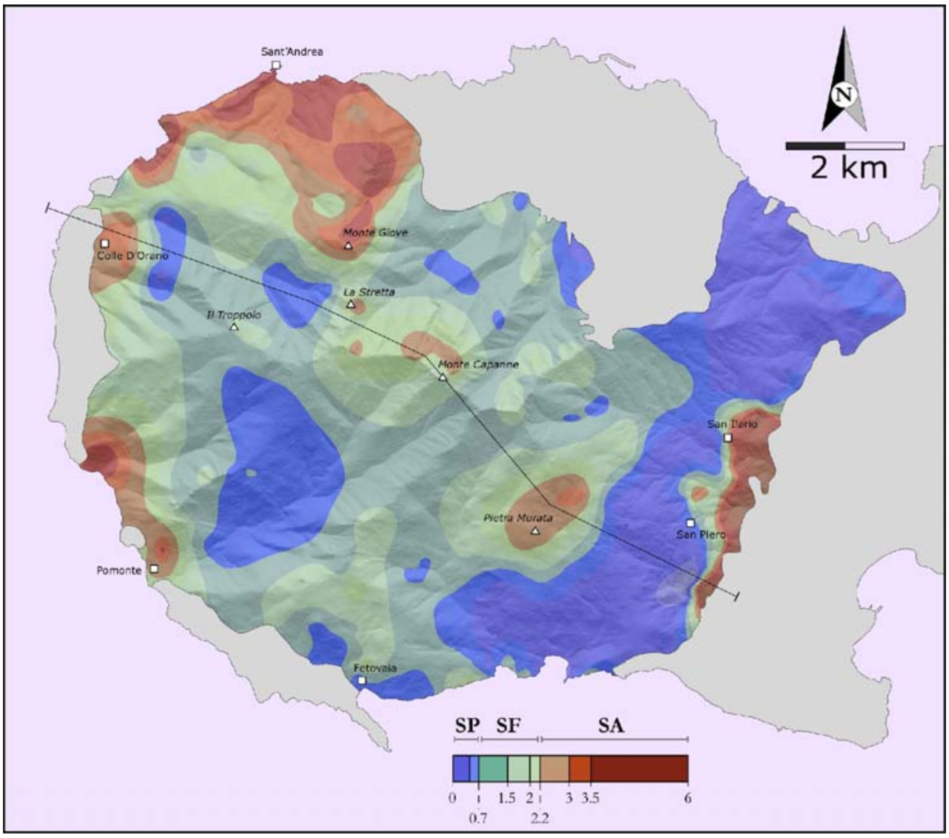

Fig. 3 – Countour map of Monte Capanne pluton. The contour map allows the direct visualization of megacrysts content variability in the pluton. Different intrusive facies (SP - San Piero, SF - San Francesco, SA - Sant'Andrea) are evidenced with different colours on the base of the thresholds defined above. Cross-section drawn through the Monte Capanne is reported in Fig. 5.

THE FACIES: GEOCHEMICAL DIFFERENCES

Whole rock analyses

The three facies display limited but systematic compositional differences as shown on selected major and trace element variation diagrams (Fig. 4a,b). The Sant'Andrea facies is the most felsic, with relatively high SiO_2 and low CaO, MgO, Fe_2O_3 and Al_2O_3 contents. The San Francesco facies defines an intermediate compositional field partly overlapping the characteristics of both the Sant'Andrea and San Piero facies.

Trace element distributions display limited yet significant variations among facies. Positive correlations exist between Sr and transition metals and Ba (Fig. 4b), with the San Piero facies being richest in all these elements. On the other hand, Rb, Pb, Th and Ta correlate negatively with Sr.

The Sr isotopic composition of samples from the Monte Capanne pluton is significantly variable ($^{87}Sr/^{86}Sr$ = 0.7144-0.7156; Fig 4c). Each facies shows a significant Sr isotope variability with a large overlap among them. Nevertheless, a systematic difference between the average $^{87}Sr/^{86}Sr$ ratios exists: 0.71506±0.00032 (1σ) for Sant'Andrea facies, 0.71478±0.00035 (1σ) for San Francesco facies, and

0.71474±0.00023 (1σ) for San Piero facies. The Nd isotopic ratios show a restricted range ($^{143}Nd/^{144}Nd$ 0.512164-0.512200), and no systematic differences among the facies exists.

Biotite mineral chemistry

Compositional data for biotites of the different intrusive facies define positive correlation trends between Al_{tot}, F and Fe/(Fe+Mg) (Fe#) coupled with a negative correlation between Si and Fe# (Fig. 4d). In particular, San Piero biotites have higher Si coupled with lower Al, F and Fe# than do Sant'Andrea biotites, with San Francesco biotites showing intermediate compositions. Thus, the Fe# is the most useful micro-chemical parameter to discriminate between the facies. San Piero biotites are characterized by the lowest Fe# values (average 0.49±0.01) while Sant'Andrea biotites have the highest values (average 0.54±0.01).

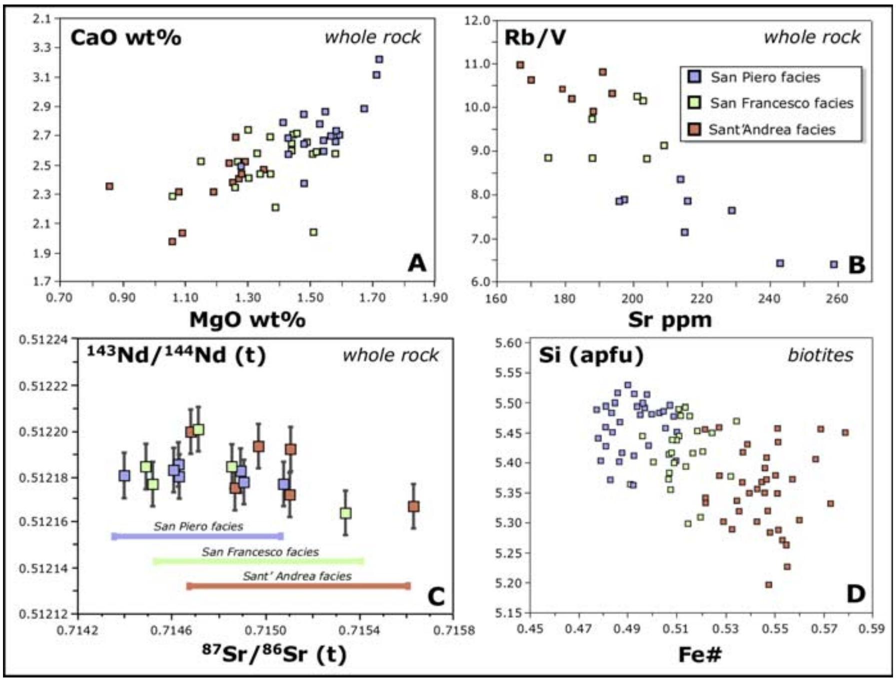

Fig. 4 – Geochemical differences among the intrusive facies. A) selected major elements binary diagrams; B) selected trace elements binary diagrams; C) initial $^{143}Nd/^{144}Nd$ *vs.* $^{87}Sr/^{86}Sr$ plot. Samples are plotted with their errors (±2σ), the error for $^{87}Sr/^{86}Sr$ is contained in the symbol. D) Major elements compositions for biotites. Chemical formulas calculated on the basis of 22 cation charges. Fe# is Fe/(Fe+Mg).

DISCUSSION

Origin of the intrusive facies

The distinct textural features of the intrusive facies of the Monte Capanne pluton, together with their significant and systematic geochemical, isotopic and mineralogical differences, raise important questions such as how, when and where the facies formed. In order to understand the origin of these intrusive facies, the following contrasting hypotheses must be taken into account and discussed on the basis of the whole data set:

1. They differentiated *in-situ* (*i.e.* at the emplacement level) from a single homogeneous batch of magma.

2. The two end-member facies represent two distinct batches of magma sequentially emplaced in the magma chamber, while the transitional San Francesco facies derived from in-situ mixing/mingling processes at their interface;

3. The three intrusive facies represent three distinct batches of magma sequentially emplaced to build the pluton.

The first two hypotheses can be discarded on the basis of the intrinsic geochemical, isotopic and mineralogical differences among the intrusive facies described in the previous chapters:

The first hypothesis contrasts with observations on trace element and isotopic composition of megacrysts compared with whole rocks and matrices. Even though the the Ba and Sr content of Monte Capanne megacrysts is systematically higher than their host (Franzini *et al.*, 1974; Gagnevin *et al.*, 2005), the Sant'Andrea megacryst-rich facies shows Ba and Sr contents lower than the megacryst-poor San Piero facies (Fig. 4b). Furthermore, the three facies show significant yet small differences in their Sr isotopic compositions, ruling out the simple occurrence of closed-system fractionation processes.

Following the second hypothesis, the compositions of the earliest phases (crystallized at depth) of the San Francesco facies (megacrysts and their included biotites) should have a bimodal distribution, reflecting the chemistry of these phases in the two parent magmas. However, the compositions of biotites included in megacrysts from the San Francesco facies have their own compositional field, separated from those of the other two facies (Fig. 4d), pointing out that the earliest, pre-emplacement stages of crystallization occurred separately for the three facies.

Thus we are left with the third hypothesis, *i.e.* emplacement of three distinct pulses of magma that can actually account for all the compositional data collected. On this basis, we infer that the Monte Capanne pluton is a composite intrusion fed by three distinct batches of magma that acquired their textural and geochemical features at depth.

The Monte Capanne pluton: internal structure and emplacement sequence

The internal architecture of the Monte Capanne pluton (Fig. 5) can be reconstructed on the basis of the geometric distribution of outcrops of the three facies, the surface morphology, and of the projected "threshold" surfaces separating them as derived from the facies contour map (Fig. 3).

The intrusion shows a shell structure with the facies constituting three sheets extending over the whole pluton. The Sant'Andrea facies represents the uppermost sheet, partly removed by erosion with the pluton's current morphological surface mimicking the original Sant'Andrea facies contact against the country rock, as supported by the occurrence of scattered caps of contact metamorphic host rocks preserved over the granite, *e.g.* in the Monte Perone area. The San Francesco facies represents the

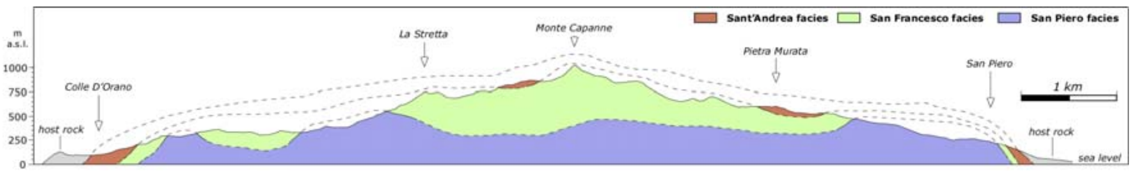

Fig. 5 – Interpretive NW-SE geologic cross section of the Monte Capanne pluton (see Fig. 4). The Sant'Andrea, San Francesco and San Piero facies are geometrically represented as three sheets extending across the whole pluton with an overall slightly upward convex shape.

underlying intermediate sheet. For the San Piero sheet, the upper boundary against the overlying San Francesco sheet is reconstructed by the contour map (Fig. 3), while the lower boundary is constrained by geophysical data.

This internal sheet structure resulted from the emplacement of three distinct batches of magma that arrived sequentially as the Sant'Andrea, the San Francesco and the San Piero batches. This emplacement scenario is supported by two main evidences: i) no traces of feeding structures to the uppermost Sant'Andrea sheet have been observed crosscutting lower sheets; ii) the sequential emplacement of increasingly more mafic facies (from Sant'Andrea to San Piero facies) follows the overall temporal trend of progressive increase of mantle contribution to the magmas reported for the whole western-central Elba magmatism (Dini *et al.*, 2002).

On the basis of these observations and the considerations of McCaffrey & Petford (1997) we envision the following emplacement scenario. First, the Sant'Andrea magma batch reaches the emplacement level and spreads laterally forming a sill-like intrusion likely thicker and shorter than presently observed. Then the San Francesco batch reached the emplacement level, underplating the Sant'Andrea sheet and partially displacing it. Finally, emplacement of the most voluminous San Piero batch pushed up and squeezed out the two former sheets to generate the observed geometry.

Rapid pluton assembly

The lack of sharp contacts between the intrusive facies implies that the time span between emplacements of two different magma batches must have been short enough to allow partial amalgamation processes at the boundary with formation of diffusive contacts. The batches were emplaced in a temporal succession in which the earlier batch had no time to completely solidify before emplacement of the following batch.

To constrain the lag time between emplacement of magma batches, a three-dimensional thermal modelling has been performed based on dimensional parameters measured for the first and the second magma sheets, in order to reconstruct the thermal-rheological conditions during the emplacement of the second and third magma batches, respectively. The thermal model has been calculated using the HEAT code (Wohletz, 2003), with the following thermal conditions: magma temperature at emplacement = 800°C, intrusion top 6 km deep, country rock T = 150°C (corresponding to a geothermal gradient of 25°C/km), thermal conductivity = 3.0 W m^{-1} K^{-1} for the magma and 2.5 for the ophiolitic country rock.

Model results indicate that the temperature of the Sant'Andrea intrusive batch (thickness = 250 m, width = 9.5 km) crossed the *solidus* temperature in about 0.5 ka that has to be regarded as the maximum time lag between the first and the second magma emplacement pulses. To reconstruct the time lag between the emplacement of San Francesco and San Piero batches, the model was run taking into account the thermal perturbation produced by the Sant'Andrea body (local temperature of 300°C). San Francesco body crossed the *solidus* temperature in about 7 ka, which has to be regarded as the maximum time lag between the second and the third magma emplacement pulses.

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