The Miocene anatectic-hybrid granite complex of Elba Island (Tuscany, Italy): about 2.5 million years of magmatic “attempts” in order to succeed to make a single LCT pegmatite field

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The investigation of post-collisional, extensional magmatism may provide fundamental constraints on the reconstruction of the late- to post-orogenic evolution of the deepest part of a mobile belt, as it rises, heats up, decompresses and sends messages toward the surface in the form of crustal and subcrustal melts. In the Apennine orogenic belt, late Miocene to Recent post-collisional magmatism affected southern Tuscany and the northern Tyrrhenian Sea, producing peraluminous rhyolites coupled with some of the youngest exposed peraluminous granites in the world. Igneous activity associated with extensional processes migrated from west (14 Ma) to east (0.2 Ma) as the west-dipping Adriatic plate delaminated and rolled back to the east.

The magmatic processes in most igneous complexes of the Tuscan Magmatic Province have been short-lived and the information they give about deep-seated processes and materials is restricted to inter-complex comparisons. On the contrary, the Miocene intrusive activity of Elba Island covers a significant time span (from about 8.5 to 5.9 Ma), thus offering the opportunity to investigate temporal variations of deep-seated processes and materials. In particular, ten intrusive units of various geometry, sizes and chemistry are exposed on Elba Island, occupying almost half of its surface (two plutons, four laccoliths and four dyke systems): seven of them build up the older central-western Elba complex (8.5-6.8 Ma), while the last three define the younger, and much smaller, eastern Elba complex (5.9 Ma). The aim of this contribution is to provide a general overview of the Miocene Elba magmatism giving a short discussion of the exclusive spatial and temporal association between the LCT pegmatites and two of the intrusive units: the Monte Capanne pluton and its leucogranite dykes.

The central-western intrusive complex was made up by the sequential emplacement, into a tectonic stack of nappes (flysch and ophiolite units), of a multiple laccolith complex, intruded at the base by the Monte Capanne pluton and its associated leucogranites (and late aplite-pegmatite dykes). Finally, the Orano dyke swarm was emplaced, cutting through the entire succession (Dini et al., 2002).

The oldest intrusive units (Capo Bianco aplite and Nasuto microgranite, ca. 8-8.5 Ma) are two layers of porphyritic rock of alkali-feldspar granite/syenogranite composition. The slightly younger monzogranitic-syenogranitic Portoferraio porphyry consists of a multilayer laccolith containing sanidine phenocrysts. Such products do not show any evidences of interaction with mafic magmas and are considered to be pure anatectic magmas derived by the muscovite- and biotite-dehydration melting of the Tuscan crust. Next, the monzogranitic San Martino porphyry (ca. 7.4 Ma) with prominent sanidine megacrysts and mafic enclaves was emplaced as a multi-layer laccolith; it is considered the first hybrid product derived by the interaction of small amount of mantle-derived magmas with a dominant crustal melt. All these intrusive units constitute a Christmas-tree laccolith complex made up by at least 9 layers, originally emplaced at a depth range of 1.9-3.7 km, and totaling approximately a volume of more than 65 km^3. The dimensional parameters of the intrusive layers fit a power-law distribution indicating that, after a likely first stage of horizontal expansion, the layers underwent a second stage of dominantly vertical inflation (Rocchi et al., 2002). The widespread availability of crustal magma traps in the tectonized stack of nappes, in many cases, halted the supply of magma, which then filled another layer. Laccoliths from Elba can be envisaged as sheet-like intrusions that did not coalesce to form single laccoliths or plutons with dimensions typically observed elsewhere as well as in the Monte Capanne case.

The deepest layers of the laccolith complex were then intruded and/or deformed by the large Monte Capanne pluton (ca 6.9 Ma) which was fed by several magma pulses that coalesced into a single intrusion. Several facies can be detected in the pluton but two are more important: 1) the monzogranitic Sant'Andrea Facies, characterized by numerous large K-feldspar megacrysts and mafic enclaves; 2) the granodioritic-monzogranitic San Piero Facies, typically quarried for its homogeneous texture almost devoid of large megacrysts and mafic enclaves. The patchy distribution of the Sant'Andrea facies, dominantly around the margin of the pluton, suggests that it arrived first and was then disturbed by arrival of the San Piero facies. Both the facies are hybrid products and their geochemical/isotopic features can be modeled by the interaction of a mafic component geochemically similar to K-andesites of the Island of Capraia and crustal melts like the Cotoncello dyke at Elba (Dini et al., 2002). The leucogranite dykes have syenogranitic compositions, and they occur mainly close to the pluton's contact, within both the pluton and its thermometamorphic aureole. They commonly have a thickness of up to tens of metres. These dykes were emplaced late in the crystallization sequence of the Monte Capanne pluton, and are locally cut by dykes of the Orano porphyry. Their isotopic age is indistinguishable from that of the Monte Capanne pluton. The leucogranites are interpreted as a series of fractionation products from a magma having characteristics similar to those of the San Piero facies of the Monte Capanne pluton, a hypothesis further supported by the overlapping Sr and Nd isotopic compositions of the Monte Capanne pluton and the leucogranite dykes. Aplites and pegmatites occur commonly as thin (0.1 to 2 m) and short (up to a few metres) veins and dykes, cross-cutting the pluton, its thermometamorphic rocks and, in some places, the leucogranite dykes.

Finally, the Orano mafic dike swarm was emplaced at 6.8 Ma, cutting the entire laccolith-pluton succession. Orano porphyries are typically dark and contain an olivine, clinopyroxene, phlogopite assemblage that, coupled with geochemical and isotopic data, suggest a genesis from strongly modified mantle, as products intermediate between Capraia K-andesites and Tuscan lamproites. They are distinctly different than those involved in the earlier main hybridization process (San Martino, Monte Capanne).

The magma formation processes recorded between ca. 8.5 and 6.8 Ma in central-western Elba, changed from crust-, to hybrid-, to mantle-dominated, as the Apennine fold belt was progressively thinned, heated and intruded by mafic magmas during late Miocene time. Very unusual melts emplaced at the beginning and at the end of the igneous activity did not contribute to the generation of main hybrid magmas. They do, however, emphasize the highly variable nature of crustal and mantle sources that can be involved, during a short time span, in post-collisional, extension magmatism.

Approximately 1 million years later, the next locus of igneous activity developed further east in eastern Elba where the Porto Azzurro pluton, a leucogranite dyke-sill system and the Monte Castello shoshonitic dykes were emplaced. Also in this case a general temporal transition from crustal- to mainly mantle-derived magmas can be observed.

The portions of the igneous complex cropping out in western and central Elba have not preserved their original emplacement geometry (Westerman et al., 2004). All the intrusive units were emplaced within the tectonic units when they were stacked above the present western Elba. Then, shortly after the intrusion sequence was completed, the upper part of the igneous-sedimentary complex (the laccolith complex and the upper zone of the Orano Dyke swarm) was tectonically translated eastward along the low-angle Central Elba Fault, leaving the lower part (the pluton/leucogranites and the roots of the Orano Dyke swarm) to be found in western Elba while the upper part came to rest in central Elba. Following this eastward translation, a "west side up" movement occurred along the high-angle Eastern Border Fault, on the eastern border of Monte Capanne, with a throw of 2 to 3 km. A sequence of events similar to those described above occurred also for the tectonic evolution and pluton exhumation in eastern Elba, where the Zuccale Fault displaced a 2 km wide slice from the front edge of the Central Elba fault along with part of the contact metamorphic aureole of the Porto Azzurro pluton. Therefore, the movement on the

Zuccale Fault occurred after emplacement of the upper Miocene Porto Azzurro pluton. The common history of western-central and eastern Elba can be summarized as follows. Initially, dominantly sub-horizontal movement on a low-angle detachment fault with top-to-the-east sense of shear (Central Elba and Zuccale faults) translated the overlying rocks eastward, trimming out part of the contact aureole of the pluton with which it is associated. Then, high-angle structures were activated mainly at the eastern edge of the pluton, i.e. the Eastern Border fault east of the Monte Capanne pluton and off-shore faults east of the Porto Azzurro pluton. In this scenario, pluton emplacement occurred before the main faulting, and promoted its activation.

It is interesting to note that although the main displacement occurred when magmatism was already stopped, some structural features registered by the Monte Capanne granite and leucogranites along the eastern edge of the pluton indicate that the movement was in part coheval with the magma emplacement. In fact, in the San Piero area, flattened mafic enclaves and aligned K-feldspar megacrysts have been observed in the granite respectively parallel to the plane and the dip of the contact. In addition, in the same area, a strong orientation of the tourmaline and biotite crystals from leucogranite intrusions hosted near the contact is common. Such a mineral orientation has been also indicated by microstructural and AMS (anisotropy of the magnetic susceptibility) studies. All these observation are coherent with an orientation acquired by magmatic flow or by application of an oriented stress field, while sub-solidus deformations are minor. It seems that the movement along the Central Elba Fault was already activated during the emplacement of the granite/leucogranites and, although active at a higher level, the fault was able to induce a significant stress field into its footwall. Furthermore, as observed by Pezzotta (2000) the general attitude of the leucogranite intrusions along the eastern edge of the pluton is consistently sub-parallel to the contact between the granite and the thermometamorphic rocks, while aplite-pegmatite dykes share the same stryke but are oriented at high angle with the contact, crosscutting the granite, the leucogranites and the thermometamorphic rocks.

Such a distribution is again coherent with a top-to-the-east movement of the overlying block during which dilational jogs parallel to the shearing were early exploited by the leucogranite magmas and later, during a phase of higher strain rate, extensional Riedel-like jogs were exploited by the most evolved aplite-pegmatite fluids. It is significant that such a regular distribution of leucogranites, pegmatites and textural features of the granite have been observed only along the eastern edge of the pluton, while in the rest of the intrusion they are randomly distributed.

An additional intriguing question is why strongly evolved LCT pegmatites at Elba Island are restricted to a narrow N-S belt on the eastern edge of the Monte Capanne pluton while they are completely absent in the remaining 70 km^2 of the Monte Capanne granite as well as in all the other intrusive units of the island. Such a situation is much more intriguing when the totality of the Tuscan peraluminous granites is considered: with the exception of few minor finds of millimetric schorl-elbaites in pegmatite pods of the Giglio Island monzogranite, the rest of Tuscan granites do not show a similar geochemical signature. However, granites of the Tuscan Magmatic Province (including the Monte Capanne) have high boron (in the range 20-700 ppm, up to 1300 ppm) as well as significant F (900-2000 ppm) and Li (50-350 ppm) contents. Black tourmaline (schorl-dravite s.s.) is widespread as late magmatic interstitial aggregates and spots (mm to cm in size; variable frequency from rare to tens per m^2) randomly distributed in the 3D rock structure. Tourmaline is also frequently associated to quartz, feldspars, muscovite, andalusite and garnet in swarms of aplite-pegmatite dykes that, in some cases, pass laterally to quartz-tourmaline hydrothermal veins. In summary, the Tuscan acidic rocks are all rich in B (and Li, F) but only on the eastern edge of the Monte Capanne pluton right conditions were met for the formation of a significant LCT miarolitic pegmatite field.

The answer to this problem must be addressed with a multidisciplinary approach where the recent advances obtained on geology, geochronology and petrology of Elba granites should be joined with new geochemical and isotopic studies on the aplite-pegmatite dykes (mainly studied until now from a geological, petrographic and mineralogical standpoint). As an example the recently performed boron isotopic data (Tonarini et al., 1998; Dini et al 2001) coupled with the very old Sr isotopic compositions of pegmatite minerals, determined in the '60 by Pisa CNR researchers (the age of the Monte Capanne granite was published on "Nature" as one of the first K-Ar and Rb-Sr dates of very young granites; Eberhardt and Ferrara, 1962), indicate a very similar isotopic signature between the LCT pegmatites, leucogranites and the main granite. However, even if a cogenetic relationship could be established, and then correlated with the peculiar tectonic setting of the eastern edge of the Monte Capanne pluton, new geochemical data are needed in order to model the exact evolution of this magmatic system from the potential parent magma to the final pegmatite fluid. Such a study could clarify why in just one case, the Tuscan anatectic magmas were able to produce an evolved LCT pegmatite field.

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