MAGMA FLOW IN SHALLOW-LEVEL LACCOLITHS AND THEIR FEEDER DYKES (ELBA ISLAND AND ORCIATICO, TUSCANY) REVEALED BY AMS AND STRUCTURAL DATA

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INTRODUCTION

The study of subvolcanic and shallow-level intrusions has the potential to unveil the possible link between pluton construction and large, silicic eruption. In fact igneous intrusion can be seen as linked to volcanic processes via melt extraction from granitic mushes or, alternatively, as a process independent from plutonic activity. For this reason the understanding of the mode of formation and geometry of shallow intrusive bodies, as well as their feeding-replenishment histories and geochemical evolution, can provide information on the factors controlling whether or not intrusions develop into shallow magma chambers.

Additionally, the study of magma generation, transport and emplacement could be fundamental for many fields of the earth science research as the comprehension of the evolution of the continental crust, the direct reduction of laccolith-linked volcanic hazard, the increase of the petroleum prospectivity in sedimentary basins, the evaluation of the evolution and formation of ore deposits and of geothermal systems.

For the overall process of felsic magma transfer and emplacement in the upper crust, a blooming wealth of multidisciplinary data (including field mapping, structural geology, mineral chemistry, petrology, geochemistry, gravity, magnetic, and anisotropy of magnetic susceptibility-AMS) indicate that igneous bodies often grow by incremental thickening/inflation of an initially thinner sheet by the addition of successive magma pulses, often emplaced as either sub-vertical or sub-horizontal sheets that sheeting in granite plutons can be linked to the amalgamation of magma fingers and tongue-like lobes.

As for felsic systems, sub-horizontal mafic sheet intrusions also constitute a main reservoir for magma emplaced in the shallow crust. However, magma flow in horizontal sheet-like mafic intrusions has still received much less attention than the flow in mafic dykes or lava flows and in particular how magma is injected into sills changing its propagation from sub-vertical to sub-horizontal is still poorly understood also for the lack of works studying horizontal igneous bodies with their own feeder dykes.

On the other hand, if most of the research on magmatic intrusions has focused on the investigation of internal structures useful to reconstruct magma flow direction, some works have also investigated marginal features developed at the magma-host contact that could be useful to add new information about the flow directions and the “space-making” processes; however careful descriptions of such features are scattered and regard almost exclusively mafic bodies.

Based on these premises, the aim of this study is to give a contribution to the understanding of feeding and growth mechanisms of shallow-level intrusions (less than 3-4 km deep) through the study of the emplacement dynamics of some well exposed intrusive bodies within the Miocene-Quaternary Tuscan Magmatic Province (TMP).

The TMP intrusive sheets investigated in this work are represented by the felsic San Martino and Portoferraio laccoliths (central and western Elba Island) and the lamproitic laccolith/sill of Orciatico in mainland Tuscany. These igneous bodies have been chosen because they offer the chance to study internal structures that are undoubtedly magmatic for two main reasons: the shallow depth of emplacement (< 2 km) induced a very fast crystallization and no younger ductile deformation occurred after the emplacement.

The feeding and filling modalities of these intrusions has been studied by means of the reconstruction of the magma flow by the investigation of internal fabric and contact structures. Relevant data are represented by

field observations, structural measurements of mineral and vesicle foliations and lineations and especially the analysis of the anisotropy of magnetic susceptibility (AMS).

FEEDING AND GROWTH OF THE SAN MARTINO LACCOLITH (ELBA ISLAND, ITALY): INSIGHTS FROM AN INTEGRATED AMS-STRUCTURAL STUDY

The aim of this study is to investigate the potential for fabric patterns to reveal details about the feeding and growth mechanisms of shallow-level intrusions (less than 3-4 km deep). We have focused on the late Miocene San Martino multilayer felsic laccolith and its two large sub-vertical feeder dykes (Elba Island, Tuscan Archipelago, Italy). These intrusive bodies have monzogranite composition with prominent sanidine megacrysts set in an aphanitic groundmass affected by hydrothermal alteration and weathering. They were emplaced at a depth around 2 km with an estimated filling time in the order of 100 years.

The fabric data are derived from field measurements of the attitudes of K-feldspar megacrysts (50 sites/2500 measurements) and from anisotropy of magnetic susceptibility (AMS) determinations (150 sites/1500 cores). Magnetic mineralogy investigations outlined the paramagnetic nature of the AMS signal, carried by chloritized biotite with negligible contribution of ferromagnetic minerals. The K-feldspar foliation is very strong while the lineation is poor. AMS data show almost everywhere strong foliation and a definite lineation.

Despite this fact, a good correlation between the AMS and K-feldspar is generally observed, suggesting that almost everywhere hydrothermal alteration did not affect significantly the orientation of the magnetic anisotropy. Strong discrepancy found at a few stations could be linked to some effect of alteration and/or weathering such as a higher contribution from tourmaline or of secondary ferromagnetic phases (maghemite and magnetite). So, the magnetic fabric is thus generally considered to mimic megacryst statistical attitude which is in turn inferred to reflect a flow-related petrofabric, but wherever AMS data deviates substantially (> 30°) from megacryst data, the megacryst fabric has been considered as the most reliable indicator of magmatic fabric and the AMS data has been dropped.

The feeder dykes have been sampled across cross sections to constrain both direction and sense of flow. Only two sections have a “normal” fabric (internal foliation plane parallel to the walls and imbrication of the foliation close to the walls) indicating sub-vertical flow (imbrication in vertical section). The other sections present a complex fabric pattern that could be explained invoking tectonic activity, (as testified by asymmetric fabric) but also backflow or cyclic variation of orientation.

The AMS data of the main body have evidenced the presence of the of a central dike that fed the main body with a lateral spreading of the magma as a single propagating and inflating pulse where the particles arranged perpendicularly respect to the magma displacement direction. The absence of internal discontinuities substantiates the hypothesis of continuous feeding of magma injected as a single pulse or as a series of coalescing pulses/lobes emplaced fast enough to hamper the development of such internal structures.

FLOW-INDUCED STRUCTURES AT THE INTRUSIVE CONTACTS OF THE ELBA ISLAND LACCOLITH COMPLEX (TUSCANY)

Felsic porphyritic multilayer laccoliths of the “Elba Island Miocene igneous complex” offer a wide range of examples of contact features, many of which constraint magma flow direction. The Portoferraio laccolith intruded ~ 8 Ma at an average depth of about 2.6 km into Jurassic serpentinites and overlying Cretaceous flysch (dark shale, feldspathic sandstone, marly limestone) that make up the top two complexes of a thrust stack assembled by about 20 Ma. The three main layers of the megacrystic San Martino laccolith were emplaced in the Cretaceous host ~ 7.4 Ma at an average depth of 1.9 km. Two main distinctive features have been definite linked to “deformation” and “disruption” processes. Features in the first set are defined by deformation of external morphology of intrusive surfaces with formation of folds (waves, lobes and ropes) and solid-state stretching

lineation. An AMS investigation of samples close to the contact with such features has pointed out a strong correlation between the magnetic fabric and these features showing that both are flow-related and can be considered good flow indicators but on a very local scale.

The second set of features is characterized by disruption of materials on one or both sides of the contact with formation of chaotic structures with blocks of rigid host and angular porphyry fragments "swimming" throughout the fluidized host. Locally, decimetric-scale apophyses of porphyry occur within fluidized flysch and disrupted breccias near contacts are seen incorporated within the intrusive rocks.

This structures suggest the loss of cohesion of the host material and in particular the development of a condition in which two fluids of differing viscosity are in contact, as well as undulation and crenulation of the contacts are expected if one viscous fluid propagates into another. The absence of pore fluids in the laccolith host rocks excludes fluidization *s.s.* processes while preliminary XRD analyses have excluded the importance of dehydration processes. It is therefore plausible that fluids responsible of such structures have a magmatic origin and that such processes developed in a very late stage of magma emplacement.

AMS AND STRUCTURAL ANALYSIS OF MAGMA FLOW IN A LAMPROITIC DIKE-SILL COMPLEX (ORCIATICO, TUSCANY)

The case study is the small Early Pliocene intrusion of Orciatico (Pisa, Italy), a lamproitic igneous body that was emplaced at very shallow depths (*ca.* 50 m). The Orciatico intrusion is composed of four units: the main body (maximum axis ~ 600 m, mean thickness ~ 50 m); a sub-vertical dike (length ~ 300 m, width ~ 5-15 m); the connection zone between the dike and the main body, containing blocks of stoped host rock and roof pendants; a thin sill extending northward (maximum axis ~ 500 m; thickness ~ 5 m).

The internal fabric of the laccolith has been studied by means of the anisotropy of magnetic susceptibility (AMS) technique (43 sites/430 cores). The comparison of AMS results (14 stations) with the measured vesicle (particularly abundant in the dike and at the main body contact) attitude strengthens his validity. The magnetic mineralogy, investigated with heating/cooling experiments, is dominated by paramagnetic phases (iron-rich phlogopite) with very minor ferromagnetic phases (Ti-magnetite and Ti-maghemite).

Fabric data suggest that the intrusion was feeded laterally by the dike bordering the main body and that the growth is probably related to a simple inflation model after the propagation of a sill.