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Intrusive sheets and sheeted intrusions at Elba Island, Italy

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ABSTRACT

The processes leading to successful versus failed coalescence of similar magma batches upon their emplacement are investigated at Elba Island (Tuscany), where several magma bodies were generated at a single magmatic center over a time span of ~1 Ma during the Late Miocene. Three nested Christmas-tree laccoliths made up of separated, shallow-level felsic sheets were emplaced at 2–3 km depth with associated roof uplift. Then, at a deeper level, a granite pluton was constructed over a short time span by three magma pulses stacked downward as subhorizontal intrusive sheets, with space for magma generated mostly by roof uplift and tectonic-gravitational displacement of the overburden. Length-to-thickness relationships for individual laccolith layers, as well as for pluton sheets, show a power-law correlation interpreted as the frozen evidence for the occurrence of a vertical inflation stage during intrusion growth. We infer that laccolith sheets failed to coalesce and form a larger pluton because their magma driving pressure exceeded the lithostatic load in a crustal section rich in subhorizontal magma traps (a thrust stack of bedded rocks). However, the driving pressure of the first magma batch of the Monte Capanne pluton was presumably enhanced by an increased magma supply rate, so that the driving pressure exceeded the load at the level of a deeper magma trap represented by a major thrust fault. The following magma batches arrived in rapid succession and were not able to penetrate the still mushy tabular mass. Thus the laccolith sheets and the sheeted pluton represent different outcomes of similar processes occurring under slightly different conditions.

INTRODUCTION

A wealth of recent data and reviews shows that most igneous intrusions in the upper crust have tabular shapes (McCaffrey and Petford, 1997; Cruden, 1998; Petford et al., 2000; Cruden and McCaffrey, 2001) resulting from the assembly of discrete pulses of magma (Miller, 2008) that spread out at the emplacement level to form subhorizontal sheets (Michel et al., 2008) fed by subvertical dikes (Petford et al., 1993). Such multipulse magma input is a common feature shared by plutonic and volcanic complexes, and deciphering the intrusive records of magma systems is thus essential to unveiling why some magmas erupt while others do not, as well as understanding the relationships between large felsic eruptions and long-term storage of magma in subterranean reservoirs (Bachmann et al., 2007; de Silva and Gosnold, 2007; Miller et al., 2007). Therefore, identifying magma batches within a pluton is crucial to constraining both the possible episodic nature of pluton growth and the time-integrated magma supply rate over the life of the system (Coleman et al., 2004; Matzel et al., 2006; Saint-Blanquat et al., 2006; Farina et al., 2010), and the workings of volcanic plumbing systems (Lipman, 2007; Annen, 2009). In this respect, a key issue is clarifying the emplacement histories of magma pulses, sometimes as separated sheets (Jackson and Pollard, 1988; Rocchi et al., 2002), in other instances as composite (sheeted) intrusions with either clear or cryptic internal contacts (Saint-Blanquat et al., 2006; Farina et al., 2010; Horsman et al., 2010), and in other cases forming magma chambers that eventually give way to large felsic explosive eruptions (Bachmann and Bergantz, 2008).

At Elba Island (Tuscany), these issues can be fruitfully investigated, owing to the availability of an exposed crustal section representing ~5 km of original thickness containing a prominent example of shallow, multilayer laccoliths and a medium-level sheeted pluton. Evidence for the emplacement histories and geometric-physical parameters of these intrusions, along with their petrographic features, led to the assessment of the role played by magma driving pressure, crustal magma traps, and regional tectonics in the genetic relationships between laccoliths and plutons.

GEOLOGICAL SETTING

Elba Island is located at the northern end of the Tyrrhenian Sea, a region affected by extensional processes leading to the opening of an extensional ensialic backarc basin behind the eastward-progressing compressive front of the Apennine mobile belt (Fig. 1) (Malinverno and Ryan, 1986). In this framework, magmas were generated in the mantle and interacted with crust-derived felsic magmas to generate the variety of intrusive and extrusive products of the Tuscan Magmatic Province exposed across an

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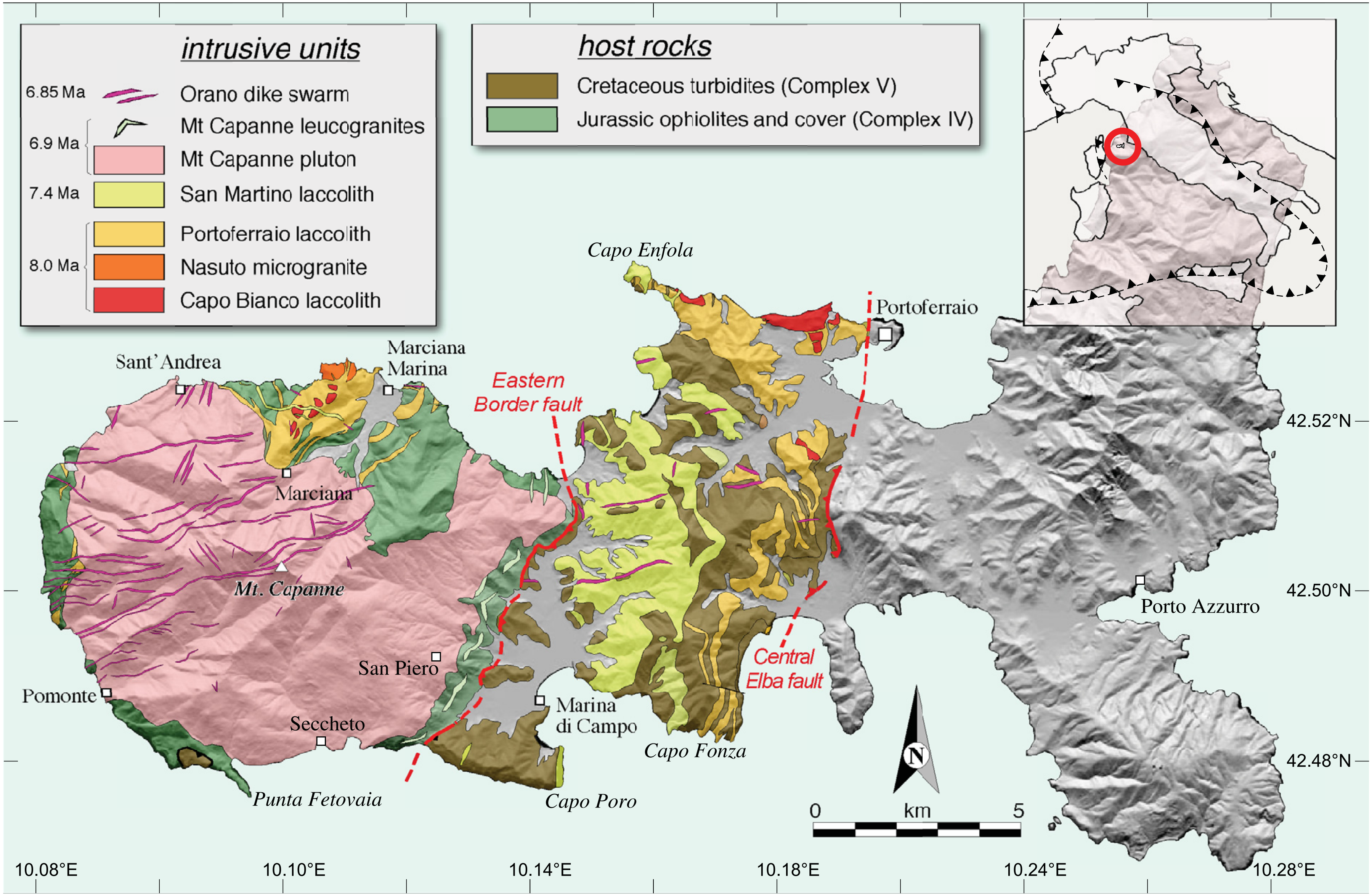

Figure 1. Simplified geological map of western and central Elba Island. In the inset, the hachured line represents the present front of the Apennine-Maghrebide and Alpine chains. (For comparison, see the Central Elba fault as represented in the schematic geological section of the laccolith-pluton complex in Fig. 6.)

area of ~30,000 km^2 of southern Tuscany and the northern Tyrrhenian Sea. This igneous activity migrated from west (14 Ma) to east (0.2 Ma) as the west-dipping Adriatic plate delaminated and rolled back to the east (Serri et al., 1993).

The structural framework of Elba Island (Fig. 1) consists of five tectonic complexes that were stacked on east-verging thrusts during the Apenninic compressional event before 20 Ma. The three lowest complexes (I–III) have continental features, consisting of metamorphic basement and shallow-water clastic and carbonate rocks, while the upper two complexes (IV and V) have oceanic characteristics: Complex IV consists of Jurassic oceanic lithosphere of the western Tethys Ocean (peridotite, gabbro, pillow basalt, and ophiolite sedimentary breccia) and its Late Jurassic–middle Cretaceous sedimentary cover (chert, limestone, and argillite interbedded with siliceous limestone); Complex V consists mostly of a Late Cretaceous siliciclastic turbidite sequence (Pertusati et al., 1993). This stacking of tectonic complexes on top of the Apennine fold-and-thrust belt is characterized by a large number of physical discontinuities at both thrust contacts between tectonic complexes and bedding planes within the turbidite sequence of Complex V.

Igneous activity in western-central Elba Island (Tuscany) led to the emplacement of several magma bodies over a time span of ~1 Ma during the Late Miocene. The igneous sequence started with the construction of a multilayer laccolith complex, first by the emplacement of the layers of Capo Bianco aplite, followed in succession by the layers of the Portoferraio laccolith, and finally by the intrusive layers of the San Martino laccolith (Rocchi et al., 2002). The deepest layers of this laccolith complex were then intruded and/or deformed by the Monte Capanne pluton and its associated late leucocratic dikes and veins (Farina et al., 2010). Finally, ~200 mafic dikes of the Orano swarm were emplaced, cutting through the entire succession (Dini et al., 2008).

Shortly after the intrusive sequence was assembled, the upper part of the igneous-sedimentary complex was tectonically translated eastward along the Central Elba fault (Fig. 1). Following this eastward translation, a west-side-up movement occurred along the Eastern Border fault (Fig. 1) with a throw of 2–3 km, so that the lower part of the sequence is currently exposed in western Elba at the same level as the upper part in central Elba (Westerman et al., 2004). The minimum amount of displacement along the Central Elba fault is constrained at ~8 km, with a rate of displacement in excess of 5–6 mm/a. This movement was at least partly linked to gravitational instability as a result of growth of the plutonic complex. In ~1 Ma, a 2700-m-thick tectonostratigraphic section was inflated by the addition of a total of 2400 m of intrusive layers (Rocchi et al., 2002), leading to a steep, unstable dome. Finally, oversteepening by the intrusion of the Monte Capanne pluton at its base triggered the gravitational collapse. The result of these tectonic-gravitational splitting and tilting of the intrusive complex is a serendipitous sequence of exposures of ~5 km of the original crustal vertical section.

LACCOLITH COMPLEX

The first intrusive cycle produced, between ca. 8 and 7.4 Ma (Dini et al., 2002), nine main separate, shallow-level, granite porphyry sheets connected by feeder dikes (Fig. 2), eventually constructing the three nested Christmas-tree tabular intrusions of Capo Bianco (two layers, plus the minor Nasuto microgranite intrusive body), Portoferraio (four main layers) and San Martino (three main layers; Figs. 2 and 3) (Dini et al., 2002, 2006). The Capo Bianco tabular intrusion is not discussed in this paper because its disruption by the intrusion of the Portoferraio magma makes it impossible to precisely reconstruct its emplacement setting and history. The Portoferraio porphyry laccolith (Fig. 4A) contains prominent phenocrysts of sanidine set in an aphanitic groundmass (Fig. 4B) and has monzogranite to syenogranite compositions. Most of that magma (99 vol%) was emplaced in two main layers at an

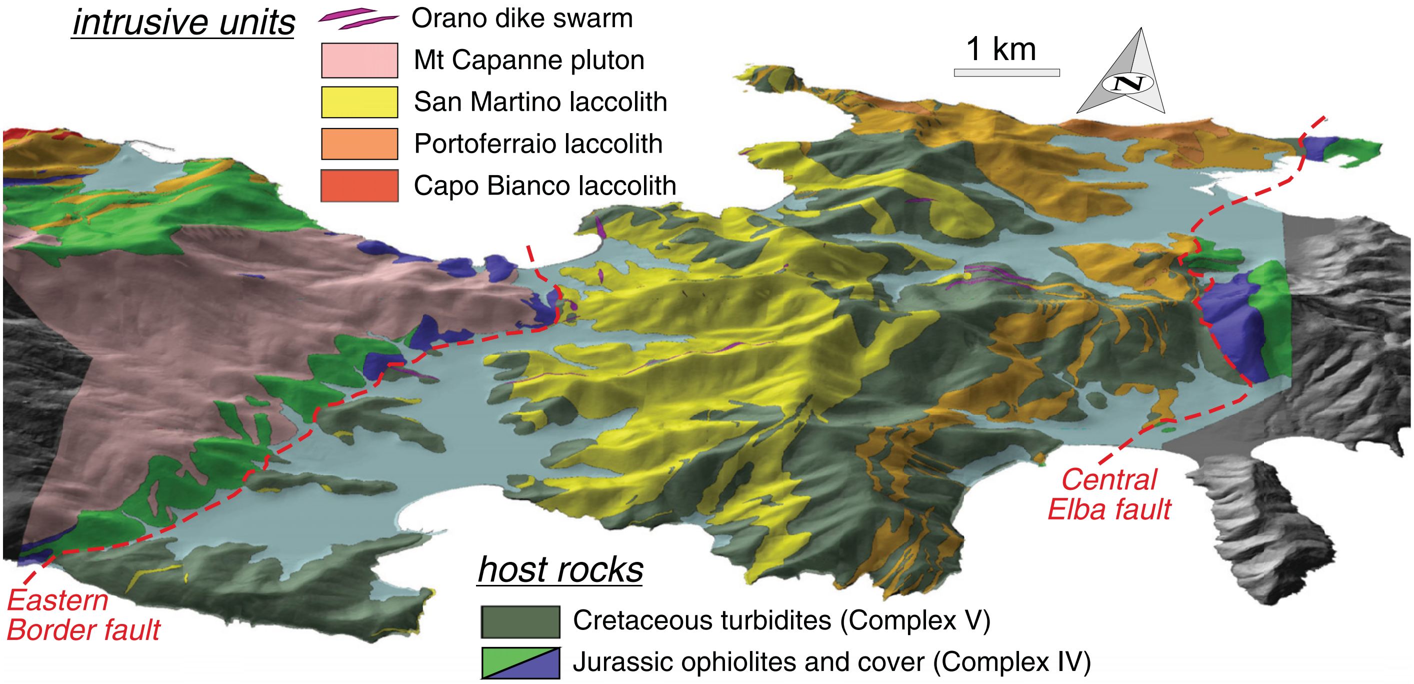

Figure 2. Geological map of the western-central Elba laccolith complex draped over a digital elevation model. View from the south. Scale varies in perspective view.

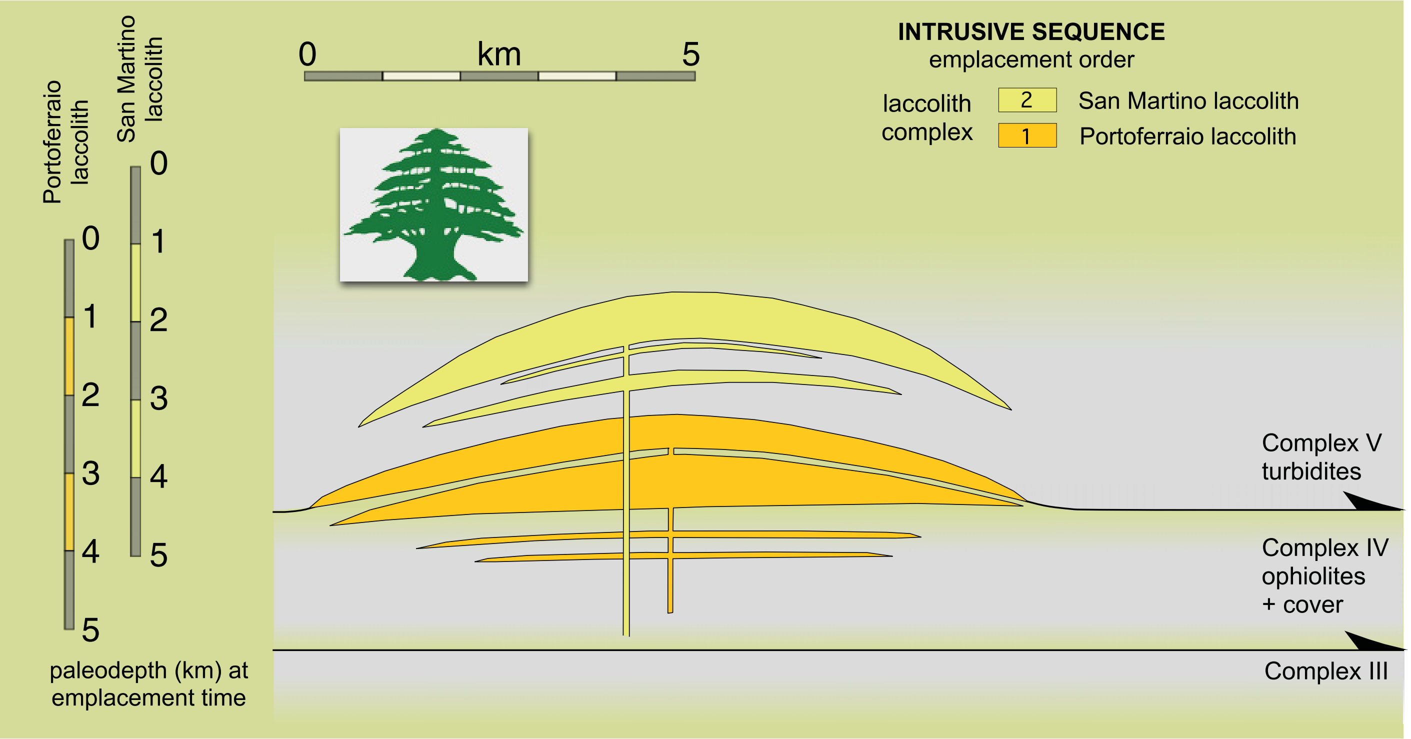

Figure 3. Schematic illustration of the two main multilayer laccoliths of the western-central Elba laccolith complex. Note the progressively deeper paleodepths as the laccolith layers thicken the crustal section and lift up the Earth's surface (see Fig. 7 for an integrated explanation). Also shown is a schematic picture of the Lebanon cedar from the Lebanese national flag, showing how the laccolith complex is more similar to the shape of that tree than to a Christmas tree, as is commonly referenced (B. Bonin, 2002, personal commun.).

average depth of ~2900 m (Table 1 in Rocchi et al., 2002), a value that can thus be assumed as the average emplacement depth for the entire Portoferraio laccolith. The San Martino porphyry laccolith has a monzogranite composition and is characterized by prominent megacrysts of sanidine set in an aphanitic groundmass (Figs. 4D, 4E). Large subvertical feeder dikes are observed (Fig. 4F) and mapped (Fig. 1). Most of the San Martino magma (90 vol%) was emplaced in the uppermost sheet, so the emplacement depth for the San Martino laccolith has been established as 1900 m (Rocchi et al., 2002) for the purpose of pressure calculations.

Overall, the space for magma to build these laccoliths was created by roof uplift (Rocchi et al., 2002); there is no evidence for an active role of stoping or ductile rock deformation. The resulting laccolith intrusive layers range from 50 to 700 m thick, with diameters between 1.6 and 10 km (Fig. 3). Length-to-thickness relationships for individual layers define a power-law correlation that has been interpreted as frozen evidence of a vertical inflation stage during laccolith growth (Rocchi et al., 2002). No effects of contact metamorphism have been observed at laccolith-host rock contacts, except local biotite recrystallization in zones <1 mm thick.

SHEETED PLUTON

A second magmatic cycle, ca. 7 Ma, led to the buildup of the granitic Monte Capanne pluton along with a mafic dike swarm (Fig. 1). Recognition of different petrographic facies internal to the pluton (Dini et al., 2002), and

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Figure 4. (A) Portoferraio laccolith sheets, viewed from south of the east-west shoreline east of the Gulf of Marina di Campo. Vertical relief of the cliff is 300 m. (B) Portoferraio porphyry, with sanidine phenocrysts to 2 cm long. Width of field of view is 35 cm. (C) Foliated Portoferraio porphyry, 1.5 km northwest of Marciana; the foliation is N52W, 55N (parallel to the local contact with the Monte Capanne pluton) with stretching lineation 50, N5E, pointing out a genetic link between pluton emplacement and deformation. Width of field of view is 10 cm. (D) San Martino porphyry, Scoglio della Triglia, seen looking north toward Capo Fonza, showing abundant sanidine megacrysts, typically 2–15 cm long, as well a rare mafic microgranular enclave (close to the center of the picture). Vertical relief of the islet above sea level is 5 m. (E) San Martino porphyry sheet, close to Capo Enfola, showing abundant sanidine megacrysts in relief after seawater weathering. Diameter of coin is 2 cm. (F) San Martino porphyry, a feeder dike crosscutting bedding of the Cretaceous turbidite host. (G) Megacryst-rich Sant'Andrea facies, Sant'Andrea shore. Note the euhedral shapes of megacrysts (as opposed to those in the San Piero facies). Length of book is 18 cm. (H) Megacryst-poor San Piero facies, abandoned quarry close to Seccheto. Length of hammer is 32 cm. (I) Megacryst-poor San Piero facies in an abandoned quarry close to San Piero: the K-feldspar megacrysts are typically visible only with sunlight reflection on cleavage surfaces, owing to late-stage crystallization of the feldspar with very abundant matrix inclusions (Farina et al., 2010). Diameter of coin is 1.5 cm.


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mapping of the pluton's petrographic variability relying on K-feldspar megacryst abundance (Farina et al., 2010), led to the construction of a geological contour map of the pluton showing the boundaries between the pluton's three internal facies (Fig. 5). Cross sections from this map allowed reconstruction of the internal, sheeted structure of the pluton and its sequential filling history (Fig. 6) via emplacement of three magma batches, each generated separately at depth (Farina et al., 2010) from the same melting-hybridization zone. The first magma batch (Sant'Andrea facies, ~250 m thick) is characterized by a high abundance of K-feldspar megacrysts and quartz phenocrysts set in a coarse-grained matrix (Fig. 4G). It crops out in the northwest part of the pluton, as well as on the most elevated ridges and in the marginal parts in contact with country rocks. The second magma batch (San Francesco facies), characterized by a moderate abundance of K-feldspar megacrysts, constitutes a sheet ~650 m thick underlying the Sant'Andrea sheet. A third magma batch (San Piero facies) is typically poor in K-feldspar megacrysts (Figs. 4H, 4I) and crops out structurally beneath the San Francesco sheet. Given the pluton's estimated total thickness of ~2.5 km (Dini et al., 2008), and assuming that no deeper unexposed facies are present, the San Piero Facies constitutes a 1500-m-thick sheet. The first sheet was likely emplaced at a depth of ~6 km; that is the sum of the estimations of the total thicknesses of intrusive layers (~2400 m) and intervening host rock (~2700 m) plus the erosion loss (~800 m) (Rocchi et al., 2002). This first sheet was then incrementally uplifted, prior to complete solidification, by the emplacement of the two following sheets. This process led to the upwarping, ductile deformation (to mylonitization; Fig. 4C), and partial lateral displacement of wall rocks such that the top of the intrusion reached a depth of ~5 km (Fig. 7).

Overall, space for construction of the Monte Capanne plutonic body was created by a complex set of mechanisms including mainly vertical displacement of the country rock above the pluton, coupled with shortening and upwarping of the country rock. In detail, the large surface uplift resulting from laccolith and pluton intrusion led to gravitational instability that triggered eastward translation of the entire overburden along a detachment fault, soon after pluton emplacement (Westerman et al., 2004). Space around the pluton was also generated by subsolidus shortening of the adjacent country rock, with development of mylonitic structures in the country rock that was simultaneously undergoing pervasive thermal metamorphism (Dini et al., 2002; Rossetti et al., 2007). In summary, for earlier laccoliths the emplacement involved only roof uplift, while the magmas building up the Monte Capanne pluton generated their room both by uplift and by deformation of surrounding country rock. This difference is in accord with the general observations for intrusive bodies emplaced at different crustal levels characterized by varying country-rock ductilities (Cruden, 2006). The host rock ductility was greatly influenced by the very different effects of thermal metamorphism, which was negligible for laccoliths but significant (to 500–600 °C) close to the Monte Capanne pluton.

DISCUSSION

The laccolith complex and the sheeted pluton of Elba Island have similar compositions and magma sources, and were emplaced in a

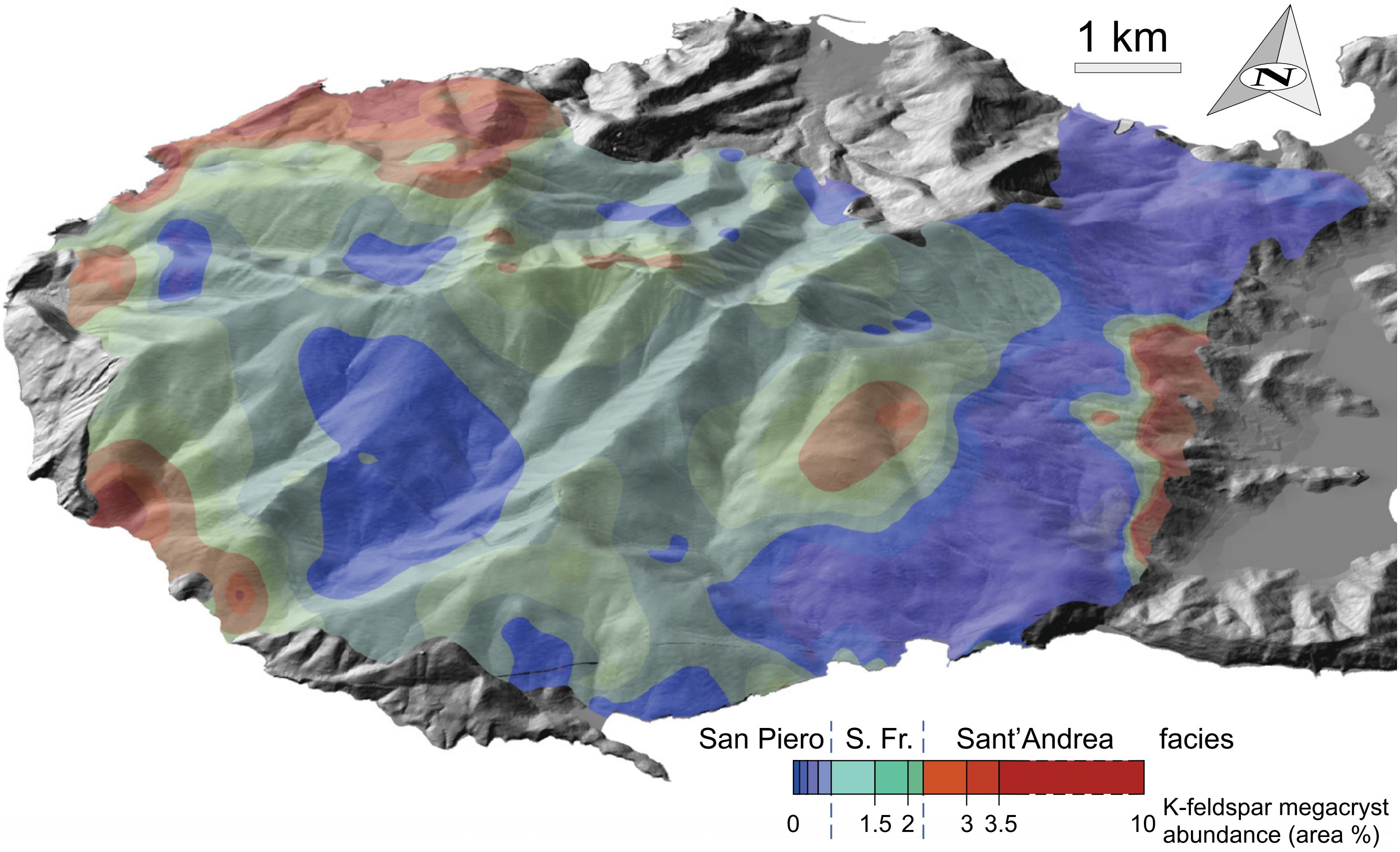

Figure 5. Geological map of the intrusive facies of the Monte Capanne pluton draped over a digital elevation model. Data for map construction after Farina et al. (2010). S. Fr.—San Francesco. View from the south. Scale varies in perspective view.

rather short time span at a single magmatic center in the same tectonic setting. They thus share several of the parameters that are commonly acknowledged to exert a controlling role on magma emplacement processes. These prominent similarities are, nevertheless, coupled with some remarkable differences.

A set of characteristics that is significant in the interpretation of igneous emplacement mechanisms is that defining the overall geometry of plutons, in particular their length (i.e., diameter) to thickness relationships (McCaffrey and Petford, 1997). For the individual Elba laccolith layers, length-to-thickness relationships show a power-law correlation (Fig. 8) that has been interpreted as the frozen evidence for the occurrence of a vertical inflation stage during laccolith growth (Rocchi et al., 2002). Also, the reconstructed original dimensional parameters of the three intrusive sheets making up the Monte Capanne pluton (Farina et al., 2010) display a power-law correlation that, in analogy with the laccolith layers, can be interpreted as indicative of a similar vertical inflation stage (Fig. 8). This evidence for a vertical inflation stage led to inference of a former horizontal expansion, as is commonly acknowledged for laccolith intrusions (Johnson and Pollard, 1973), so that both the multilayer laccoliths and the sheeted pluton formed in a laccolith-type way.

When the dimensional parameters of the Monte Capanne pluton as a whole (i.e., the result of the amalgamation of three sheets in a single intrusive body) are plotted in a length-versus-thickness diagram (Fig. 8), they fit those predicted for plutons worldwide (McCaffrey and Petford, 1997; Cruden and McCaffrey, 2001). If a similar (virtual, in this case) amalgamation is considered also for the sheets that make up the Portoferraio and San Martino laccoliths, the resulting parameters fit the same curve described for plutons (Fig. 8). In summary, the magma batches forming the pluton amalgamated in a single, composite intrusive body, while the amalgamation did not occur for the laccolith sheets. This evidence suggests that, if the laccolith sheets had coalesced, they would have ended up as two plutons having aspect ratios compatible with both (1) the power-law fit curves for plutons worldwide (McCaffrey and Petford, 1997; Cruden and McCaffrey, 2001), and (2) the S-type fit curve proposed for all intrusive bodies (Cruden and McCaffrey, 2002).

These observations lead to a significant question regarding the mechanisms that controlled the emplacement of magma batches in western Elba Island between ca. 8 and 7 Ma. In particular, it has to be explained why the ca. 8 Ma and the ca. 7.4 Ma magma batches were emplaced at depths <3 km as separated intrusive sheets developing aphanitic groundmass, whereas the three ca. 7 Ma magma batches coalesced at a deeper level to form a single, coarse-grained intrusive body. Another distinction between the two magmatic episodes is that during emplacement, the laccoliths created room by lifting the overburden, and the pluton created room by a combination of processes, including significant roof uplift and displacement and lateral host-rock deformation. These observations indicate that the magma driving pressure was greater than the vertical stress, allowing the magma to lift the rock overburden (Hogan et al., 1998; Kerr and Pollard, 1998). However, despite having magma driving pressures exceeding the vertical stress, no evidence is known for eruption of any of these Elba magmas. The only volcaniclastic

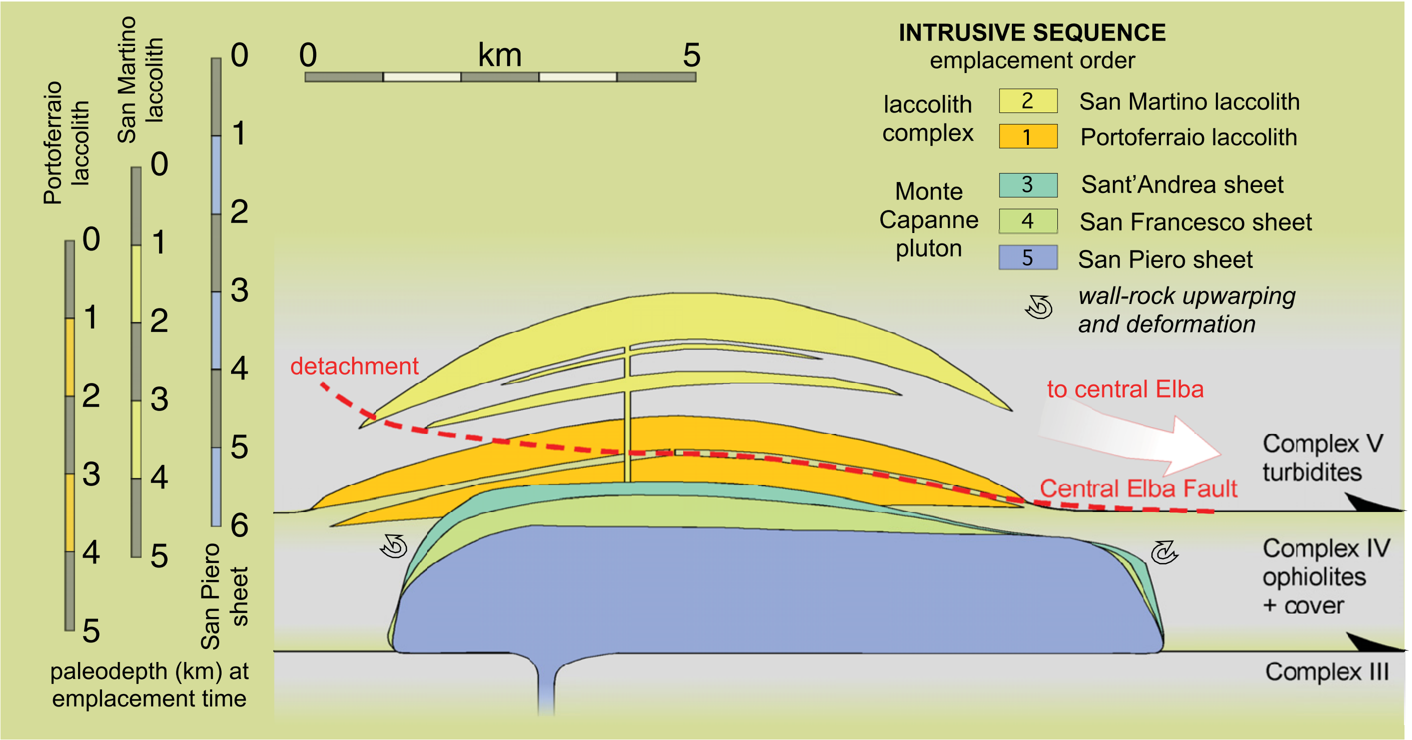

Figure 6. Schematic illustration of the three sheets constituting the internal structure of the Monte Capanne pluton and their geometric relationships with the multilayer laccoliths of the western-central Elba laccolith complex. Note the progressively deeper paleodepths as the laccolith layers thicken the crustal section and lift up the Earth's surface (see Fig. 7 for an integrated explanation). Also shown is the detachment fault (Central Elba fault) along which the upper part of the complex moved to the east soon after emplacement of the Monte Capanne pluton. Monte Capanne emplacement paleodepths are only valid for the San Piero sheet, because the younger Sant'Andrea and San Francesco sheets were likely emplaced deeper, and then pushed up and partly squeezed out by the intrusion of the larger San Piero magma pulse.

layers of comparable age on mainland Tuscany have mineral and chemical features linking them to the contemporaneous volcanic activity of Capraia Island (D'Orazio et al., 1995). In addition, no evidence for magma extraction, e.g., such as crystal mush compaction, has been found in outcrops of either the laccoliths or the pluton at Elba. These two conditions provide evidence that crustal magma traps arrested the vertical ascent of Elba magmas (Hogan and Gilbert, 1995; Hogan et al., 1998).

A significant control on the ascent of Elba magma by magma driving pressure is supported by the aspect ratios of all the Elba intrusions (i.e., their overall tabular shapes), coupled with the occurrence of vertical dikes below the subhorizontal sheets, indicating that magma ascent at Elba occurred through feeder dikes that likely remained connected to the magma reservoir (Brown and Solar, 1998; Dehls et al., 1998; Hogan et al., 1998). In order to better understand the emplacement histories and mechanisms of these intrusions, the magma driving pressure for each magma batch has been reconstructed based on the specific magma composition, and the density profile and stress state of the crust at the time of emplacement. In this case, the magma driving pressure, P_{d}, is:

$$P_{\mathrm{d}} = P_{\mathrm{h}} + P_{0} - P_{\mathrm{vis}} - S_{\mathrm{h}}, \tag{1}$$

(Reches and Fink, 1988; Baer and Reches, 1991; Hogan and Gilbert, 1995; Hogan et al., 1998), where P_{h} is the hydrostatic pressure, P_{0} is the magma chamber overpressure, P_{vis} is the viscous pressure drop, and S_{h} is the tectonic stress perpendicular to the ascending dike walls. The magma driving pressure is dominated by the positive contribution of the hydrostatic pressure and the negative contribution of the horizontal stress. In the case of the Elba magmas, the magma chamber overpressure can be considered negligible due to the low magma volatile contents of investigated magmas. Also, the viscous pressure drop is of little influence when values of 0.5 MPa km^{-1} are adopted (Baer and Reches, 1991; Hogan et al., 1998).

One of the two remaining influential variables controlling magma driving pressure is hydrostatic pressure, defined as the difference between the lithostatic pressure at the top of the

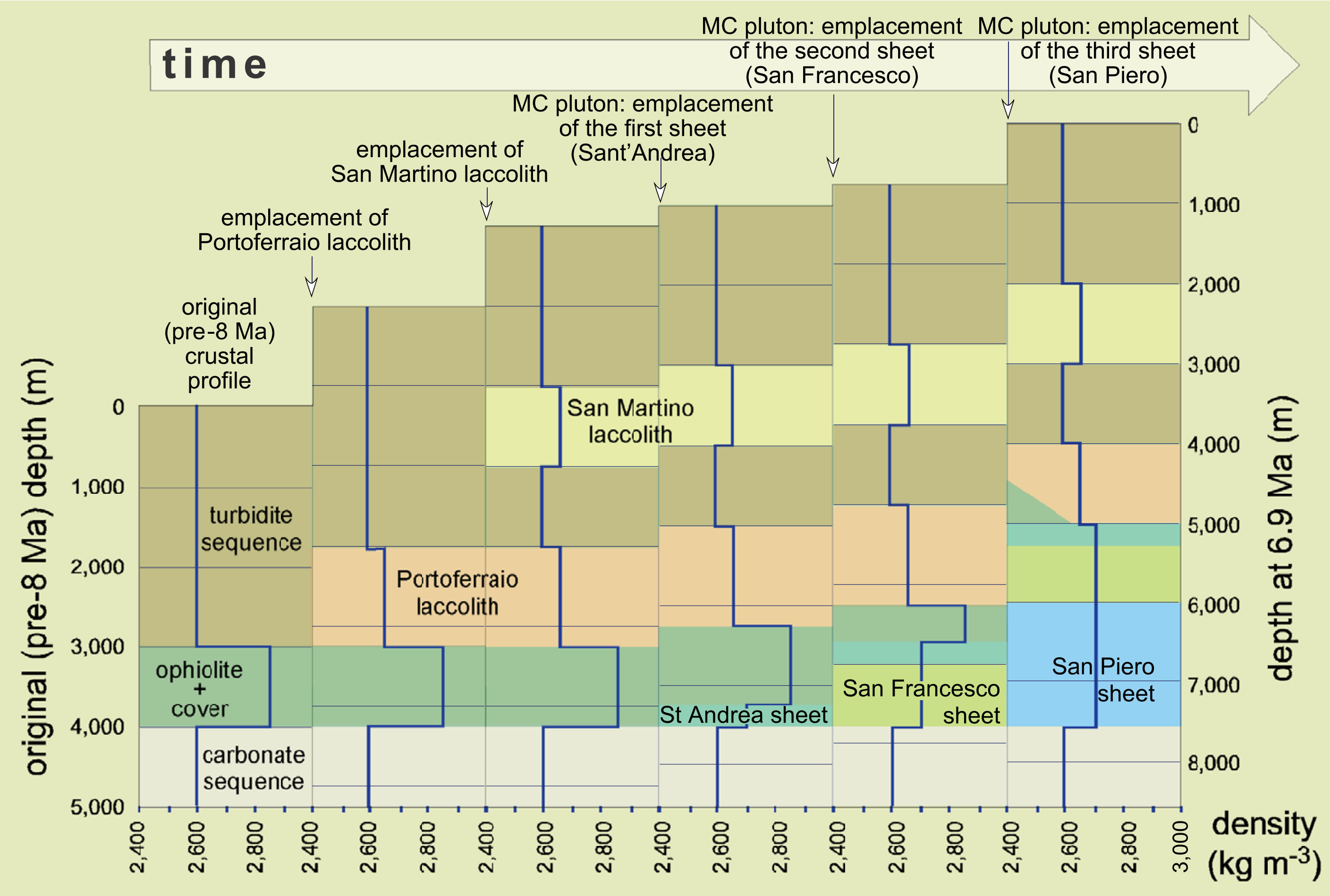

Figure 7. Evolution of the vertical profile for the crustal density throughout the emplacement history of the Elba magma batches. Density values used are: indurated turbidite (mainly sandstone)—2600 kg m^{-3}; ophiolitic sequence (mainly serpentinized peridotites, gabbro, and basalt along with minor sedimentary cover)—2850 kg m^{-3}; felsic Portoferraio and San Martino porphyries—2650 kg m^{-3}; Monte Capanne (MC) granite—2700 kg m^{-3}; Mesozoic carbonate sequence—2600 kg m^{-3}. The thicknesses of rock units and the emplacement depths are taken from Table 1 in Rocchi et al. (2002). Note how paleodepths of sheets and layers move up as they are lifted by the intrusion of magma pulses. In the last column, the ophiolitic Complex IV and the deepest sheets of the Portoferraio laccolith are reported with a reduced thickness to account for the observed deformation and lateral displacement that occurred during the emplacement of Monte Capanne magma pulses. (See Fig. 2C for mylonitic structures developed during this process.)

magma reservoir (i.e., at the source depth) and the pressure at the tip of the column of magma as it rises through the crust (Hogan and Gilbert, 1995). Calculation of the hydrostatic pressure at any depth relies on the knowledge of the depth of the magma source, the integrated density of the crust overlying the magma source, and the integrated density of the rising magma.

Reconstruction of the depth of magma generation is always a difficult task. Compositional data compared with experimental data on thermal minima in the Q-Ab-Or system (Ebadi and Johannes, 1991) can be used to obtain a rough estimate of pressure in the source zone. However, refinement is necessary when phenocrysts are recognized to have crystallized in the source zone before ascent (Hogan, 2008). All the Elba magma batches (from laccolith to pluton systems) were laden with K-feldspar and quartz phenocrysts that were generated in the source zone, before emplacement, as witnessed by flow alignment of K-feldspar, by some quartz resorption, and also by chemical data (Westerman et al., 2003; Farina et al., 2010). Thus, a better indication of the source pressure is given by the composition of the melt in equilibrium with these phenocrysts. The composition of such a melt has been determined by mass balance in terms of Q-Ab-Or (quartz-albite-orthoclase) components, taking into account the phenocryst content (20–30 vol%), K-feldspar/quartz phenocryst abundance ratio (0.6/0.4–0.5/0.5), and the K-feldspar composition (Or_{77} to Or_{81}; Dini, 1997). For all the studied intrusive units, calculations indicate a pressure of ~0.5 GPa, corresponding to a depth of ~18 km. Such a depth is within a reasonable depth window between ~10 km, as constrained by metamorphic xenoliths carried by the Monte Capanne pluton (Bussy, 1990) and, given that negligible crustal thinning occurred after 7 Ma, the present Moho depth of 22–25 km beneath western Elba Island (Nicolich, 2001). The initial 18 km depth has been adjusted to 19.3 km for the source of San Martino magma to take into account the 1250 m of upper crust thickening due to the intrusion of the Portoferraio magma layers (Rocchi et al., 2002). The source depth has then been further adjusted to 20.3 km for the first magma batch of the Monte Capanne, to take into account the 1000 m thickening due to the intrusion of the San Martino magma layers.

The vertical distribution of densities in western Elba is quite well known from detailed mapping of the dismembered crustal section (Rocchi et al., 2002). However, changes occurred in the density distribution in the shallow crust following every magma emplacement episode. A detailed reconstruction of the integrated density of the crustal column must, therefore, be based on the actual crustal vertical density profile at the time of emplacement of each unit (Fig. 7). The integrated density of the rising magma between the source and the dike tip has been reconstructed using whole-rock average chemical compositions (Dini et al., 2002) to determine the low-pressure values (Niu and Batiza, 1991), taking into account density variations with pressure and imperfect adiabatic behavior of magma during the ascent (Hogan et al., 1998). In addition, these calculated melt densities have been corrected for the crystal charge carried by the different magma batches. The laccolith magmas had slightly lower densities than did the Monte Capanne magmas, due to their slightly more felsic compositions.

Horizontal stress, the second highly influential variable controlling magma driving pressure, consists of the sum of the lithostatic stress (the vertical stress) and the tectonic stress, which is a function of the regional state of crustal stress. During Late Miocene time, the upper crust in the Elba area was in a tensional stress regime, and all the intrusions were emplaced in the brittle part of the upper crust, i.e., within the two uppermost tectonic complexes derived from oceanic ophiolitic and turbiditic units thrust onto the Apennine fold-and-thrust belt. Accordingly, we calculated the horizontal stress by subtracting the calculated crustal yield strength profiles (Ranalli, 1997; Liotta and Ranalli, 1999) from the vertical stress. Using a parameter of 0.75 (normal faulting setting) and a pore fluid factor (ratio of pore fluid pressure to overburden pressure) of 0.15, we obtained a gradient of 15.6 MPa km^{-1} for the brittle part of the crust, very similar to the value of 16 MPa km^{-1} obtained for the tensional stage of the Cambrian Southern Oklahoma aulacogen (Hogan and Gilbert, 1995).

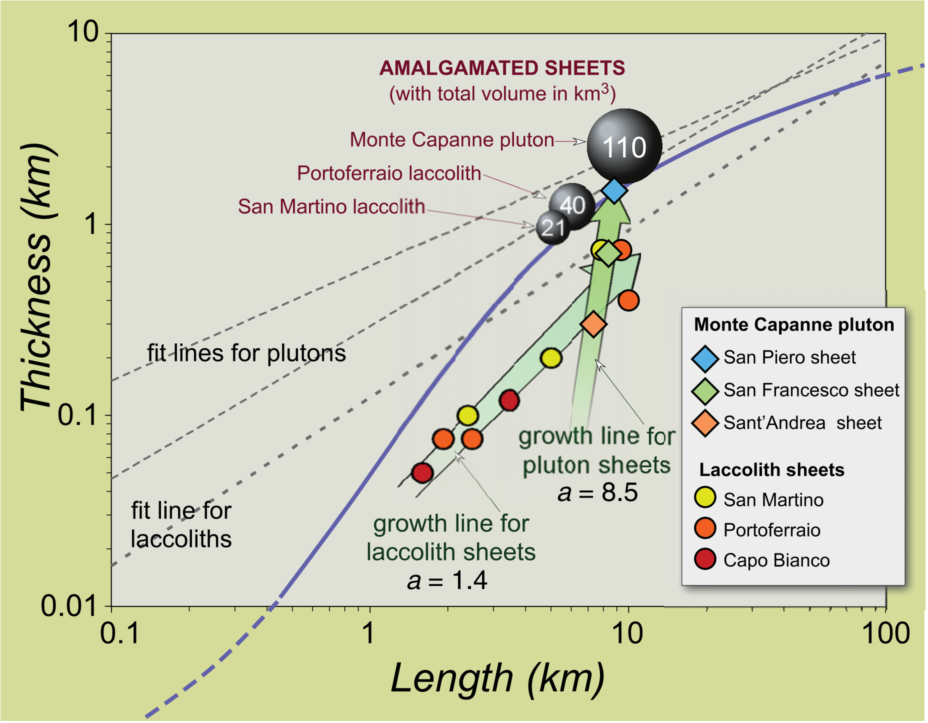

Figure 8. Log-log plot of the thickness (*T*) versus the diameter of sheets (*L*). The general power-law equation describing the relationships between L and T has the form $L = kT^a$ (where *k* is a constant and *a* is the slope of a regression line in a log-log plot). Dimensional data and power-law equation (with *a* = 1.4) for laccoliths are from Rocchi et al. (2002); data for Monte Capanne pluton sheets are from Farina et al. (2010).

All the Elba magma batches project a positive driving pressure value at the surface, thus having the potential to erupt. However, none of them did so. The two laccolith units were emplaced at depths shallower than the point where the ascending magma driving pressure first exceeded the vertical stress. The Portoferraio laccolith layers were emplaced at a depth only slightly shallower than that point, i.e., the magma switched from vertical to horizontal movement as soon as the magma left behind the densest host rock unit (the ophiolite sequence, Fig. 7) and acquired the ability to lift the overburden (i.e., driving pressure exceeds vertical stress; Fig. 9A). Furthermore, a prominent physical discontinuity occurred at that depth, namely the thrust level between tectonic complexes IV and V. The San Martino laccolith layers were emplaced ~1000 m above the Portoferraio magmas. The magma was able to ascend higher than the previous batch and switched from vertical to horizontal propagation when it met crustal magma traps and had the ability to lift the overburden (Fig. 9B), i.e., the physical discontinuities within the turbidite sequence (competence contrast between sandstone and shaley layers plus internal thrusts).

The first magma batch of the Monte Capanne pluton (Sant'Andrea sheet) was emplaced deeper than the laccoliths, slightly below 6 km (Fig. 7). The petrochemical features of the Sant'Andrea magma batch (chemical composition and megacryst content of ascending magma) do not differ enough from those of the San Martino magma to explain the difference in emplacement level. A possible explanation for halting the rise of Sant'Andrea magma at 6 km is linked to elevation of the crustal brittle-ductile transition during this period of increasing heat flow in the area, owing to ongoing lithospheric delamination, asthenosphere rise, and mafic magma intraplating in the middle crust (Serri et al., 1993), much like the present setting of the Larderello geothermal area in southern Tuscany (Gualteri et al., 1998; Dini et al., 2005; Bertini et al., 2006). However, the crustal anisotropy represented by this hypothetical elevated brittle-ductile transition could not behave as an effective crustal magma trap, because the magma driving pressure at this depth would not have exceed lithostatic load: a reduction in yield strength of the crust will increase S_h in equation 1, leading to a lowering of P_d. In addition, no evidence for regional ductile behavior has been found in the Elba tectonic units at the emplacement depth of the pluton.

An alternative explanation is linked to the combined occurrence of (1) magma source deepening owing to the uppermost crust thickening following laccolith intrusions, and (2) abundant mafic microgranular enclaves of meter size in the Sant'Andrea magma batch (Fig. 10) (Westerman et al., 2003), indicating a prominent change in the conditions of the chamber source: the hybridization zone was now fully active owing to the increased subcrustal mafic magma input and efficiency of hybridization (Dini et al., 2002). Thus, the magma could be delivered toward the shallower crust at an increased supply rate. We hypothesize that this increased rate of supply gave way to a transient reduction of the horizontal stress (Hogan and Gilbert, 1995), that is an increase of the tensional stress, possibly supplemented by ongoing slab rollback. In this context, a stress reduction of ~40% is enough to cause an increase in magma driving pressure (Fig. 9C, magenta dashed line) sufficient to overcome the vertical stress at a depth corresponding to the emplacement depth (~6 km) of the Sant'Andrea magma pulse. This batch of magma was thus emplaced as a rather thin (250 m) sheet, very rich in K-feldspar megacrysts, large quartz phenocrysts, and large mafic microgranular enclaves. The following San Francesco magma batch was emplaced below the Sant'Andrea sheet: the cryptic nature of the contact between the two facies suggests that the second one was emplaced at the base of a mushy tabular body (Saint-Blanquat et al., 2006; Farina et al., 2010). Such mushy bodies are natural traps for ascending batches of magma (Brown, 2007) because they generate a rigidity anisotropy that triggers horizontal expansion of subsequent magma batches (Menand, 2008) and growth of the intrusion by underaccretion. A similar history was

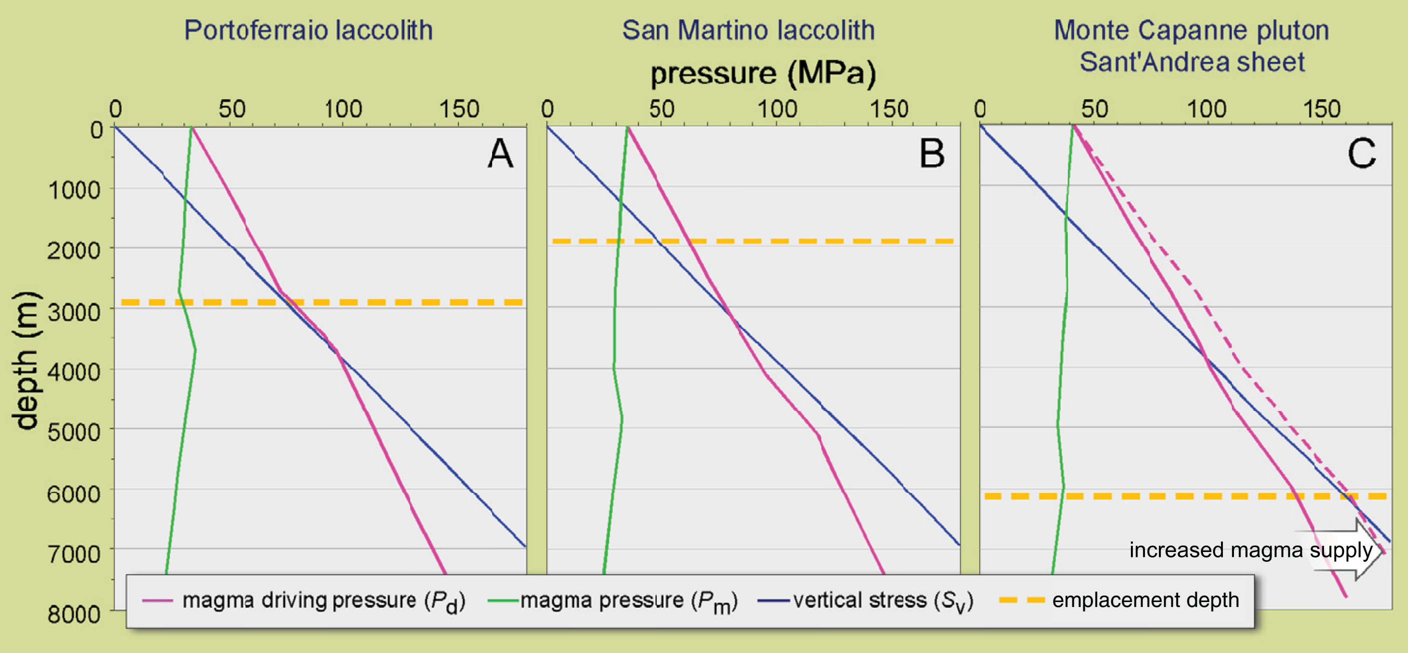

Figure 9. Variations in magma driving pressure, magma pressure, and vertical stress as a function of depth for Portoferraio laccolith magma, San Martino laccolith magma, and the Sant'Andrea sheet magma (the first magma batch of the Monte Capanne pluton). Each curve is constructed according to Hogan and Gilbert (1995) and Hogan et al. (1998). The crustal density profiles for each emplacement stage are those reported in Figure 7.

Figure 10. Extreme local enrichment in large mafic microgranular enclaves in the Sant'Andrea facies of the Monte Capanne pluton at Capo Sant'Andrea.

repeated on the arrival of the third (San Piero) magma batch that was emplaced at the base of the San Francesco sheet and, being the most voluminous and thickest sheet (~1500 m), led also to some lateral deformation of the country rock and triggered the eastward tectonic-gravitational removal of the overburden (Westerman et al., 2004). The remarkable increase in matrix grain size from laccoliths to pluton is a likely consequence of the more extended crystallization history of the pluton's magma batches. This is, in turn, linked to the greater depth of the pluton's magma trap that, at such low pressures (<200 MPa), can give rise to a significant increase in water solubility, thereby allowing higher water content of residual melt, depression of solidus temperature, and extension of the crystallization temperature range, all leading to a coarser-grained granite matrix (Hogan et al., 2000). This extended crystallization is also the key to explaining the cryptic nature of the contacts between facies of the pluton.

The shape, emplacement, and assembly history of the Monte Capanne intrusion raises questions as to which category of intrusive bodies it belongs. For its medium- to coarse-grained texture and emplacement depth, Monte Capanne has been classically regarded as a pluton. Nevertheless, it could also be regarded as a sheeted laccolith that was emplaced deeper than the normal depth limit of 3 km, and slightly exceeded the ~2 km limiting thickness owing to the rapid removal of the roof by tectonic-gravitational collapse. The steep-sided shape of the pluton, clearly visible at least in its western portion, could be a consequence of the fact that the magma driving pressure exceeded the lithostatic load only minimally (Fig. 9C) (Hogan et al., 1998).

The strong tilting of the overburden and the steep contact on the western side of the pluton, which tended to evolve as a fault structure, makes the scenario partly reminiscent of the asymmetric intrusion of the Black Mesa bysmalith, Henry Mountains, Utah (Horsman et al., 2010). However, more important than its categorization is the understanding that at Elba Island, similar magma batches in similar settings resulted in intrusive bodies that differ widely in their shape, texture, and emplacement depth. In an upper crust characterized by abundant magma traps, the failed or successful assembly of magma batches can thus be linked to variations in rates of magma supply and/or transient increase in the horizontal extensional tectonic stress (which in Elba could be linked to slab rollback). Significant constraints on the style of intrusive body construction can also arise by the downward migration of both the source region and the magma traps as a result of addition of magma layers to the uppermost crust.

CONCLUSIONS

We suggest that the Elba laccolith sheets failed to coalesce and form a larger pluton or laccolith with more typical dimensions due to the availability of a large number of magma traps in the host crust that consists of a thrust stack of bedded rocks. However, the first magma batch of the Monte Capanne pluton, under the influence of an increased magma supply rate, exploited a deeper thrust fault that separated rheologically distinctive tectonic units. Then the two closely following magma batches were halted by the first still mushy sheet. Thus, all three pulses of magma were assembled in a downward stack, building a "successful" pluton as opposed to the "failed" plutons represented by the multisheet laccoliths. Also possible is the opposite view, that the Monte Capanne pluton be regarded as a "failed" laccolith, as opposed to the "successful" multilayer laccoliths of Portoferraio and San Martino.

We speculate that in the upper crust, laccoliths and plutons represent different outcomes of the same geological process operating under different transient conditions. The tipping point allowing for transition from a laccolithic to a plutonic intrusive form having a higher thickness-to-diameter ratio can be regarded as a combination of factors such as variations in rates of magma supply and transient variations in the horizontal extensional tectonic stress, as well as downward migration of both the source region and the magma traps as a result of the addition of magma layers at higher levels in the crust.

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