Rise and fall of a nested Christmas-tree laccolith complex, Elba Island, Italy

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Abstract: In two separate areas of western and central Elba Island (Italy), Late Miocene granite porphyries are found as shallow-level intrusions inside a stack of nappes rich in physical discontinuities. Detailed mapping of intrusive rocks, along with their relations with country rocks, show that outcrops from western and central Elba Island expose the same rock types, with matching intrusive sequence, petrography and geochemical features. Structural and geological data indicate that these layers were originally part of a single sequence that was split by eastward-directed décollement and tilting. The two juxtaposed portions of the original sequence allow the restoration of a 5-km thick sequence, made up of nine main intrusive layers, building three Christmas-tree laccoliths nested into each others to support a structural dome. During their construction, the role of the neutral buoyancy level was of minor significance with respect to the role played by the relatively thin overburden and/or the large availability of magma traps inside the intruded crustal section. Emplacement of the Monte Capanne pluton into the base of the domal structure likely caused oversteepening and initiated decapitation of the complex, with gravity sliding of the upper half off the top.

Mechanisms related to the generation, movement and emplacement of granitic magmas are the subject of intensive study and conflicting hypothesis (Bouchez *et al.* 1997; Castro *et al.* 1999; Petford *et al.* 2000; Brown 2001). Efforts to understand such mechanisms benefit greatly from the collection of well-constrained data on the depth and shape of the granitic intrusions. By their nature, most granite intrusions become directly accessible only after loss of the overburden, and then generally for only two-dimensional observations. In this context, opportunities to examine crustal sections exposing an intrusion's roof and floor, such as from tilted plutons, are invaluable (Wiebe & Collins 1998). These opportunities are scarce for deep intrusions, but a little more common for shallow intrusions such as laccoliths. Additional insights on emplacement mechanisms come from analogue experimental modelling (Roman-Berdiel *et al.* 1995; Benn *et al.* 1998; Roman-Berdiel 1999) and geophysical modelling coupled with geobarometric estimates, all of which are valuable in reconstructing the 3D shape and depth of an intrusion (Améglio & Vigneresse 1999). In addition, understanding of the build-up of igneous complexes requires reconstruction of their tectonic evolution, as well as addressing the problems associated with uplift, oversteepening, tectonic dismemberment (gravity sliding, décollement), and denudation.

On Elba Island, the processes associated with both the construction and destruction of a well-documented complex are clearly illustrated in the field. Serendipitous tectonic–gravitational splitting and tilting of a Miocene igneous complex resulted in roof and floor exposures of several intrusive layers. This allowed direct field observations to determine the emplacement sequence, and to estimate the thickness of the intrusive layers and host rock, and hence emplacement depths. The geometry of the complex as a whole represents a prime example of a nested Christmas-tree laccolith complex. On the other hand, the dimensional parameters of the single layers provide a coherent data-set, suggesting that the filling of intrusive layers was halted during vertical inflation, owing to the widespread availability of crustal magma traps that promoted magma injection in new horizontal planes before the layers were completely filled. Finally, the primary intrusive geometric relationships and the reconstructed tectonic evolution suggest that the instability leading to the dismemberment of the complex was at least in part of gravitational origin, and therefore instigated by construction of the complex itself.

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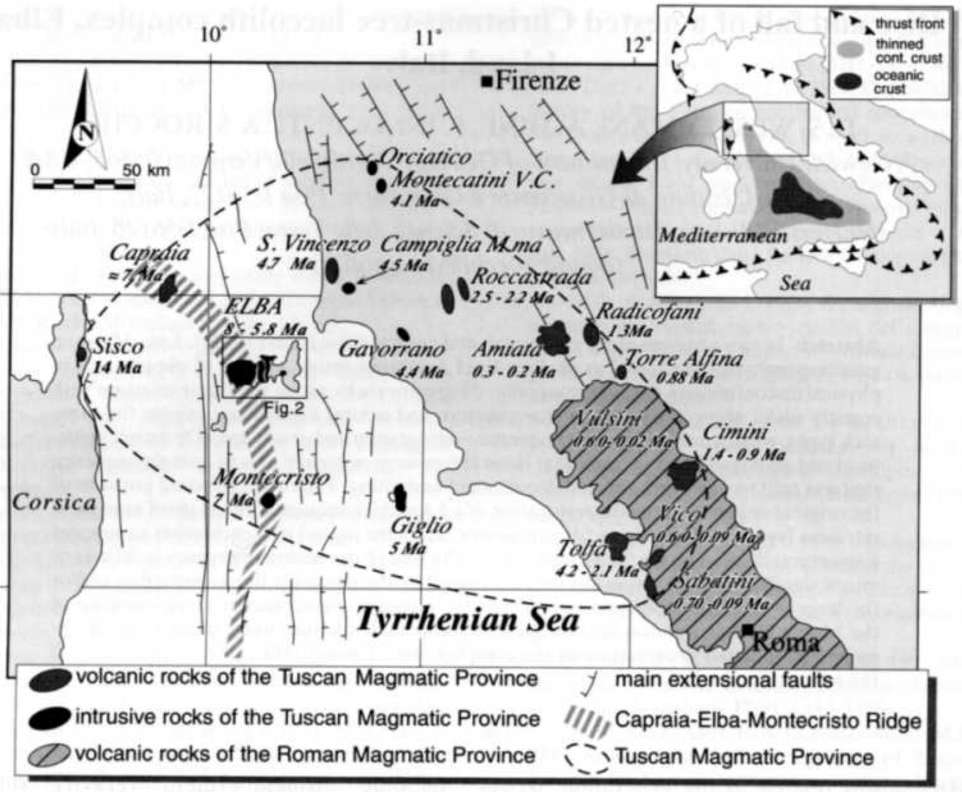

Fig. 1. Location map for the Tuscan Magmatic Province, with outcrops of intrusive–subvolcanic and volcanic rocks. Also reported are the younger potassic–ultrapotassic outcrops of volcanic rocks of the Roman Magmatic Province.

Geological outline

Regional geology

Elba Island is located at the northern end of the Tyrrhenian Sea, a region affected by extensional processes behind the eastward-progressing front of the Apennine mobile belt (Fig. 1). The backbone structure of the Apennines was constructed when the Sardinia–Corsica block collided with the Adria plate (Malinverno & Ryan 1986). This orogenic system evolved diachronously as the extensional regime migrated from west to east, trailing the retreat of the compressive regime (Brunet *et al.* 2000) and giving way to the opening of the extensional ensialic back-arc Tyrrhenian Basin.

Igneous activity associated with extensional processes also 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). Intrusive and extrusive products of mantle–crustal hybrid composition built the Tuscan Magmatic Province, spreading over about 30 000 km^2 in southern Tuscany and the northern Tyrrhenian Sea (Poli 1992; Westerman *et al.* 1993; Innocenti *et al.* 1997; Dini *et al.* 2002). Extensional processes and igneous activity affected the area of Elba Island during the Late Miocene (Bouillin *et al.* 1993; Jolivet *et al.* 1994).

Local geology

The structure of Elba Island is made up of five complexes (Fig. 2) which were stacked on to each other during the eastward Apenninic compressional event prior to 20 Ma (Deino *et al.* 1992). The lower three complexes (I–III) have continental features, consisting of metamorphic basement and shallow-water clastic and carbonate rocks, while the upper two (IV–V) are oceanic in character (Trevisan 1950; Keller & Pialli 1990; Pertusati *et al.* 1993). In more detail, Complex IV consists of Jurassic oceanic

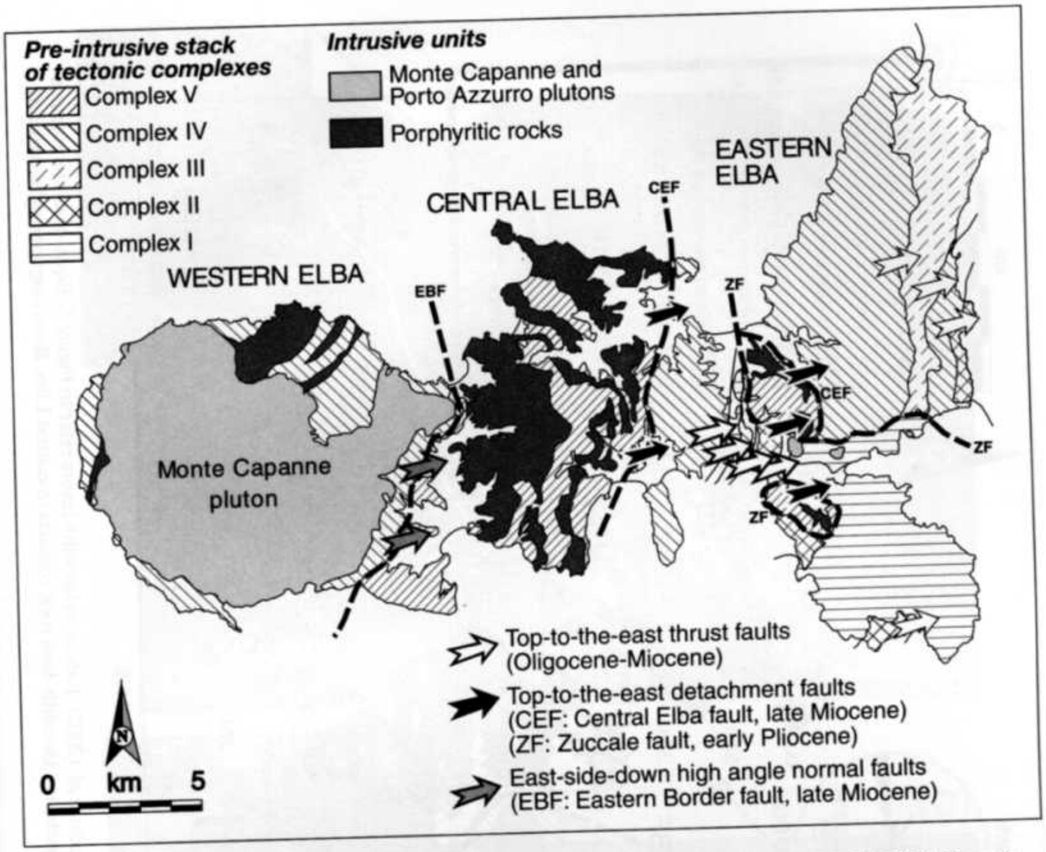

Fig. 2. Tectonic sketch map of Elba Island. Eastern Border Fault (EBF), Central Elba Fault (CEF), Zuccale Fault (ZF).

lithosphere of the western Tethys Ocean (peridotite, gabbro, pillow basalt and ophiolite sedimentary breccia) and its Upper Jurassic–Middle Cretaceous sedimentary cover (chert, limestone, and argillite interbedded with siliceous limestone). These rocks were deformed and metamorphosed during the Apenninic compression, to form east-verging folds. Complex V consists of argillite, calcarenite and sandy marl of Palaeocene to Middle Eocene age, overthrust by an Upper Cretaceous flysch sequence (Keller & Pialli 1990). Several intrusive bodies of various sizes and Miocene ages are exposed within Complex IV in western Elba and within Complex V in central Elba, making up the western intrusive complex. A younger and much smaller eastern intrusive complex is restricted to eastern Elba. Large-scale faults subdivide Elba Island into these three main zones (Fig. 2) and are the key to the reconstruction of the original geometry of the intrusive complex.

Current structural framework

Western Elba and the Eastern Border Fault

Western Elba consists of the Monte Capanne pluton and its thermometamorphic carapace of Complex IV rocks containing hypabyssal porphyry intrusions. It is separated from central Elba by the Eastern Border Fault that parallels the east side of the Monte Capanne pluton and put in contact the pluton's thermally metamorphosed host rock of Complex IV with the unmetamorphosed flysch of Complex V (Figs 2, 3 & 4). The Eastern Border Fault is marked, for the most part, by a distinct plane that dips moderately to steeply to the east. This fault separates a western footwall breccia of hornfelsed Complex IV rocks (ophiolitic material and deep-marine cover rocks) plus fragments of the Monte Capanne pluton (Fig. 4a), locally mineralized by quartz and hematite, from an eastern hanging-wall breccia made of Complex V flysch and megacrystic San Martino porphyry.