THE INTRUSIVE COMPLEXES OF ELBA ISLAND

Hutton Symposium on Granites and Related Rocks

Post-conference field trip

17 – 21 September 2023

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Table of contents

Information

Abstract

Located in the northern Tyrrhenian Sea, Elba Island is a charming destination holding a complex geological evolution that started with the stacking of tectonic complexes during the Apennine orogeny and was successively affected by extensional tectonics during the late Miocene. Investigations of this latter event, which resulted in the emplacement of two shallow-level magmatic complexes, shed light into the emplacement, architecture and chemical evolution of upper crustal felsic magma reservoirs. Moreover, Elba Island is famous for its iron deposits and lithium-cesium-tantalum pegmatites, whose generation and relations with the magmatic evolution of the Island will be discussed in the field.

In the central and western portions of Elba, a prime example of a late Miocene shallow-level intrusive complex is exceptionally preserved. This includes multiple multisheet laccoliths, a sheeted monzogranitic pluton, and extensive dike swarms emplaced over a time span of about 1.5 Ma. Shortly after the intrusive sequence was assembled, the upper part of the igneous system was tectonically translated eastward leading to the serendipitous exposure of a tilted 5-km-thick crustal section. In this area, we will be able to observe the internal structure of the shallow-level intrusions and their contact with the host.

In eastern Elba, a tourmaline-bearing, dike-sill swarm of Late Miocene age is associated with abundant tourmaline-quartz hydrothermal veins and metasomatic masses. In this area, the uppermost part of a magmatic-hydrothermal system is well-preserved, exhibiting boron-rich veins and skarn iron deposits.

In addition to visiting fascinating outcrops, you will discover an island, rich in history and characterized by breathtaking landscapes and beaches. We are looking forward to welcoming you on Elba!

Elba Island field trip: scientific questions and themes

- Mechanism of emplacement of shallow level intrusions: plutons, laccoliths, sills and dikes (*Bouillin et al., 1993; Dini et al., 2008a; Farina et al., 2010; Rocchi et al., 2010; Cifelli et al., 2011, Westerman et al., 2018).*
- Genesis and evolution of upper crustal granitic reservoir (*Dini et al., 2002*, Westerman et al., 2003; *Gagnevin et al., 2005, Farina et al., 2014; Barboni et al., 2015*).
- Sources of granitoid magmas. Deciphering the relative importance of crustal melting vs. differentiation of mantle-derived magmas (*e.g. Dini et al., 2002, 2004; Westerman et al., 2004, Gagnevin et al., 2004, 2011; Farina et al., 2012*).
- Granite magmatism in a back-arc setting, relation with low-angle extensional faults and formation of ore deposits (*Jolivet et al., 1994; Daniel and Jolivet, 1995*; *Dini et al., 2008b*; *Smith et al., 2011; Liotta et al., 2015; Jolivet et al., 2021*).
- Fluid circulation in contact aureoles: investigating fossil hydrothermal systems (*Rossetti et al., 2007; Dini et al., 2008b*)

Program Summary

- Day 1 – Sunday 17 Sept. Arrival at Elba Island. Introduction to the geology of the Island. Leucogranitic dikes and tourmaline veins associated to the Porto Azzurro pluton.
- Day 2 – Monday 18 Sept. The Eastern Elba intrusive complex. Tabular intrusions, low-angle extensional faulting and ore deposits.
- Day 3 – Tuesday 19 Sept. The Western Elba intrusive complex: the sheeted Monte Capanne pluton and the late plutonic felsic and mafic dikes.
- Day 4 – Wednesday 20 Sept. The Western Elba intrusive complex: the multilayer felsic laccolith complex.
- Day 5 – Thursday 21 Sept. Back to Pisa!

Practical information and logistics

The field trip starts on the morning of Sunday the 17th from Pisa and the participants will be picked-up at 9:00 o'clock at the train station (Pisa Centrale). Participants must organize their own travel from Baveno to Pisa, preferably on Saturday. Pisa can be reached by plane from Milano Malpensa or Milano Linate or by train from Baveno. Transport to the field trip location and from site to site will be with 9-seater minibuses. The field trip ends on Thursday 21st. We will take the ferry from Elba Island (Portoferraio) at 11 AM and reach Pisa train station at around 2 PM.

Important: **Elba Island is a protected area in a National park and rock sampling is forbidden.**

Important. The trunk of the minivans has only limited space. Therefore, it is highly recommended to carry only a small luggage containing the field gear and the personal belongings required for the duration of the field trip. We are aware that many of you are likely travelling with large suitcases, and we strongly suggest leaving them in the lock room available at the Pisa train station. The deposit costs 5 euros per day per luggage. As. an alternative, if you sleep over in Pisa on the 16th, ask if you can store your suitcases at the hotel and collect them on the 21st.

Safety

Usual field equipment (hand-lens, field book, backpack, etc ; please note: no hammers allowed). Short hikes are planned, thus light field boots are recommended. Basic equipment must also include sunscreen, both light and warm clothes, a hat and a waterproof jacket. Several outcrops are located on the seashore; we suggest bringing a swimsuit. Passport and/or ID-card + valid EU Visa for non-EU residents are required.

Important. On the 20th, we will visit a beautiful section along the seashore (Stop 4.1). To reach some of the best outcrops we must walk for a few tens of meters in seawater moving from one beach to the other. Depending on the tide, the water can be up to 1 meter high. To make the experience safe and enjoyable, we suggest wearing a pair of spare sneakers or light boots and a swimming suit and bring a towel and a change (socks, t-shirt).

Hospitals

In case of serious need for immediate assistance on the field trip, you may call the emergency number 112, free of charge. In Italy, medical assistance is provided to anyone in need, regardless of nationality and without asking for upfront payment. Below is contact information for the nearest hospital:

- Ospedale Civile di Portoferraio (Elba Island). Locality: San Rocco - 57037 Portoferraio (LI) – Elba Island. Phone number +39 0565-926111. The hospital is located just 1 km from the port and 10 km from the hotel.

Overnight accommodation and “gala” dinner

At the hotel Villa Wanda (Lido di Capoliveri, https://www.hotelvillawanda.com/). Breakfasts and dinners will be served at the hotel. Lunch packages are provided and included in the total cost. On the 20th, the dinner (the last together on the Island) is organized at the restaurant “Da Oreste” in Rio Marina. This is a traditional fishmeal restaurant and we agreed on a menu of nine different starters and two first courses. If someone has food allergies or simply does not eat fish, we will organize a special menu. Water and house wine (1/4 of litre per person) are included.

Excursion notes

Overview of the field area

Elba Island is located at the northern end of the Tyrrhenian Sea and with its 220 km^2 of areal extent represents the largest island in the Tuscan Archipelago and the third largest in Italy. Elba has been inhabited since the Palaeolithic and was renowned in the Mediterranean area for its ore potential since three thousand years ago when the exploitation of copper started. Thereafter, Elba joined the history of the main Mediterranean civilizations: the island is reported in the myth of Jason and the Argonauts, and the Greek philosopher Aristotle refers to Elba when he describes a little island in the region of the Etruscans where metals were mined. In the third century BC, the Romans took control of the Island along with its valuable ores. They also started to quarry the granite of western Elba, and columns from the Island can be admired today in the Pantheon and Saint Paul cathedral in Rome. In the Middle Age, Elba became a possession of Pisa, which exploited the iron ores and defended the territory against the Saracen pirates, building mountain- and sea-towers and fortresses, many of which remain well-preserved (e.g. Volterraio and Marciana). Elba was again in the spotlight in the 19th century when it was chosen as the destination for the first exile of Napoleon. He arrived on Elba in May 1814, and during his short stay, the island flourished, with the construction of new roads and villas, improvements in the public health system and a new development of the mining industry. After Napoleon's departure and his final defeat, Elba was annexed to the Grand Duchy of Tuscany in 1815, and in 1861 became part of the newly born Kingdom of Italy. The Italian Elba was an important iron extraction centre and went through a flourishing period of trade development that terminated after the Second World War. From 1950 onwards, the arrival of tourism, as well as increasing competition in the iron market, led to the progressive halt of the mining activity, and in 1981, the last mine still in operation (the Ginevro Mine) was closed down. Today, the Elba Island is an important touristic site, famous for its beautiful beaches, cultural and historical heritage and for the extraordinary richness of its landscapes. Moreover, thanks to the Elba Mineral Park and the Calamita Mineral Park, many visitors have the opportunity to know and appreciate the outstanding geological, mineralogical and mining heritage of the Island.

Geological background

The contractional orogens and extensional basins of the Mediterranean region (Fig. 1) have formed since Late Mesozoic in a tectonic setting dominated by the northward relative motion of Africa toward Eurasia (Dewey et al., 1998). Overall, the thrust belts were formed by shortening the old passive continental margins created during the early Mesozoic breakup of Pangea. In the Apennine orogenic system, Neotethyan oceanic lithosphere is being subducted along seismically active and tomographically imaged zones in the Calabrian–Tyrrhenian systems, while in the northern Tyrrhenian sector evidence for subduction of Alpine Tethys oceanic lithosphere is fragmentary and the plate boundaries are complicated by the existence of the Adria subplate. During the Late Cenozoic, a distinctive pattern has evolved of arcuate thrust belts or accretionary wedges surrounding extensional basins floored by new oceanic crust (such as in the southern Tyrrhenian Sea) or thinned continental crust (such as in the northern Tyrrhenian Sea) (Jolivet and Faccenna, 2000). Therefore, since the Cretaceous, the northern Tyrrhenian and Apennine regions of Italy experienced two main phases of deformation, both of which migrated progressively from west to east (Pauselli et al., 2006). An early phase of Cretaceous to Quaternary compression related to collision between the Adria microplate and the Corsica-Sardinia block (i.e. part of the European plate, Malinverno and Ryan, 1986) was followed by post-collisional extension. This second phase led to the opening of the ensialic back-arc Tyrrhenian basin and continues to the present day within the Apennine mountains of central Italy (Collettini et al., 2006). Extension was intimately associated in both space and time with magmatic activity that migrated from west (14 Ma) to east (0.2 Ma) as the west-dipping Adria plate delaminated and rolled back to the east (Serri et al., 1993). In this tectonic setting, the interaction between mantle-derived and crust-derived magmas produced the large variety of igneous rocks of the Tuscan Magmatic Province (Fig. 2). This province is made of intrusive and extrusive products exposed over about 30,000 km^2 in southern Tuscany and in the northern Tyrrhenian Sea (e.g. Innocenti et al., 1992; Poli, 1992).

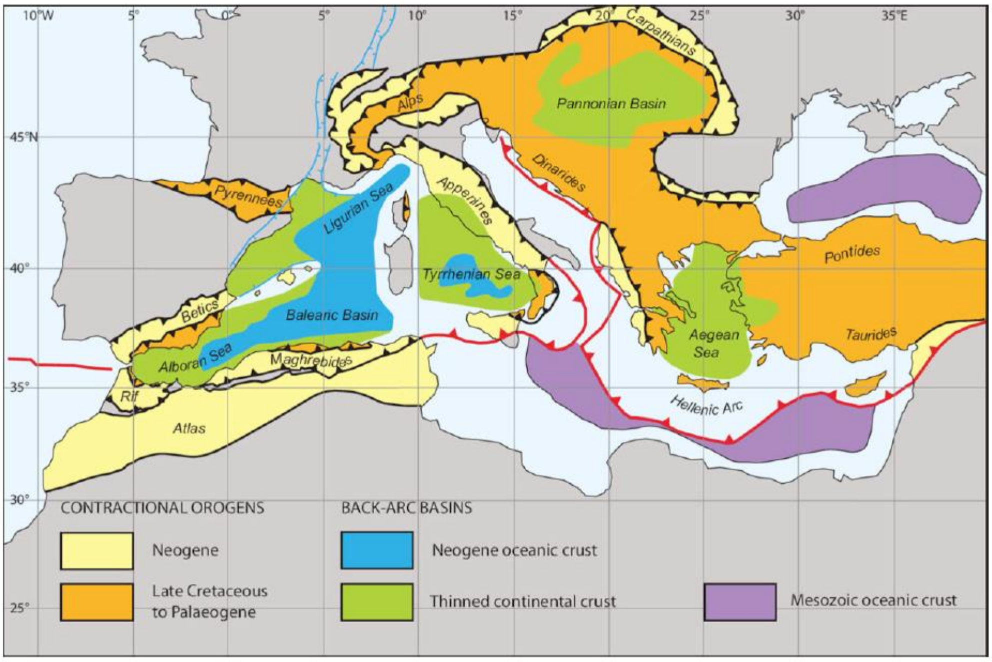

***Figure 1**. Tectonic map of the Mediterranean region, showing Mesozoic–Cenozoic contractional orogens and Neogene extensional basins. The Africa–Eurasia plate boundary is shown in red (from Platt, 2007).*

Geology of Elba Island

The structure of Elba Island consists of a series of stacked thrust sheets formed during the Late Cretaceous - early Miocene Apenninic convergence. Trevisan (1950) recognized five thrust "complexes" composed of diverse lithological units that have continental (Complexes I–III) or oceanic (Complexes IV–V) affinities, all of which dip to the west (Fig. 3). The three lowest complexes (I-III) consist of the metamorphic basement and shallow-water clastic and carbonate rocks. Complex IV is made of the 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). At the top of the sequence, Complex V is composed of argillite, calcarenite and sandy marl of Palaeocene to middle Eocene age, overthrust by an upper Cretaceous flysch sequence (Keller and Pialli, 1990). More recently, Bortolotti et al. (2001) proposed a different and more complex tectono-stratigraphic subdivision of Elba Island recognizing nine major tectonic units. In late Miocene time, extensional processes affected the area of Elba Island (Jolivet et al., 1994), and intrusive units were emplaced within the stacked tectonic complexes. These intrusive bodies are exposed across the whole of Elba Island, which is geologically subdivided by large-scale faults into three main zones: western, central and eastern Elba (Fig. 3). These zones and their bounding faults are the keys to reconstruction of the original geometry of the intrusive complexes.

Western Elba and the Eastern Border Fault **–** Western Elba is formed by the Monte Capanne pluton and its thermometamorphic aureole of Complex IV rocks containing sub-volcanic porphyry intrusions. It is separated from central Elba by the Eastern Border fault that parallels the east side of Monte Capanne (Fig. 3). The Eastern Border fault, which is marked by a surface dipping moderately to steeply to the east, separates a western footwall breccia of hornfelsed Complex IV rocks (ophiolites and deep marine cover rocks) and fragments of the pluton, from an eastern hanging wall breccia made of Complex V flysch and porphyries. Movement on the Eastern Border fault was "west side up" and juxtaposed western rocks from 4-5 km depth (Dini et al., 2002) with shallowly buried sedimentary rocks and their enclosed porphyries on the east side (Fig. 3).

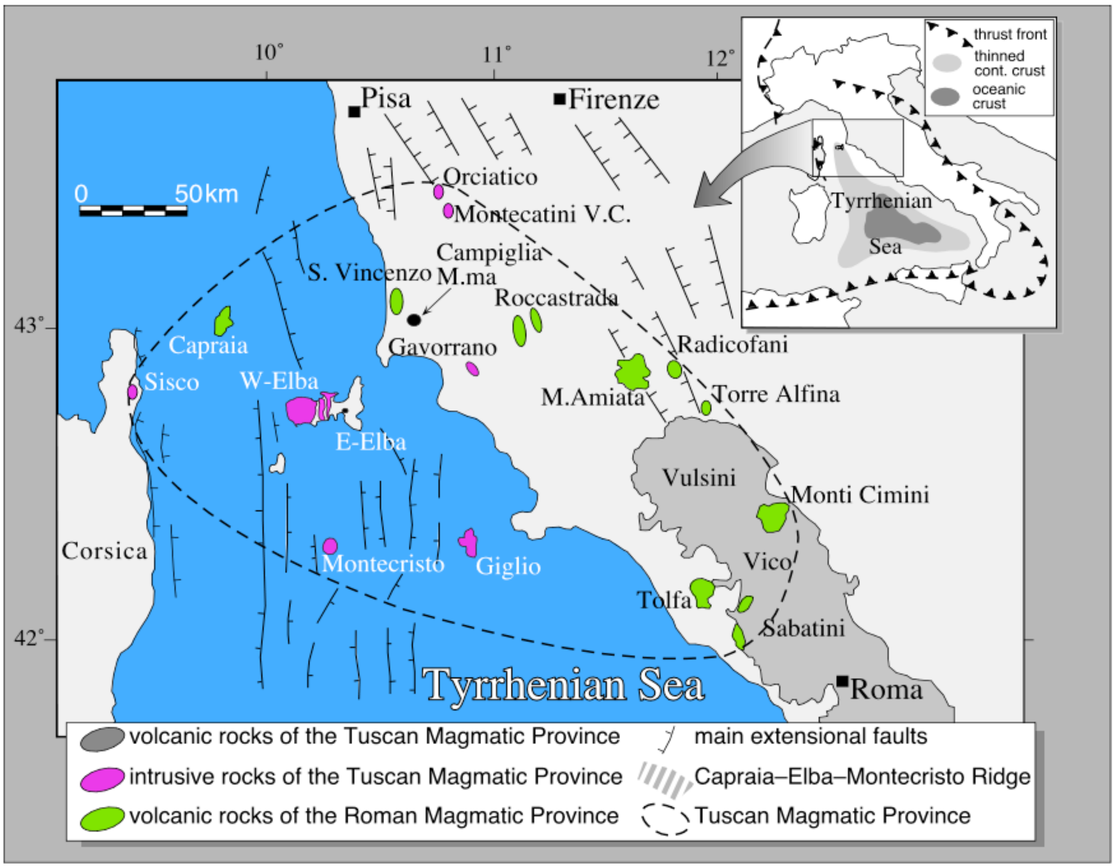

***Figure 2**. Geological sketch map of the Tuscan Magmatic Province (modified form Dini et al., 2008b).*

Central Elba and the Central Elba Fault **–** Central Elba is bound to the west by the Eastern Border fault and is separated from eastern Elba by the low-angle Central Elba fault, marked by a zone containing a tectonic mélange of rocks from Complexes IV and V (Trevisan, 1950). The fault dips gently westward, as does the dominant fabric of the rocks resting on it, such that the highest part of the section occurs at the western edge against the steeply-dipping Eastern Border fault (Fig.3).

Eastern Elba and the Zuccale Fault **-** In eastern Elba, a younger low-angle detachment fault, the Zuccale fault, has been documented with eastward transport of 5-6 km (Pertusati et al., 1993, Smith et al., 2011). This fault movement post-dates that on the Central Elba fault since it sliced off the leading edge of the Central Elba fault to produce a klippe of Complex V rocks in eastern Elba (Fig. 3). The relations between the Zuccale fault and igneous bodies intruded into the immediate footwall of the fault indicate that faulting and intrusion overlapped in time, and brittle and ductile kinematic indicators yield consistent WNW-ESE extension direction (Smith et al., 2011). The Zuccale fault has a regional domal morphology interpreted as being related to the emplacement of the Porto Azzurro pluton, involving some component of vertical inflation and roof uplift.

Magmatic activity at Elba Island

Magmatic activity on Elba occurred between ca. 8.5 Ma and 6.4 Ma and involved both crust- and mantle-derived melts, whose interaction produced the chemical variability exhibited by the intrusive rocks of the Island (Dini et al., 2002). On Elba, two separate intrusive complexes occur: the Central-Western and the Eastern complexes. The main characteristics and units forming these intrusive suites are presented individually.

The Central-Western Elba intrusive complex – It is the oldest and the best exposed complex in the island. The relative chronology of the intrusive sequence has been established based on crosscutting relations and is supported by isotope chronology (Dini et al., 2002). The igneous sequence started with the construction of a multilayer laccolith complex, first by the emplacement of the layers of Capo Bianco aplite and followed in succession by the layers of the Portoferraio laccolith and, finally by those of the San Martino laccolith. The deepest laccoliths were then intruded and deformed by the Monte Capanne pluton and its associated late leucocratic dikes. Finally, the ca. 200 "mafic" dikes of the Orano swarm were emplaced, cutting through the entire succession. Shortly after the intrusion sequence was completed, the upper part of the igneous-sedimentary complex was tectonically translated eastward along the Central Elba fault (CEF), so that the lower part is presently found in western Elba, while the upper part is well preserved in central Elba (Westerman et al., 2004). A brief description of the units forming the Central-Western complex follows.

The Capo Bianco aplite is a white porphyritic alkali feldspar granite containing phenocrysts (1–5 mm) of muscovite, K-feldspar, oligoclase and quartz set in a fine-grained (5–250 µm) K-feldspar–albite–quartz groundmass (Dini et al., 2007). The aplite is locally characterized by the widespread occurrence of black tourmaline clots (orbicules) with variable size, from a few millimetres up to 15 cm and show fine-scale layering with alternating white quartz–feldspathic layers and pinkish muscovite-rich layers.

This rock displays a unique chemical composition relative to the other granites of the complex. The aplite is high in silica (72-75 wt% SiO_2), strongly peraluminous (A/CNK = 1.3–1.5) and shows very low content in TiO_2, MgO, $FeO_{(tot)}$ and CaO, with notably high Be, Cs, Rb, Nb and Ta. The boron content of this rock is low (5–30 ppm) in the tourmaline-free portions near the base of the laccolith and reaches very high values (2000–3000 ppm) in the tourmaline-rich zone at the top of the intrusive layer. The relatively high $^{87}Sr/^{86}Sr$ (0.712–0.713), the low $^{143}Nd/^{144}Nd$ (0.51213–0.51214; ε_{Nd} = -10), and the $\delta^{11}B$ (-7.2 up to -7.6 ‰), coupled with major and trace element geochemical data, suggest a crustal origin for the Capo Bianco aplite by muscovite dehydration melting of a metapelitic source (Dini et al. 2002).

The age of Capo Bianco aplite is constrained by dates between 7.91–7.95 (muscovite–whole rock Rb–Sr) and 8.5 Ma (muscovite $^{39}Ar/^{40}Ar$; Maineri et al. 2003)

The aplite forms two tabular bodies, both partially intruded by younger granite porphyries. The deeper layer occurs in western Elba within metaophiolites and hornfels (Complex IV) while the upper layer is exposed in central Elba, near Portoferraio, and is hosted by pelitic-siliciclastic sequences (Complex V). This upper layer originally had a length of about 3.5 km, thickness ca.120 m and was emplaced at a depth of 2.6 km (Rocchi et al. 2002).

The Portoferraio porphyry has monzogranite to syenogranite composition and contains prominent phenocrysts of sanidine (up to 8 cm in length) set in an aphanitic groundmass made of quartz and K-feldspar. Phenocrysts also include quartz, plagioclase and biotite. This porphyry has silica content ranging 70-73 wt%, MgO + $FeO_{(tot)}$ between 2 and 3 wt% and is peraluminous (A/CNK = 1-1.2). Moreover, there is a positive linear correlation between peraluminousity and maficity (i.e. Mg + Fe, Farina et al., 2012). The Portoferraio porphyry has a crustal Sr and Nd signature similar to that observed for the Capo Bianco aplite. Taken together these chemical features suggest a direct derivation by fluid-absent melting of biotite from a clastic aluminous source (Dini et al., 2002) together with a low degree of entrainment of peritectic cordierite and/or garnet (Farina et al., 2012).

Zircons from the Portoferraio porphyry were analysed by Chemical Abrasion Isotope Dilution Thermal Ionization Mass Spectrometry (CA-ID-TIMS) by Barboni et al. (2015). The results show a limited spread of $^{206}Pb/^{238}U$ dates ranging from 7.942 ± 0.008 to 8.009 ± 0.012 Ma.

The porphyry occurs as four major layers commonly interconnected and accompanied by minor dikes and sills. Three major layers occur in western Elba. The two lower layers, both with a maximum thickness of about 75 m, intruded the metabasalts of complex IV while a higher layer, emplaced between hornfelsed argillite and ophiolitic rocks, crosscuts the Capo Bianco aplites. This layer terminates to the SW against the Monte Capanne pluton and was likely connected with the Chiessi outcrops (Fig. 3) before the Monte Capanne pluton intruded and deformed the porphyry. The total length of the layer was, therefore, ca. 9 km, but only 3 km are presently exposed in the north-eastern part of western Elba. The fourth layer of Portoferraio porphyry, which occurs in central Elba between Cretaceous flysch and Eocene calcarenites, has a maximum thickness, of ca. 400 m.

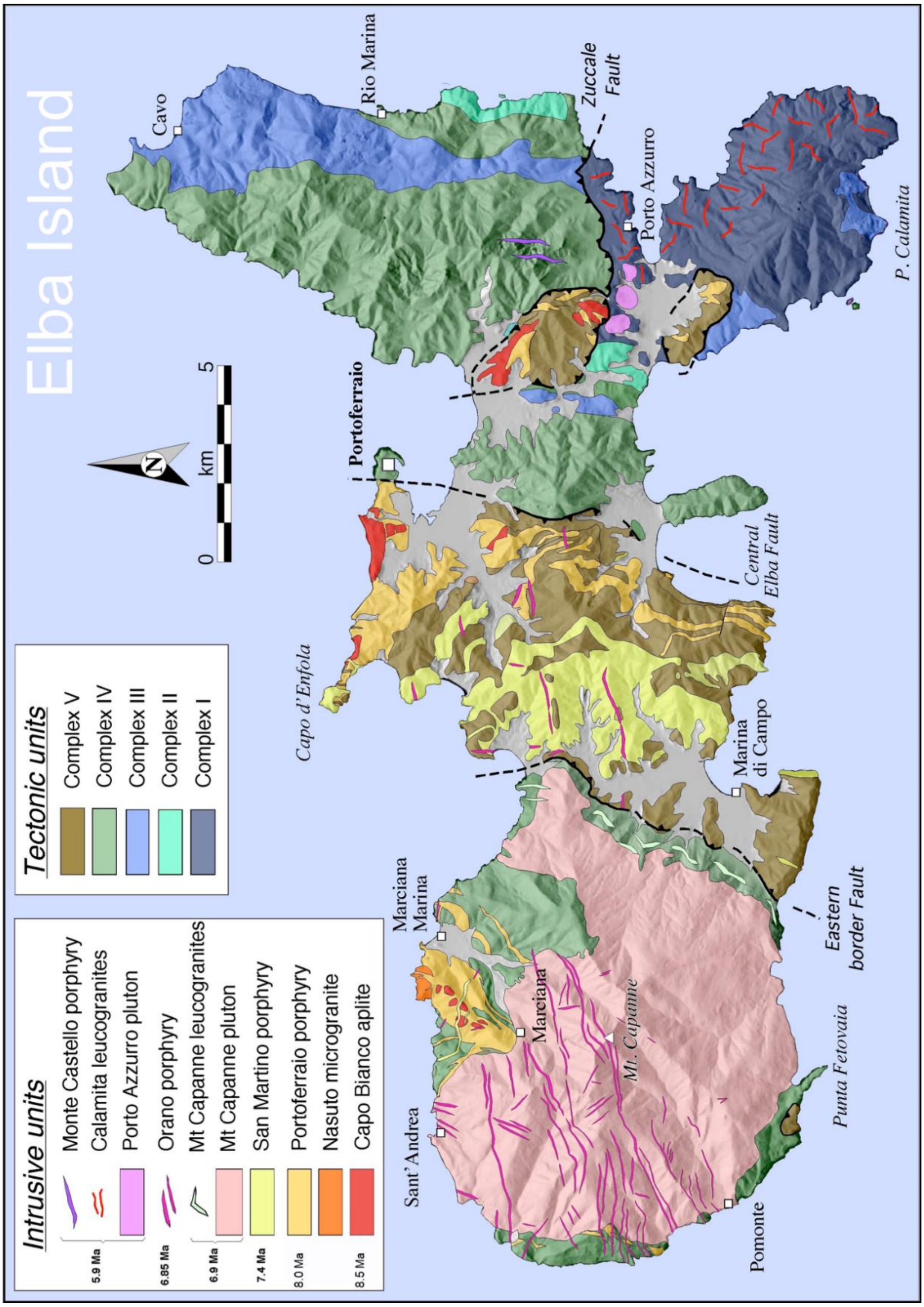

Figure 3 – Geological map of Elba Island (modified from Rocchi et al., 2010).

The San Martino porphyry is a monzogranitic porphyry occurring as dikes or thick laccolithic layers and characterized by prominent megacrysts of sanidine set in a very fine-grained groundmass. Megacryst abundance is 50–200 megacrysts/m^2 corresponding to 3–12 vol%. Phenocrysts also include quartz (1–2 cm), plagioclase (0.1–0.5 cm) and biotite (0.1–0.5 cm). The groundmass consists of an equigranular, isotropic aggregate of quartz and feldspars, along with accessory apatite, zircon and monazite. The San Martino porphyry hosts mafic microgranular enclaves.

San Martino is peraluminous (A/CNK = 1-1.2), has silica content in the range 67-70.5 wt% and MgO + $FeO_{(tot)}$ varying from 2.5 to 3.5 wt%. The San Martino porphyry has higher $^{143}Nd/^{144}Nd$ (ε_{Nd} = -9) and $^{87}Sr/^{86}Sr$ (0.71622) than the earliest intrusive units. Importantly, Farina et al. (2014) documented clear evidence of Sr isotopic disequilibrium among the different rock forming phases, with $^{87}Sr/^{86}Sr$ ranging 0.710-0.718 among minerals in individual samples.

Zircons analysed by CA-ID-TIMS for the San Martino porphyry (Barboni and Schoene, 2014) exhibit a large variation in $^{206}Pb/^{238}U$ ages, spreading between 7.437 ± 0.011 and 7.947 ± 0.005 Ma, with most of the ages ranging between 7.437 ± 0.011 to 7.541 ± 0.006 Ma. The youngest U-Pb age is identical within error to a sanidine $^{40}Ar/^{39}Ar$ age of 7.44 ± 0.08 (Dini et al., 2002).

The San Martino laccolith is composed of three main, westward-dipping subparallel layers cropping out in central Elba, as well as several dikes below these laccolithic layers. The topmost layer is the most voluminous, reaching a thickness of ca. 700 m with a north–south length of 8.3 km. Layer 2 represents less than 5% of the total laccolith volume, striking NW–SE for about 1 km in the northern half of the complex. The lowermost Layer 3 parallels Layer 2 with an exposure length of 2 km and a thickness of ca. 250 m. The subvertical NE–SW-oriented Sansone dike is exposed over 400–500 m with widths of 3–20 m. Its structural location below the laccolith suggests that it locally fed Layer 3 (Roni et al., 2014). In western Elba, San Martino crops out as the roots of the original laccolith complex left behind after its eastward translation. Six steeply dipping dikes of San Martino porphyry are mapped in western Elba. The largest, the WNW–ESE Marciana dike, which is 1500 m long and 10–20 m thick, is interpreted as the main feeder (Rocchi et al. 2002).

The Monte Capanne pluton is a monzogranitic intrusion with a total volume of ca. 110 km^3 and a mineralogy chiefly consisting of plagioclase, microperthitic K-feldspar, quartz and biotite. The pluton is characterized by the heterogeneous distribution of K-feldspar megacrysts and by the common occurrence of mafic microgranular enclaves of variable size and composition. Megacryst abudance is strongly variable with zones ranging from 0 to 2 megacrysts/m^2 to 100 megacrysts/m^2 (up to 7 vol%). Such a variability has been used to defines three main facies (Farina et al., 2010), with respectively, low (San Piero facies), intermediate (San Francesco facies) and high (Sant'Andrea facies) megacryst abundance (Fig. 4). The three facies show minor yet systematic differences in whole-rock major and trace element composition, isotopic composition and biotite mineral chemistry, and have been interpreted to represent three different batches of magma formed at depth and emplaced sequentially (Farina et al., 2010). The pluton is also characterized by the occurrence of rare amphibole clots replacing former pyroxene crystals and by metasedimentary xenoliths ranging in size from 1 to 10 cm.

The pluton exhibits Sr isotopic disequilibrium among its rock forming phases (Farina et al., 2014), with the biotite included in the K-feldspar megacrysts being extremely radiogenic (0.730) and higher in $^{87}Sr/^{86}Sr$ than the megacryst cores (0.718-0.720) and rims (0.7155), as well as than the plagioclase and K-feldspar in the matrix (0.7145-0.7150).

Zircon high-precision CA-ID-TIMS U-Pb ages determined for the three facies (Barboni et al., 2015) showed: i) large intra-sample age variations of 200-400 kyr; ii) overlapping but progressively younger age from Sant'Andrea (younger age = 7.236 ± 0.005), to San Francesco (younger age = 7.166±0.007) and San Piero (younger age = 7.007 ± 0.007), supporting pluton assembly by under-accretion.

The Monte Capanne pluton is cut by leucogranite dikes and aplite-pegmatite veins and dikes commonly occurring as thin (0.1 to 2 m) and short (up to a few meters) masses. Leucogranites and pegmatites occur mainly close to the pluton's contact, within both the pluton and its contact metamorphic aureole. The gem-bearing pegmatites cropping out along the eastern border of the pluton display a marked Li-Cs-Ta (LCT, Pezzota, 2000) signature showing a variety of inner structures and a complex mineralogy (e.g. elbaite, petalite, pollucite, microlite).

The Cotoncello dike crops out at Punta Cotoncello in the northwestern part of the pluton. This intrusive body has syenogranitic composition, is characterized by the presence of K-feldspar megacrysts and by a distinctively finer-grained matrix with respect to the host pluton (Dini et al., 2002). The Cotoncello body intrudes the pluton but it also displays striking textural evidence of mixing/mingling with the Monte Capanne magma. This feature indicates that the Monte Capanne pluton was still partially crystallized during the emplacement of the Cotoncello body.

The Orano dike swarm occurs as a swarm of more than 200 darkly coloured dikes of quartz monzodioritic to granodioritic composition. The E–NE Orano dike swarm crops out in western and central Elba intruding all the other intrusive units of the sequence and representing the closing event of igneous activity in western and central Elba (Dini et al., 2008a). Orano dikes are porphyritic with plagioclase, biotite, clinopyroxene and amphibole phenocrysts as well as quartz and K-feldspar xenocrysts set in a very fine-grained groundmass of plagioclase, K-feldspar and phlogopite. Some dikes are zoned, with the outer border zones, typically a few 10s of centimeters thick, distinguished from the inner zones by (i) finer grained groundmass, (ii) lower content of K-feldspar and quartz xenocrysts, and (iii) higher ferromagnesian mineral concentrations.

A western Elba sample yielded a Rb-Sr isochron of 6.87 ± 0.28 Ma, matching a sanidine $^{40}Ar/^{39}Ar$ isochron age of 6.83 ± 0.06 Ma obtained for a dike in central Elba (Dini et al., 2002). More recently, like the Monte Capanne pluton, a large spread in zircon $^{206}Pb/^{238}U$ ages was observed, ranging from 7.080±0.005 to 7.503±0.007 Ma (Barboni et al., 2015).

In western Elba, more than 80 km of Orano dikes have been documented, primarily within the Monte Capanne pluton and to a lesser extent within the surroundings contact metamorphic rocks. The structural pattern of the dikes suggests emplacement of the Orano magma as primary fractures (R1) of a dextral Riedel shear system trending NE-SW. Therefore, the Orano dike swarm, marking the end of magmatism in western Elba, has been interpreted as evidence for the activity of a transfer fault zone in the northern Tyrrhenian region (Dini et al., 2008b).

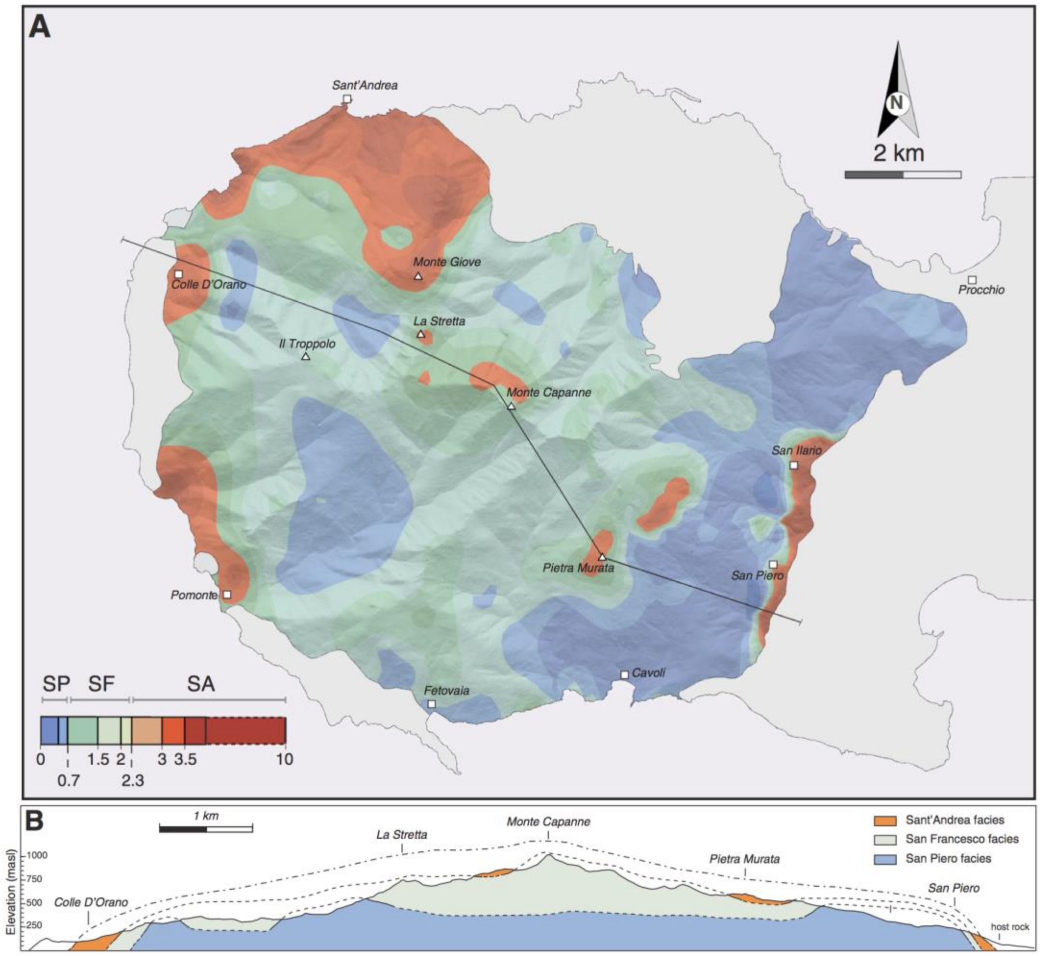

***Figure 4**. A. Contour map of Monte Capanne pluton showing the variability of megacryst content (from Farina et al., 2010). Line of cross section is drawn through Monte Capanne. (B) Interpretive NW-SE geologic cross section of the Monte Capanne pluton. The Sant'Andrea (SA), San Francesco (SF), and San Piero (SP) facies are geometrically represented as three sheets extending across the whole pluton with overall slightly upward-convex shapes.*

The Eastern Elba intrusive complex - The Porto Azzurro pluton, a few mafic dikes and a widespread association of felsic tabular intrusions and hydrothermal veins-masses intruded the eastern Elba Island tectonic stack. In particular, these intrusive units occur in the Calamita schists (Complex I) which consist of psammitic-pelitic hornfels along with minor interlayered amphibolite bodies.

The Porto Azzurro pluton is a biotite-tourmaline-bearing megacrystic monzogranite (Spiess et al., 2021). The pluton has only limited exposure in the south-central part of eastern Elba (Fig. 1.5), but a significant size (i.e. ca. 60 km^2 of areal extent) has been inferred by the extent of its thermometamorphic aureole to the south and supported by gravimetric profiles (Musumeci and Vaselli, 2012). Magma emplacement took place at pressures of 200 - 175 MPa, as determined from mineral assemblages in the contact aureole (Caggianelli et al., 2018).

A ^{40}Ar-^{39}Ar biotite age of 5.9 ± 0.2 Ma was obtained by Maineri et al. (2003). More recently, zircon U-Pb data obtained by Laser Ablation ICP-MS by Spiess et al (2019) gave a weighted mean age of 6.4 ± 0.4 Ma. A brownish-grey porphyritic shoshonitic dike, similar to the Orano dikes, was emplaced in eastern Elba at 5.8 Ma (Conticelli et al., 2001). The occurrence of this dike, whose chemistry and mineralogy is akin to that of the Orano dikes in western Elba, suggests a sequence of emplacement that was repeated in eastern Elba ca. 1 Myr after the Western-Central complex developed.

Felsic dikes and sills crop out in the eastern part of the Calamita peninsula and in the Porto Azzurro area. They have variable thickness (from 3 cm to 6 meters; Papeschi et al., 2022) and strike N40E - N160E, with sub-horizontal (sills) to sub-vertical (dikes) attitudes and para-concordant to discordant geometric relationships with host rock foliation. The felsic tabular bodies are coarse-grained pegmatitic or microgranitic and invariably have leucogranitic compositions. They are composed of quartz, K-feldspar, plagioclase and mutually exclusive primary muscovite or biotite. Tourmaline is ubiquitous as an early crystallizing phase, as testified by its euhedral shape, indicating an original high boron content of the magma. Based on the relative abundance of white mica, biotite and tourmaline, three types of leucogranitic dikes were distinguished: (1) tourmaline-bearing leucogranite (tourmaline ± white mica ± biotite), (2) white mica-bearing leucogranite (white mica ± tourmaline) and (3) biotite-bearing leucogranite (biotite ± tourmaline ± white mica).

These felsic dikes are locally associated with massive boron metasomatic effects (e.g. Cala Stagnone). Hydrothermal tourmaline-quartz veins and metasomaic masses cut across dikes and sills, testifying to the widespread hydrothermal circulation of boron-rich saline fluids that affected both the intrusive and hornfelsed rocks (Dini et al., 2008b).

Hydrothermal Ores from Elba Island (Italy) have been extremely important for the Mediterranean region from antiquity to modern times. These ores, exploitation since Etruscan time, has yielded significant quantities of iron, sulphuric acid from pyrite, lead–copper-zinc, silver, antimony, mercury, and gold, as well as industrial minerals and ornamental stone. In particular, it has been calculated that about 60 million tons of iron ore were extracted during almost three millennia of activity on the island. The iron deposits are associated with the Eastern Elba Intrusive Complex and restricted to a relatively narrow belt extending north-south along the eastern coast of the Island. The ore bodies occur in variable settings, from stratiform to pod-like or vein-type bodies. The two main mining areas for almost three millennia were located around the Rio Marina village (hematite) and the southern part of the Monte Calamita peninsula (magnetite). Iron ores are locally associated with distal hedenbergite-ilvaite skarn bodies. The study of these skarns started in the 19th century, and they represent the type-locality for ilvaite (Torre di Rio skarn), from the Latin name of the island (Ilva).

Tectonic evolution of the intrusive complexes

The two intrusive complexes have similar tectonic evolutions. Initially, dominantly sub-horizontal movement on a low-angle detachment fault, with top-to-the-east sense of shear (Central Elba and Zuccale faults, Fig. 5), translated the overlying rocks eastward, trimming out part of the contact aureole of the plutons. Then, high-angle structures were activated mainly at the eastern edge of the plutons, i.e. the Eastern Border fault east of the Monte Capanne pluton and offshore faults east of the Porto Azzurro pluton (Bortolotti et al., 2001).

The relationship between extensional tectonics in the back-arc region and emplacement of intrusive rocks is a topic of debate in both the Tyrrhenian and Aegean basins (e.g. Jolivet et al., 2021). According to some authors, low angle normal faults started forming before the emplacement of the plutons and their development controlled partial melting and magma ascent. On the other hand, at Elba Island the eastward displacement of the upper part of the complex is at least partly linked to gravitational instability (Fig. 5). In fact, in western Elba during a time-span of about 1 Ma, a 2,700 m thick tectonostratigraphic section was inflated by the addition of at least 2,400 m of laccolithic intrusions. Thus, a dome with a 10 km diameter and a height of 2.5 km, was produced with a surface slope of about 25° (assuming an originally flat surface). Westerman et al. (2004, 2018) envisioned that emplacement of the Monte Capanne pluton beneath this dome caused oversteepening and triggered the main eastward displacement of the upper section (Fig. 5). Final movement on the Eastern Border fault took place entirely in the brittle regime, truncating the Central Elba fault that has since been eroded in western Elba and lies almost completely buried below central Elba.

The tectonic evolution of the intrusive complex in eastern Elba took place following a sequence of events like that described for western Elba, leading to fast pluton exhumation (Pertusati et al., 1993). Initially, dominantly sub-horizontal movement on the low-angle detachment Zuccale Fault with top-to-the east sense of shear translated the overlying rocks eastward, trimming out part of the contact aureole of the Porto Azzurro pluton as well as a 2 km wide slice from the front edge of the Central Elba Fault. Then, high-angle structures were activated at the eastern edge of the pluton, offshore from the eastern Elba coast.

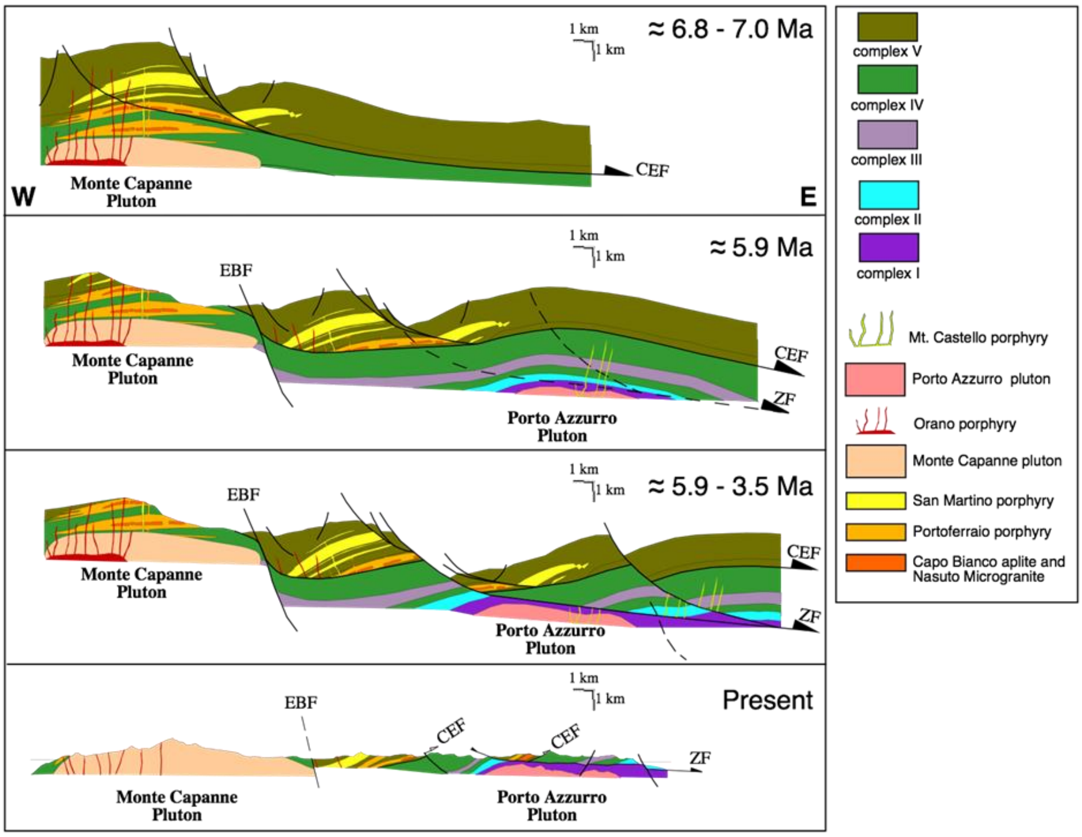

Figure 5 *- Fall of the nested Christmas-tree laccolith complex: unroofing of the Monte Capanne pluton showing progressing stages of décollement (from Westerman et al., 2004).*

Itinerary

Day 1

Arrival on Elba Island and introduction to the geology of the Northern Apennines and Elba Island.

Stop 1.1 – Lookout point

Coordinates: Lat. 42°47'42" N; Long. 10°23'25'' E

Location: Cima del Monte

Topic: *Introduction and geological background*

Stop description – We will stop the vans at the locality "Le Panche" and after a trail of ca. 800 meters (45 minutes), reach the lookout of Cima del Monte. Along the trail, we cross the contact between the basalt and the folded, thin-bedded cherts of Complex IV (Middle to Late Jurassic).

From this location, it is possible to see the beautiful landscape of the Island and the northern Tyrrhenian Sea. Tothe west lies the gulf of Portoferraio and Capo d'Enfola and farther away the peak of the Monte Capanne. On clear days, even Corsica Island is visible. Looking east, we have a panoramic view of the area between the villages of Porto Azzurro and Rio Marina and of the sea separating Elba from the coast of Tuscany.

Stop 1.2 – The Porto Azzurro pluton

Coordinates: Lat. 42°46'08" N; Long. 10°24'24'' E

Location: Barbarossa Beach and Capo Bianco promontory

Topic: *Relationship between the pluton, leucogranitic dikes and tourmaline veins*

Stop description – The small Barbarossa Bay is located a few km east of the village of Porto Azzurro. In the bay, it is possible to observe the relation between the Porto Azzurro monzogranite, felsic dikes and different generations of normal faults. The monzogranite crops out on the western and eastern cliffs of the bay, in contact with the micaschist and quartzite of the Monte Calamita Formation (Complex I). The host rock has a well-developed schistosity, generally dipping gently westward to north-westward and it is characterized by a high-temperature, low-pressure paragenesis generated during contact metamorphism. The host rocks reached muscovite-out conditions (T = 600-650°C e P = 0.18 GPa), producing K-feldspar + andalusite and, in quartz-free domains, K-feldspar + corundum.

The monzogranite is coarse grained, biotite-bearing and characterized by the widespread occurrence of large K-feldspar megacrysts, reaching up to 15 cm in length. Accessory phases are tourmaline, ilmenite, zircon, monazite, xenotime and apatite. Tourmaline is mostly of post-magmatic origin, being found in veins or along thin, branched fractures. The likely occurrence of former cordierite in the pluton is revealed by the presence of clots of sericite and chlorite. Felsic dikes intruding the monzogranite and wall rocks are widespread on both cliffs. The dikes are medium- to fine-grained tourmaline leuco-monzogranite made of K-feldspar, plagioclase, quartz, tourmaline ± biotite ± white mica ± cordierite, with accessory phases represented by ilmenite, apatite, zircon and monazite.

The micaschists, as well as the monzogranite and the related dikes, are cut by three discrete faulting episodes: i) syn-magmatic N–S and NNE-striking sub-vertical faults; ii) subvertical NE-trending, left-lateral oblique-slip faults exposed in the western part of the bay and (iii) subhorizontal to gently E-dipping normal faults.

On the western cliff, a meter-thick vein of dark tourmaline (schorl) cuts the monzogranite. The vein is formed along a strike-slip fault zone at the contact between the micaschist and the monzogranite. Tourmaline hydraulic breccias also occur. East-dipping low- to medium-angle (10-30°) normal faults are common. The eastern side of the bay can be easily accessed following the trail that goes uphill towards the old mining excavations. On the promontory, outcrops of the Porto Azzurro pluton are crosscut by tourmaline-bearing aplitic dikes striking N-S. On the top, a significant low-angle normal fault affects the roof of the monzogranite. It defines a more than 3 m thick cataclasite level, mostly made up of comminuted micaschist and monzogranite, mineralized by tourmaline and Fe-oxides and/or Fe-hydroxides.

Figure FT1. *The Porto Azzurro pluton at Barbarossa beach. A –A meter-thick tourmaline vein at the contact between the Porto Azzurro pluton (on the right) and the micaschists of the Monte Calamita. B – Thin, irregular tourmaline vein in a leucogranitic dike. C. Large K-feldspar crystals in the pluton. Tourmaline-rich clots occur in the rock matrix and included in one of the large K-feldspars at the bottom. The lens cap is 5 cm in diameter.*

Day 2

During this day, we will look at the Eastern Intrusive complex. The scientific themes of the day are: i) the late swarm of felsic dikes associated to the Porto Azzurro pluton and their connection with the formation of tourmaline-quartz hydrothermal vein; ii) the relationship between magmatism and the low angle Zuccale normal fault. Depending on the time, we might also have the opportunity to stop in Marina di Campo to observe the hedenbergite-ilvaite skarn.

Stop 2.1 – Swarm of felsic dikes in the Eastern intrusive complex

Coordinates: Lat. 42°43'31" N; Long. 10°26'03'' E

Location: Spiaggia del Ginepro – Punta Bianca

Topic: *Zoned felsic dikes and tourmaline-quartz hydrothermal veins.*

Stop description - Coarse-grained pegmatitic to microgranitic felsic dikes trend NNW–SSE with thicknesses of less than 1.7 m. Dikes discordantly cut across hornfels fabric and are locally associated with metasomatic effects. Felsic dikes are composed of quartz, K-feldspar, plagioclase and rare biotite or muscovite. Tourmaline is a significant early crystallizing phase, as testified by its euhedral shape.

Tourmaline is dominant in the related hydrothermal and metasomatic products, mainly occurring as tourmaline-quartz hydrothermal veins and metasomatic bodies. Metasomatic bodies have developed at the contact between leucogranites and the host hornfels over a distance of a few cm up to one metre, with preferential replacement of biotite-rich layers by black microgranular tourmaline and quartz. The metasomatic bodies occur as black massive rocks with relics of folded quartz veins maintaining the fabric of the hornfels. Metasomatic bodies are associated with small tourmaline veins that propagate from the felsic dikes into the hornfels. Two sets of tourmaline-quartz veins (A-veins and B-veins) characterise the hydrothermal system; both vein sets cut across felsic dikes, hornfels rock and metasomatic bodies. The observed mutual cross-cutting relationships indicate a coeval development of the two vein sets.

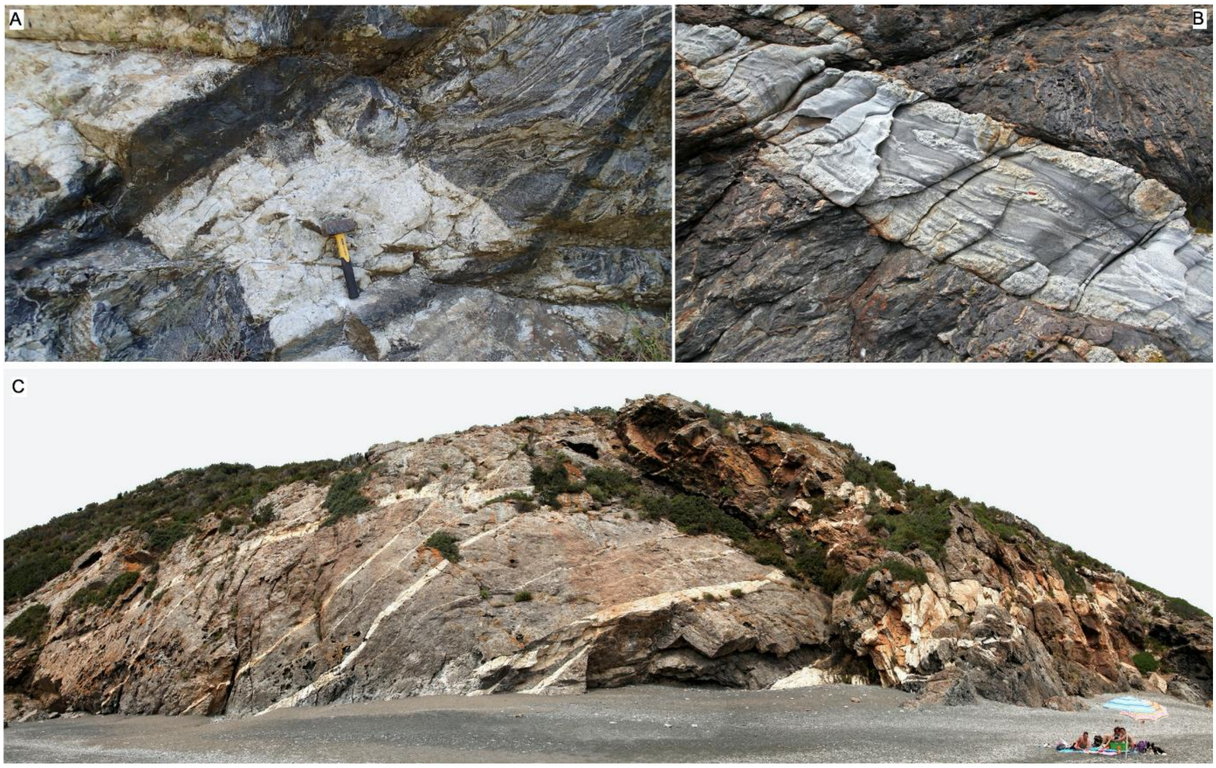

Figure FT2*. A. Tourmaline-bearing **l**eucogranitic dike cutting the micaschists. The amphibole-magnetite skarn cut the leucogranitic dike. B. Tourmaline-bearing dike showing flux structures around coarse-grained pegmatite zones. Cliff at Punta Bianca, different generation of leucogranitic dikes cutting the micaschist.*

Stop 2.2 – The Zuccale detachment fault

Coordinates: Lat. 42°46’17” N; Long. 10°25’01’’ E

Location: Reale beach – Terranera.

Topic: *The low angle Zuccale normal fault and hematite mineralization.*

Stop description - Walking along the path from Reale Beach to Terranera we will examine the grey to greenish-grey polydeformed quartzitic phyllites and micaschists of Monte Calamita Formation. The Alpine main schistosity has an attitude of N120/45 or N310/25 and is strongly overprinted by static thermometamorphic minerals (e.g. static biotite and andalusite) due to the Porto Azzurro monzogranitic intrusion. The metasedimentary rocks do not show Fe-mineralisation and are crosscut by centimetric/decimetric white tourmaline-bearing aplites belonging to the dike network of the Porto Azzurro granitoid. The structural framework of the Monte Calamita Fm. at the mesoscale is characterized by centimetric/decimetric, tight to isoclinal folding of the main continuous schistosity which were deformed by younger metric to decametric open to closed folds. Approaching the top of the lower plate, the increasing effects of the hydrothermal alteration (quartz-“adularia”veinlets) can be observed until we will reach the Zuccale low-angle fault. This fault represents a major tectonic discontinuity that acted as a sink for hydrothermal fluids, focusing alteration/mineralization effects. Here we will see a change in the alteration type. Chloritization becomes predominant and hematite-pyrite disseminations and veinlets increase.The fault damage zone is marked by the Zuccale cataclasite, a 10 m-thick horizon consisting of an yellowish-ochre, often foliated polymictic breccia. Its clasts (millimetric up to 10-15 cm) derive mostly from the underlying Monte Calamita Fm. (micaschists and phyllites cut by aplitic dikes which are more or less kaolinised) and from the overlying Monticiano-Roccastrada unit.

Crossing the sub-horizontal fault, we will pass into the upper plate (here made of Permian black shales and Triassic quartzites) and we will reach the Terranera mine. Large bodies of microcrystalline hematite were exploited in the past and the resulting open pit is now replaced by a green lake separated from the sea by a sandy beach mostly made of shining hematite grains. We will spend some time looking at hematite stockworks and massive bodies of hematite whose cavities contain some of the best pentagonododecahedral pyrite crystals ever found in Elba.

Day 3

The focus of day 3 is on the Monte Capanne pluton and its internal zoning made up of three main facies assembled incrementally. Moreover, we will also examine the leucogranitic dikes and LCT pegmatites cropping out on the east side of the pluton as well as the crosscutting swarm of mafic dikes (i.e Orano dikes) marking the end of the intrusive activity in central-western Elba.

Stop 3.1 – The Monte Capanne pluton and its pegmatites

Coordinates: Lat. 42°44’48” N; Long. 10°12’32’’ E

Location: Bontempelli quarry and Rosina pegmatite.

Topic: *Contact between the megacryst-poor and megacryst-rich intrusive facies; relations between the pluton and late felsic dikes and pegmatites.*

Stop description - This abandoned quarry exposes one of the best vertical sections of the roof of the pluton and allows observing the lowermost feeding part of some minor pegmatite dikes. The quarry exploited granites from the pluton K-feldspar megacrysts-poor facies (San Piero Facies). This facies is characterized by a very low content of K-feldspar megacrysts, and by the unique occurrence of “ghost” K-feldspar crystals, i.e. strongly poikilitic cm-sized crystals that are only visible when the sun shines on properly oriented cleavages. In this area, it is possible to recognize the transitional contact between the megacryst-poor and –rich facies, with the number of megacrysts increasing approaching the contact with the host metamorphic rocks. The contact with the host metamorphic rocks passes a few meters above the upper margin of the quarry.

A small LCT pegmatite dike has been cut by the quarry. In the upper part the 20 cm thick pegmatite dike has a typical tabular structure and texture (mostly aplitic with local axial pegmatitic portions) with sharp contacts against the granite host. Going down, the dike becomes more sinuous and irregular assuming, at the base of the bench (ca 10-15 m below the margin of the quarry) an anastomosing pattern with gradational contacts against the monzogranite host.

Stop 3.2 - Magma hybridization in the Monte Capanne pluton

Coordinates: Lat. 42°48’31” N; Long. 10°08’26’’ E

Location: Sant’Andrea beach

Topic: *Mechanism of magma mingling; relations between the host pluton and mafic microgranular enclaves*.

Stop description - From Sant' Andrea beach, we walk westward toward Capo Sant'Andrea. The granite facies cropping out is characterized by a high content of K-feldspar megacrysts (up to 15 cm in length) and quartz phenocrysts (up to 1 cm diameter), set in a coarse-grained matrix. All along the path, abundant mafic microgranular enclaves can be observed reaching sizes up to several metres. The shapes of the microgranular enclaves are sometimes ellipsoidal, sometimes irregular, although always rounded with sharp, lobate borders. The enclaves show embayments and trails of "granitic" material (mainly medium- to coarse-grained quartz and plagioclase crystals) connecting K-feldspar megacrysts to the main granite. K-feldspar megacrysts can be observed straddling enclave-granite contacts. Composite enclaves are common, with finer-grained enclaves hosted within medium-grained enclaves. At the end of the path, the granite is crosscut by a 15 cm-thick dike of the dark Orano porphyry that hosts xenocrystic megacrysts grabbed from the Monte Capanne crystal mush. The contact is sharp but shows dramatic variations in geometry at the meter-scale, from straight to sinuous.

Figure FT3. *Mafic microgranular enclaves at Sant'Andrea. For scale, the average size of the K-feldspar megacrysts is 6 cm.*

Stop 3.3 – The Cotoncello felsic dike

Coordinates: Lat. 42°48'28" N; Long. 10°08'49'' E

Location: Punta Cotoncello

Topic: *Interaction between the felsic Cotoncello dike and the Monte Capanne pluton.*

Stop description – From Sant'Andrea beach, walk 200 m to the east along the shore. Along the coastal path between Capo Sant'Andrea and Punta Cotoncello, several strongly altered brown Orano dykes can be observed. The higher alteration degree of the dykes with respect to the granite host generate decametre-sized embayment of the coastline. At Punta del Cotoncello a dike of a leucocratic facies crosscuts the main Sant'Andrea facies. The Cotoncello dike has fine-grained groundmass and lower megacryst content with respect to Sant'Andrea granite facies. The contact shows a complex geometry, owing to the interplay of brittle and plastic relative behaviour of the intruding dike and the host Sant'Andrea crystal mush. Clusters and trails of K-feldspar megacrysts, along with megacryst-laden schlieren, are common in the area. Size and abundance of mafic microgranular enclaves are lower than observed at the Sant'Andrea outcrop.

Figure FT4. *Left - Contact between the Monte Capanne pluton (Sant'Andrea facies) and Cotoncello dike. Centre - Biotite schlieren with K-feldspar megacrysts. Right – cumulate of K-feldspar megacrysts an mafic enclaves.*

Stop 3.4 – The late-plutonic mafic dike swarm

Coordinates: Lat. 42°45'37" N; Long. 10°06'42'' E and Lat. 42°45'42" N; Long. 10°06'25'' E.

Location: Chiessi

Topic: 1. *Genesis and emplacement pattern of the Orano dike swarm. 2. Metamorphism and deformation at the pluton contact.*

Stop description – Along the coast NW of Chiessi village, several Orano dikes are well exposed, either fresh (dark grey) or hydrothermally altered (green-grey). These dikes show cross-cutting relationships with the metamorphic aureole-pluton contact. The dikes have variable rheological behaviour with respect to their host: although they generally have sharp and continuous contacts, some dikes locally display flow "re-adjustment" of the dike walls. Embayments and crenulated contacts are common and testify that the granite was not completely crystallized during dike intrusion. Additionally, individual Orano dikes have been traced continuously through significant changes in orientation without petrographic variation. These dikes also show additional evidence of complex geometry, such as sudden side-steps, horn structures and bridges, and broken bridges. Resorbed K-feldspar xenocrysts commonly occur.

Along the route SP 25, north of Chiessi the contact between the Monte Capanne pluton and the host rocks is well exposed. The country rocks are mostly made of an alternation of fine-grained biotite hornfels and marbles derived from contact metamorphism of shales and silicic limestones of Complex IV. This sequence was intruded before the thermometamorphic event by the sills and laccoliths of the Portoferraio porphyry.

Figure FT5. *Orano dikes crosscutting the Monte Capanne pluton. K-feldspar xenocrysts from the Monte Capanne pluton are visible in the lower part of the main dike in the picture.*

Day 4

We dedicate this last day to the observation of the oldest units of the Western-Central Elba intrusive complex. The activity for the day consists of only two stops, both involving short to medium hikes along the northern and southern coast (total length = 4 km). These hikes allow seeing the temporal relationships between the different porphyries forming the laccolith complex and examining the main textural and mineralogical features of these units.

Stop 4.1 – The laccolith complex

Coordinates: Lat. 42°49’23” N; Long. 10°16’52’’ E

Location: Sansone beach

Topic: *Field relationships between the Capo Bianco, Portoferraio and San Martino porphyries. Genesis of the Capo Bianco aplite and its tourmaline orbicules.*

Stop description – The sequence of emplacement events that produced the Western-Central Elba Laccolith Complex can be clearly observed along the coast between Acquaviva and Capo d’Enfola. The geological transect starts at La Sorgente beach and continues to the west, along the shore. Here, the cliffs exhibit key geological sections that allow recognizing the sequence of emplacement of the three main units of the laccolith complex: Capo Bianco aplite, Portoferraio porphyry, San Martino porphyry.

The field trip starts from Case Acquaviva walking down the slope to the Sansone beach where the contact between the Capo Bianco aplite sill (the oldest intrusive unit) and the underlying Portoferraio porphyry laccolith (the third intrusive unit) is exposed. The contact between the two intrusive units is outlined by a thin layer (few cm to 1 m) of a blackish-green serpentinitic rock. The NW dipping intrusive contact surface is exposed due to the erosion of the aplite unit and the soft ophiolitic material. The top of the Portoferraio porphyry in direct contact with serpentinites was contaminated by ophiolitic material, changing its colour from whitish-grey to dark green over a thickness of few centimetres. The morphology of the contact surface is similar to the surface of pahoehoe lava flows. Sitting on top of this contact, we have a good landscape view of the cliffs where the top of the Capo Bianco sill is exposed. The upper part of the cliffs is made of Portoferraio porphyry, while a vertical dike of the younger San Martino porphyry crosscuts both the previous intrusive units.

Continuing the trip along the shoreline, we follow the Capo Bianco sill along strike for about 500 metres. In this zone Capo Bianco aplite is strongly layered with small tourmaline orbicules; the porphyritic texture (small phenocrysts of quartz and feldspars) is quite visible due to the marine erosion. The attitude of layering is strongly variable due to fractures and faults but is generally steep northward. A close-up observation of the layering indicate that it was produced by multiple injections and lateral flow of magma: folded layers, laminated and truncated layers, etc. Magmatic layering is frequently crosscut by fractures and brecciated structures cemented by blue-black tourmaline. This is a later hydrothermal event probably induced by exsolution of fluids from the aplite. Portoferraio porphyry crosscuts both magmatic layering and hydrothermal tourmaline breccias. At the end of the beach, the occurrence of several fallen blocks of Portoferraio porphyry is indicative of its presence on top of the Capo Bianco sill. The texture and mineralogy of this intrusive unit is well preserved in these particularly fresh blocks.

Climbing a few meters over a big boulder, we can observe a vertical dike of San Martino porphyry crosscutting the Capo Bianco aplite. San Martino porphyry is characterised by the presence of many K-feldspar megacrysts, and quartz, plagioclase and biotite phenocrysts embedded in a very fine-grained groundmass. The borders of the dike are quite depleted in megacrysts and phenocrysts. K-feldspar megacrysts are perfectly euhedral and can be easily separated due to the preferential phyllic hydrothermal alteration experienced by the groundmass. Some mafic microgranular enclaves can be observed.

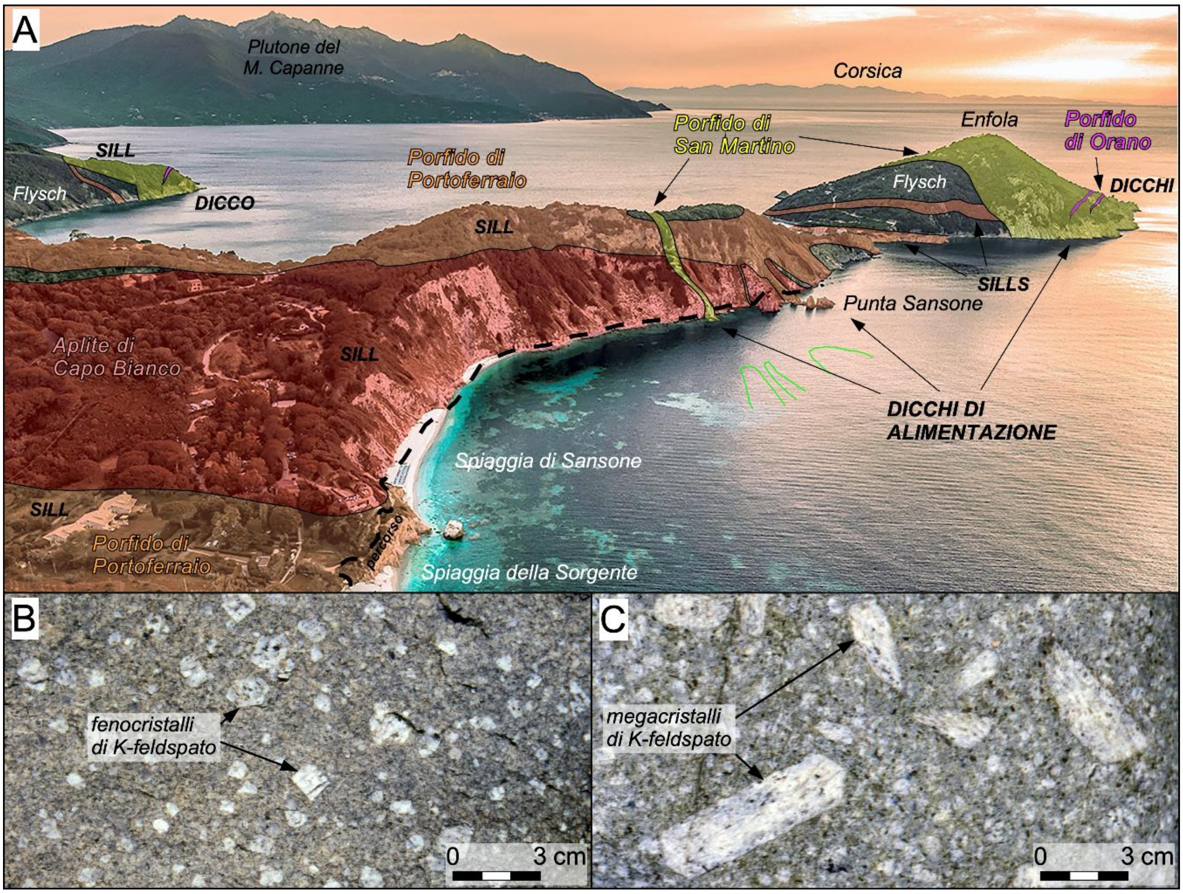

Figure FT6. *A. The cliffs between La Sorgente and Capo d'Enfola and relationships between the different porphyries. B. Portoferraio porphyry. C. San Martino porphyry.*

Stop 4.2 – The San Martino porphyry

Coordinates: Lat. 42°44’54” N; Long. 10°14’50’’ E

Location: A short walk (400 m) along the Rosmarini path, starting from Marina di Campo.

Topic: *The San Martino porphyry*

Stop description

Along the southern coast of Central Elba, east of the village of Marina di Campo, it is possible to observe the typical field appearance of the San Martino porphyry. The porphyry is rich in K-feldspar megacrysts reaching up to 15 cm in length as well as quartz phenocrysts (up to 2 cm) and scattered brown-altered mafic microgranular enclaves. The large K-feldspar crystals are high-T sanidines, testifying their magmatic origin. Locally the megacrysts show shape-preferred orientation and magmatic lineation. Along the coast, the contact between the porphyry and the Cretaceous flysch is well exposed. No thermometamorphic effects can be detected in the host rock.

Figure FT7. *K-feldspar magmatic lineation in the San Martino porphyry.*

Stop 4.3 – Santa Filomena (optional)

Coordinates: Lat. 42°46’17” N; Long. 10°25’01’’ E

Location: Rio Marina

Stop description – From the clock tower (Torre degli Appiani), walking south we reach the so-called “Torre di Rio” skarn. Here, the calcschists are progressively replaced by a skarn body characterized by spectacular mineral zonation, with hedenbergite, ilvaite ($CaFe^{+3}(Fe^{+2})_2O(Si_2O_7)(OH)$) and epidote domains. In the skarn, accessory minerals such as quartz and carbonates, sulfides (mainly pyrite, arsenopyrite and pyrrhotite) and oxides (magnetite and hematite) are found in lesser extent. The strong foliation of the calcschists dipping to the NW is preserved in most parts of the skarn.


Legenda
Stop
Elba Island
Hutton post conference field trip
Stop 1-1
Stop 1-2
Stop 2-1
Stop 2-2
Stop 3-1
Stop 3-2
Stop 3-3
Stop 3-4
Stop 4-1
Stop 4-2
Stop 4-3
N
10 km
Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

References

Barboni, M., Schoene, B., 2014. Short eruption window revealed by absolute crystal growth rates in a granitic magma. *Nature Geoscience*, 7, 524–528.

Barboni, M., Annen, C., Schoene, B., 2015. Evaluating the construction and evolution of upper crustal magma reservoirs with coupled U/Pb zircon geochronology and thermal modeling: a case study from the Mt. Capanne pluton (Elba, Italy). *Earth and Planetary Science Letters*, 432, 436–448.

Bortolotti, V., Mazzuoli, M., Pandeli, E. Principi, G., Babbini, A. & Corti, S., 2001. Geology of central and eastern Elba Island, Italy. *Ofioliti*, 26, 97-150.

Bouillin, J.-P., Bouchez, J.-L., Lespinasse, P. and Pecher, A., 1993. Granite emplacement in an extensional setting; an AMS study of the magmatic structures of Monte Capanne (Elba, Italy). *Earth and Planetary Science Letter*s, 118: 263-279.

Caggianelli, A., Zucchi, M., Bianco, C., Brogi, A., Liotta, L., 2018. Estimating P-T metamorphic conditions on the roof of a hidden granitic pluton: an example from the Mt. Calamita promontory (Elba Island, Italy). *Italian Journal of Geosciences*, 137, 238–253.

Cifelli, F., Minelli, L., Rossetti, F., Urru, G., Mattei, M., 2012. The emplacement of the Late Miocene Monte Capanne intrusion (Elba Island, Central Italy): constraints from magnetic fabric analyses. *International Journal of Earth Sciences*, 101, 787–802.

Collettini, C., de paola, N., Holdsworth, R.., Barchi, M.R., 2006. The development and behaviour of low-angle normal faults during Cenozoic asymmetric extension in the Northern Apennines, Italy. *Journal of Structural Geology*, 28, 2, 333-352.

Conticelli, S. et al., 2001. Petrology, mineralogy and geochemistry of a mafic dike from the Monte Castello, Elba Island, Italy. *Ofioliti*, 26: 249-262.

Daniel, J.-M. and Jolivet, L., 1995. Detachment faults and pluton emplacement: Elba Island (Tyrrhenian Sea). *Bulletin de la Societé Géologique de France*, 166(4): 341-354.

Dewey, J.F., Holdsworth, R.E. and Strachan, R.A., 1998. Transpression and transtension zones. In: R.E. Holdsworth, R.A. Strachan and J.F. Dewey (Editors), Continental transpressional and transtensional tectonics. *Geological Society, London, Special Publications*, pp. 1-14.

Dini, A., Innocenti, F., Rocchi, S., Tonarini, S. and Westerman, D.S., 2002. The magmatic evolution of the laccolith-pluton-dyke complex of Elba Island, Italy. *Geological Magazine*, 139(3): 257-279.

Dini, A., Rocchi, S. and Westerman, D.S., 2004. Reaction microtextures of REE-Y-Th-U accessory minerals in the Monte Capanne pluton (Elba Island, Italy): a possible indicator of hybridization processes. *Lithos*, 78, 101-118.

Dini, A., Coretti, A., Innocenti, F., Rocchi, S., Westerman D.S. 2007. Sooty sweat stains or tourmaline spots? The Argonauts on the Island of Elba (Tuscany) and the spread of Greek trading in the mediterranean sea. *Geological Society Special Publication*, 273, 227–243.

Dini, A., Westerman, D.S., Innnocenti, F. and Rocchi, S., 2008a. Magma emplacement in a transfer zone: the Miocene mafic Orano dyke swarm of Elba Island (Tuscany). In: K. Thomson and N. Petford (Editors), Structure and Emplacement of High-Level Magmatic Systems. *Geological Society, London, Special Publication*, 302, pp. 131-148.

Dini, A., Mazzarini, F., Musumeci, G. and Rocchi, S., 2008b. Multiple hydro-fracturing by boron-rich fluids in the Late Miocene contact aureole of eastern Elba Island (Tuscany, Italy). *Terra Nova*, 20(4): 318-326.

Farina F., Dini A., Innocenti F., Rocchi S., Westerman S.D., 2010. Rapid incremental assembly of the Monte Capanne pluton (Elba Island, Tuscany) by downward stacking of magma sheets. *Geological Society of America Bulletin*, 122, 1463-1479.

Farina F., Stevens G., Dini A., Rocchi S., 2012. Peritectic phases entrainment and magma mixing: origin of the chemical variability of the Elba Island granitic complex (Italy). *Lithos*, 153, 243-260.

Farina F., Dini A., Rocchi S., Stevens G., 2014. Extreme mineral-scale Sr isotope heterogeneity in granites by disequilibrium melting of the crust. *Earth and Planetary Science Letters*, 399, 103-115. DOI: 10.1016/j.epsl.2014.05.018.

Gagnevin, D., Daly, S.P. and Poli, G., 2004. Petrographic, geochemical and isotopic constraints on magma dynamics and mixing in the Miocene Monte Capanne monzogranite (Elba Island, Italy). *Lithos*, 78, 157-195.

Gagnevin, D., 2005. Microchemical and Sr isotopic investigation of zoned Kfeldspar megacrysts: insights into the petrogenesis of a granitic system anddisequilibrium crystal growth. *Journal of Petrology*, 46(8): 1689-1724.

Gagnevin, D., Daly, J.S., Horstwood, M.S.A., Whitehouse, M.J., 2011. In-situ zircon U–Pb, oxygen and hafnium isotopic evidence for magma mixing and mantle metasomatism in the Tuscan Magmatic Province, Italy. *Earth and planetary Science Letters*, 305, 45-56.

Innocenti, F., Serri, G., Ferrara, G., Manetti, P. and Tonarini, S., 1992. Genesis and classification of the rocks of the Tuscan Magmatic Province: thirty years after Marinelli's model. *Acta Vulcanologica*, 2: 247-265.

Jolivet, l., Daniel, J.M., Truffert, C. and Goffé, B., 1994. Exhumation of deep crustal metamorphic rocks and crustal extension in arc and back-arc regions. *Lithos*, 33: 3-30.

Jolivet, L., Faccenna, C. 2000. Mediterranean extension and the Africa-Eurasia collision. *Tectonics*, 19, 1095–1106.

Jolivet, L., Arbaret, L., Le Pourhiet, L., Cheval-Garabédian, F., Roche, V., Rabillard, A., Labrousse, L., 2021. Interactions of plutons and detachments: a comparison of Aegean and Tyrrhenian granitoids. *Solid Earth*, 12, 1357–1388.

Keller, J.V.A. and Pialli, G., 1990. Tectonics of the Island of Elba: a reappraisal. *Bollettino della Società Geologica Italiana*, 109: 413-425.

Liotta, D., Brogi, A., Meccheri, M., Dini, A., Bianco, C., Ruggueri, G., 2015. Coexistence of low-angle normal and high-angle strike- to oblique-slip faults during Late Miocene mineralization in eastern Elba Island (Italy). *Tectonophysis*, 660, 17-34.

Maineri, C., Benvenuti, M., Costagliola, P., Dini, A., Lattanzi, P., Ruggeri, C. & Villa, I. M. 2003. Sericitic alteration at the La Crocetta mine (Elba Island, Italy): interplay between magmatism, tectonics, and hydrothermal actvity. *Mineralium Deposita*, 38, 67–86.

Malinverno, A. and Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. *Tectonics*, 5, 227-245.

Musumeci, G., Vaselli, L., 2012. Neogene deformation and granite emplacement in the metamorphic units of northern Apennines (Italy): Insights from mylonitic marbles in the Porto Azzurro pluton contact aureole (Elba Island). *Geosphere*, 8, 2, 470-490.

Papeschi, S., Mazzarini, F., Musumeci, G., Cruden, A.R., 2022. Emplacement of a felsic dyke swarm during progressive heterogeneous deformation, Eastern Elba Dyke Complex (Island of Elba, Italy). *Journal of Structural Geology*, 159, 104600.

Pauselli, C., Barchi, M. R., Federico, C., Magnani, M. B. & Minelli, G., 2006. The crustal structure of the Northern Apennines (Central Italy): An insight by the CROP03 seismic line. *American Journal of Science*, 306, 428-450.

Pertusati, P. C., Raggi, G., Ricci, C. A., Duranti, S. & Palmeri, R., 1993. Evoluzione post-collisionale dell' Elba centro-orientale. *Memorie della Società Geologica Italiana*, 49, 297-312.

Pezzotta, F., 2000. Internal structures, parageneses and classification of the miarolitic Li-bearing complex pegmatites of Elba Island (Italy). *Memorie della Società Italiana di Scienze Naturali e del Museo Civico di Storia Naturale di Milano*, 30: 29-43.

Platt, J.P., 2007. From orogenic hinterlands to Mediterranean-style back-arc basins: a comparative analysis. *Journal of the Geological Society, London*, 164: 297-311.

Poli, G., 1992. Geochemistry of Tuscan Archipelago granitoids, central Italy: The role of hybridization processes in their genesis. *Journal of Geology*, 100: 41-56.

Rocchi, S., Westerman, D.S., Dini, A., Innocenti, F. and Tonarini, S., 2002. Two-stage laccolith growth at Elba Island (Italy). *Geology*, 30(11): 983-986.

Rocchi S., Westerman S.D., Dini A., Farina F., 2010. Intrusive sheets and sheeted intrusions at Elba Island (Italy). *Geosphere*, 6, 3, 225-236.

Roni, E., Westerman .S., Dini, A., Stevenson, C., Rocchi, S., 2014. Feeding and growth of a dyke–laccolith system (Elba Island, Italy) from AMS and mineral fabric data. *Journal of the Geological Society, London*. http://dx.doi.org/10.1144/jgs2013-019.

Rossetti, F., Tecce, F., Billi, A. and Brilli, M., 2007. Patterns of fluid flow in the contact aureole of the Late Miocene Monte Capanne pluton (Elba Island, Italy): the role of structures and rheology. *Contributions to Mineralogy and Petrology*, 153 (6): 743-760.

Serri, G., Innocenti, F., Manetti, P., 1993. Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy. *Tectonophysics*, 223: 117-147.

Smith, S.A.F., Holdsworth, R.E., Collettini, R.E., 2011. Interactions between plutonism and low-angle normal faults in the upper crust: insights from the Island of Elba. Italy. *Geological Society of America Bulletin*, 123, 329–346.

Spiess, R., Langone, A., Caggianelli, A., Stuart, F. M., Zucchi, M., Bianco, C., Brogi, A., and Liotta, D., 2019. Unveiling ductile deformation during fast exhumation of a granitic pluton in a transfer zone, *Journal of Structural Geolology*, 147, 104326, https://doi.org/10.1016/j.jsg.2021.104326, 2021.

Trevisan L., 1950. L'Elba orientale e la sua tettonica di scivolamento per gravità. *Memorie dell'Istituto di Geologia dell'Università di Padova*, 16, 1-30.

Westerman, D.S., Dini, A., Innocenti, F. and Rocchi, S., 2003. When and where did hybridization occur? The case of the Monte Capanne pluton. *Atlantic Geology*, 39: 147-162.

Westerman, D.S., Dini, A., Innocenti, F. and Rocchi, S., 2004. Rise and fall of a nested Christmas-tree laccolith complex, Elba Island, Italy. In: C. Breitkreuz and N. Petford (Editors), Physical geology of high-level magmatic systems. *Geological Society, London, Special Publication*, 234, 195-213.

Westerman, D.S., Breitkreuz, C., Stevenson, C., Wilson, P., 2018. Structures Related to the Emplacement of Shallow-Level Intrusions. In Breitkreuz, C., Rocchi, S. (eds) Physical Geology of Shallow Magmatic Systems. *Advances in Volcanology*. Springer. doi.org/10.1007/11157_2017_31.