The Late Miocene Christmas-tree laccolith complex of the Island of Elba

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ABSTRACT

In two separate areas of the west and centre of the Island of Elba (Italy), granite porphyries of late Miocene age are found as shallow-level intrusions inside a stack of nappes characterised by the occurrence of abundant physical discontinuities. Detailed mapping of intrusive rocks and their relations with country rocks, coupled with geochemical-isotopic-geochronologic data, show that outcrops in the west and centre of the Island of Elba 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 westward tilting. The two juxtaposed portions of the original sequence allow the restoration of a 5 km thick igneous-sedimentary sequence, made up of nine main intrusive layers, building three Christmas-tree laccoliths nested into each other to support a structural dome. During magma emplacement, 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. The 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.

AIMS

An integrated approach, including detailed field mapping, petrographic-mineral chemistry studies, geochemical and isotopic-geochronologic analyses has been used to address regional and general issues related to dynamic-petrological aspects of intrusive igneous activity.
Regional aspects:
- reconstruction of the tectonic history of the central-western Elba, characterised by the occurrence of discontinuous outcrops of late Miocene porphyritic intrusive rocks within a stack of nappes;
- restoration of an outstanding example of nested Christmas-tree laccolith complex;
- proposal of a reference model for the northern Tyrrhenian-Apenninic area, particularly for the interpretation of buried geological features.
General aspects:
- geometry of shallow tabular intrusions;
- mechanisms magma emplacement;
- geochemical evolution of the crust-mantle magma system in extensional postcollisional setting.

KEY WORDS

Elba Island, laccolith, intrusion shape, magma emplacement

RIASSUNTO

In due diverse aree dell'Isola d'Elba centrale e occidentale si ritrovano porfidi granitici del Miocene superiore, intrusi a bassa profondità in una sequenza di falde caratterizzate da molte discontinuità fisiche. La cartografia di dettaglio delle rocce intrusive e le loro relazioni con le rocce incassanti, associate con dati geochimici-isotopici-geocronologici, indicano che gli affioramenti dell'Elba centrale e occidentale espongono gli stessi litotipi, con sequenza intrusiva e caratteristiche petrochimiche comuni. I dati geologici e strutturali evidenziano come questi livelli intrusivi fossero originariamente parte di una unica sequenza, che è stata poi smembrata da dècollement verso est e successiva inclinazione verso ovest del settore dell'Elba centrale. Le due porzioni della sequenza originaria, oggi accostate, permettono la ricostruzione di una sequenza igneo-sedimentaria dello spessore di 5 km a forma di cupola, costituita da nove principali livelli intrusivi raggruppati in tre laccoliti "Christmas-tree" centrati uno nell'altro. La messa in posto del magma è stata influenzata in maniera significativa dal ridotto spessore delle rocce sovrastanti e/o dalla grande disponibilità di trappole per il magma nella sezione crostale intrusa, mentre il livello di galleggiamento neutro ha giocato un ruolo minore. Infine, la messa in posto del plutone del Monte Capanne alla base della struttura a cupola ha probabilmente causato un eccesso di pendenza, innescando la decapitazione del complesso igneo-sedimentario Con scivolamento gravitativo della sua metà superiore.

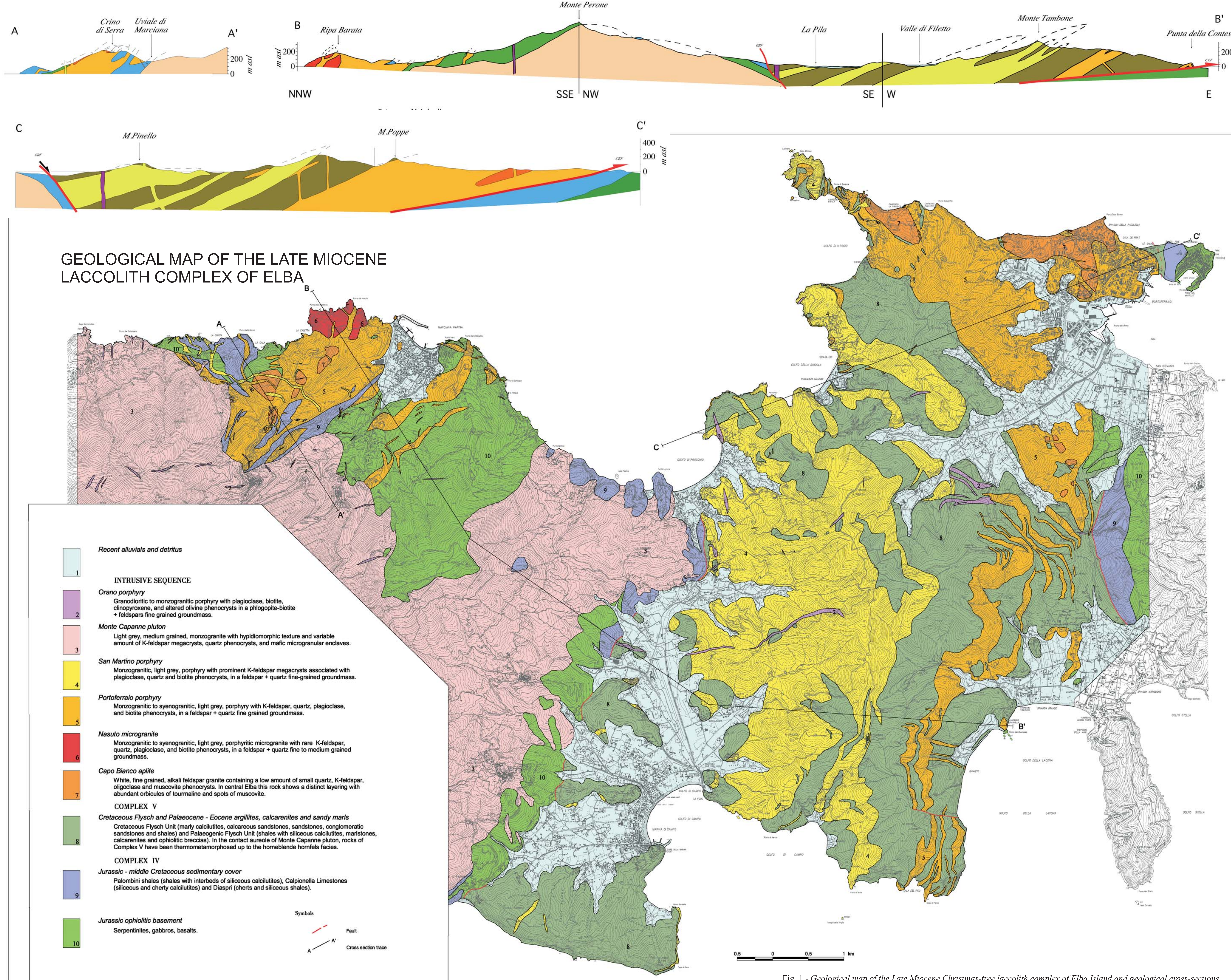


Fig. 1 - *Geological map of the Late Miocene Christmas-tree laccolith complex of Elba Island and geological cross-sections.*

INTRODUCTION

The porphyritic rocks of the Island of Elba were known and mapped before the end of the 19th century (LOTTI, 1884), and a significant evolution in the understanding of their character occurred during the 1950s and 1960s (TREVISAN, 1950; MARINELLI, 1955; TREVISAN & MARINELLI, 1967). More recently, as part of a Project to produce a new 1:50,000 scale Geological Map of Italy, geological and petrological investigations have been carried out since 1993 on the porphyritic rocks in the west and centre of the Island of Elba. One of the products of this work is a base geological map at the 1:5,000 scale.

Two different types of maps have been produced: (1) geological maps, reporting only the observed outcrops and contacts, and (2) interpreted geological maps, reporting continuous contacts (inferred and observed) and the inferred extent of the bedrock based on both outcrops and loose rock fragments floating in thin soils. The second type of map is presented in this work. This map and the cross-sections (Fig. 1), along with field observations (Fig. 5) coupled with petrographic-geochemical data, led to the reconstruction of an outstanding example of a shallow-level nested Christmas-tree laccolith complex (DINI *et alii*, 2002; ROCCHI *et alii*, 2002; WESTERMAN *et alii*, 2004).

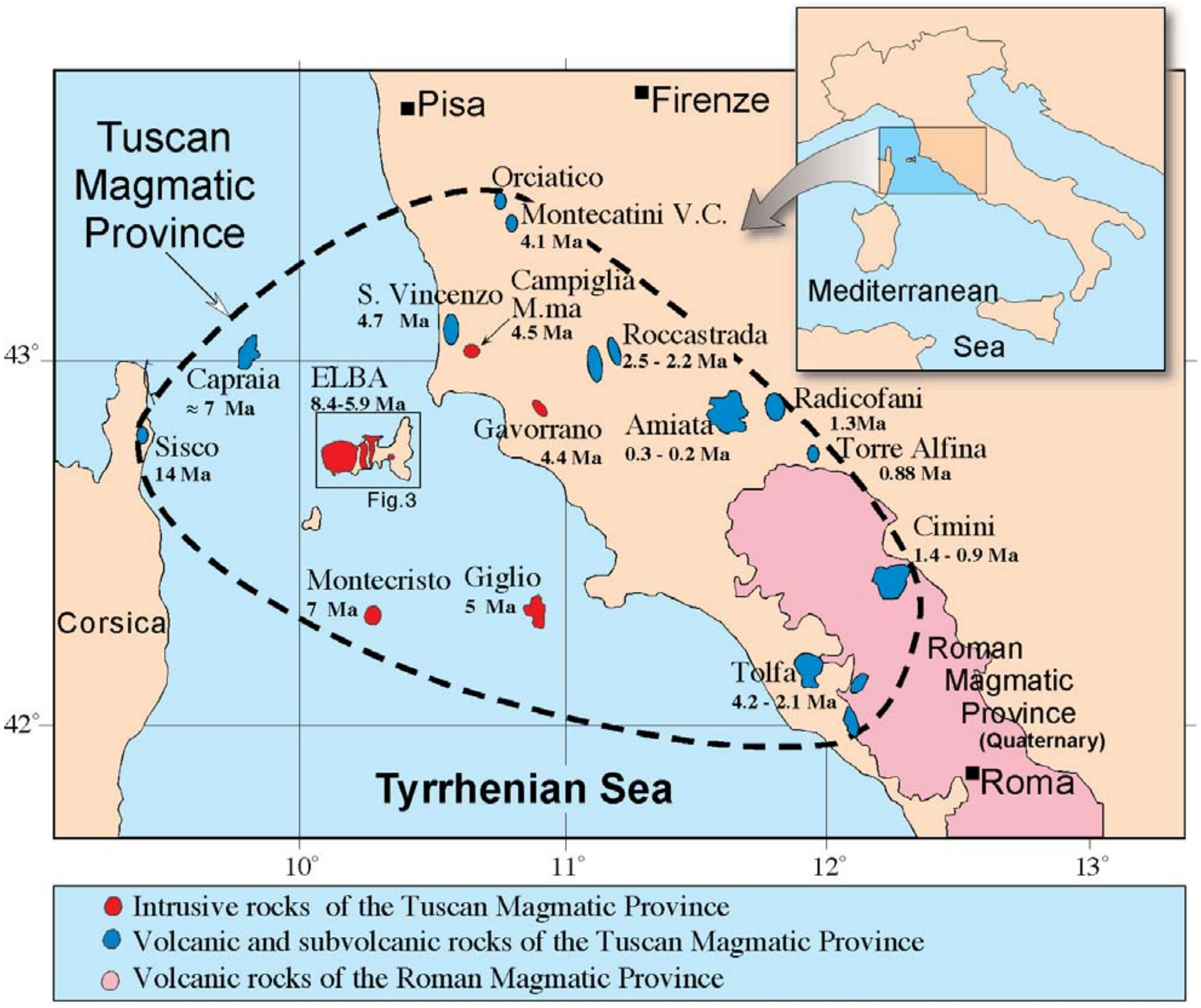


Fig. 2 - *Location map of the Tuscan Magmatic Province, with outcrops of intrusive-subvolcanic and volcanic rocks. Isotopic ages are from* SERRI et alii *(2001).*

GEOLOGICAL SETTING

Regional Geology

The Island of Elba 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. 2). 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 and giving way to the opening of the extensional ensialic back-arc northern 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 alii*, 1993). Intrusive and extrusive products of mantle-crustal hybrid nature built the Tuscan Magmatic Province, spreading over about 30,000 km^2 in southern Tuscany and the Tuscan Archipelago (POLI, 1992; SERRI *et alii*, 2001; DINI *et alii*, 2002).

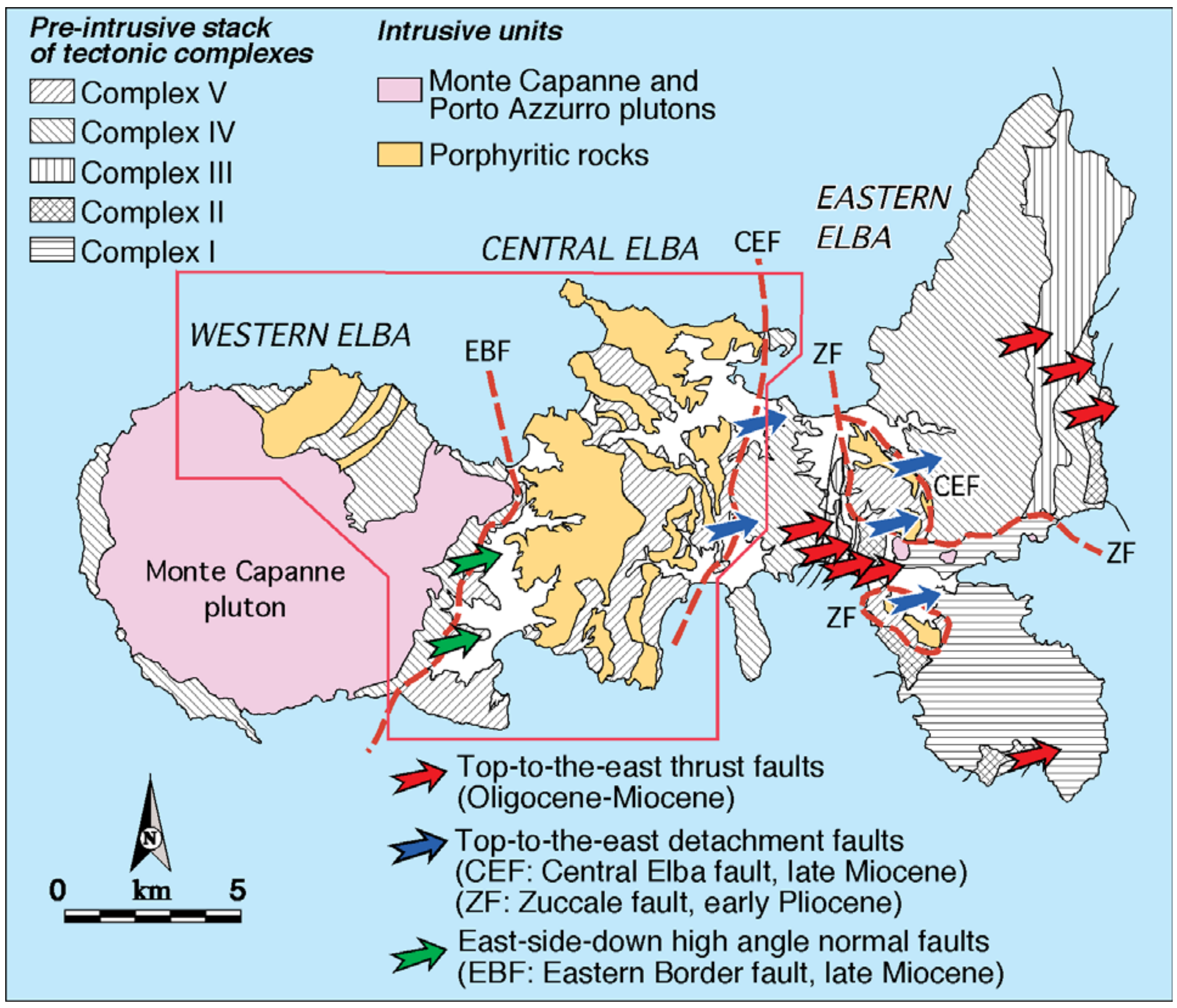


Fig. 3 - *Tectonic sketch map of Elba Island. The frame encloses the area of the geological map (Fig. 1).*

Local Geology

The structure of the Island of Elba consists of five stacked tectonic complexes (Fig. 3) assembled by about 20 Ma. The lower three (I-III) have continental features, while the upper two (IV-V) are oceanic in character (TREVISAN, 1950; PERTUSATI *et alii*, 1993). Several Miocene-age, intrusive bodies of various sizes are exposed within Complex IV in western Elba and within Complex V in central Elba, making up the western-central Elba intrusive complex. The Christmas-tree laccolith complex, that is the focus of this study, was constructed by the intrusion of the oldest four of these bodies. In order to emphasise the geological features of the laccolith complex, the host rocks have been reported on the attached geological map (hereinafter MAP, Fig. 1) as three comprehensive lithostratigraphic units: (i) Jurassic metaophiolites, (ii) their Jurassic-middle Cretaceous metasedimentary cover, and (iii) upper Cretaceous and Palaeocene-Eocene Flysch sequences. A younger and much smaller igneous complex, dominated by the Porto Azzurro pluton (5.9 Ma: MAINERI *et alii*, 2003), is restricted to eastern Elba.

Large-scale faults subdivide the Island of Elba into three main zones (Fig. 3 and MAP) and are the key to the reconstruction of the original geometry of the intrusive rocks.

Table 1. Summary of petrographic and chronologic features of the intrusive units.

Complex	Intrusive unit	rock type	texture	paragenesis	Accessory phases	MME xeno	Age (Ma)
western-central Elba intrusive complex	Orano porphyry dyke swarm	quartz monzodiorite to monzogranite	porphyritic (20-35%) very fine-grained gm	pheno: Pl, Bt, rare Amph, Cpx relics; xeno: Kfs, Qtz; gm: Pl, Mg-Bt, Qtz, Kfs	Ap, Zrc, Aln, Thr, Mag, Ilm, Per	MM X	6.8 6.9
western-central Elba intrusive complex	Monte Capanne leucogranites	leuco syenogranite	medium grain size locally anisotropic	Qtz, Kfs, Pl, Bt, Ms ± Crd or Grt	Ap, Zrc, Mnz, Tur		? 6.9
western-central Elba intrusive complex	Monte Capanne pluton	monzogranite	variable % megaKfs medium-grained equigranular matrix	Pl, Qtz (–> 15 mm), Kfs (–> 15 cm), Bt (–> 5 mm)	Ap, Zrc, Mon, Aln, Ilm Tur	MM XX	6.9
Christmas-tree laccolith complex	San Martino porphyry	monzogranite	porphyritic (40-50%) fine-grained gm miarolitic cavities	mega: San (3-15%;5 cm); pheno: Qtz, Pl, Bt; gm: Qtz, Kfs±Pl	Ap, Zrc, Mon ± Aln ±Tur	M XX	7.2 7.4
Christmas-tree laccolith complex	Portoferraio porphyry	Monzogranite (minor syenogranite)	porphyritic (25-50%) fine-grained gm	pheno: San, Qtz, Pl, Bt; gm: Qtz, Kfs ±Pl	Ap, Zrc, Aln, Mon, Thr	X	? 8 (8.4)
Christmas-tree laccolith complex	Nasuto microgranite	monzogranite	porphyritic (25-30%) microgranular gm	pheno: Qtz, Pl, Kfs, Bt; gm: Qtz, Kfs, Pl			—
Christmas-tree laccolith complex	Capo Bianco aplite	Alkali feldspar granite	porphyritic trachytoid gm	pheno: Qtz, Pl, Kfs, Ms; gm: Ab	Tur (centr Elba) Xen, Mon, Nb-Ta oxides		7.9 8.0 > 8.5

Ab: albite; Aln; allanite; Ap: apatite; Bt: biotite; Chr: cromite; Crd: cordierite; Grt: garnet; Ilm: ilmenite; Mag: magnetite; Mon: monazite; Ms: muscovite; Ol: olivine; Per: perrierite; Pl: plagioclase; Qtz: quartz; San: sanidine; Thr: uraniferous thorite; Tur: tourmaline; Xen: xenotime; Zrc: zircon; mega: megacrysts (>2 cm); pheno: phenocrysts (< 2 cm); xeno: xenocrysts; gm: groundmass; MME: mafic microgranular enclaves (M=rare, MM= common). Xeno: metamorphic xenoliths (X=rare, XX= common). ? : age inferred from stratigraphic observations. For references and discussion on isotopic ages see DINI *et alii* (2002).

Table 2. Average major element chemical compositions.

unit	Capo Bianco aplite	Nasuto microgranite	Portoferraio porphyry	San Martino porphyry	Monte Capanne pluton	Monte Capanne leucogranites	Orano dyke swarm normal	Orano dyke swarm hybrid
SiO_2	73.07	69.10	69.92	68.78	67.46	74.38	65.08	67.46
TiO_2	0.02	0.36	0.29	0.36	0.56	0.17	0.60	0.48
Al_2O_3	16.59	16.45	15.82	16.28	15.89	14.09	15.76	15.81
Fe_2O_3	0.23	0.40	0.50	0.52	0.79	0.53	1.08	0.90
FeO	0.23	1.54	1.24	1.56	2.35	0.49	2.74	2.15
MnO	0.05	0.04	0.03	0.04	0.06	0.03	0.06	0.05
MgO	0.09	0.99	0.85	0.94	1.41	0.36	2.62	1.61
CaO	0.22	0.83	1.57	2.11	2.62	0.94	3.15	2.22
Na_2O	4.24	3.82	3.60	3.38	3.48	3.20	3.22	3.55
K_2O	4.06	4.71	4.50	4.23	4.08	5.07	3.65	4.04
P_2O_5	0.02	0.06	0.10	0.14	0.20	0.06	0.19	0.19
LOI	1.26	1.69	1.60	1.99	1.08	0.68	1.75	1.54
ASI	1.42	1.29	1.18	1.22	1.10	1.15	1.09	1.15

ASI: Alumina Saturation Index, corrected for apatite. Orano normal: thin dikes and border facies of thick dikes. Orano hybrid: inner facies of thick dikes.

Structural Framework

Western Elba consists of the Monte Capanne pluton and of its thermometamorphic carapace of Complex IV rocks, that contains 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 sharply truncates its contact aureole (Figs. 1 and 3). The Eastern Border fault dips moderately to steeply to the east, separating a western footwall breccia of hornfelsed Complex IV rocks plus fragments of the Monte Capanne pluton, from an eastern hanging wall breccia made of Complex V Flysch and megacrystic San Martino porphyry. Movement on the Eastern Border fault was "west side up", juxtaposing western rocks from 4-5 km of depth (DINI *et alii*, 2002) with shallowly buried sedimentary rocks and their enclosed porphyries on the east side. Central Elba is separated from eastern Elba by the low-angle Central Elba fault, marked by a tectonic mélange of rocks from Complexes IV and V, most notably rocks whose equivalents crop out in western Elba (DINI *et alii*, 2002). The fault dips gently westward, as does the dominant fabric of the rocks resting on it, so that the highest part of the section occurs at the western edge against the Eastern Border fault. In eastern Elba, the younger low-angle Zuccale detachment fault, with eastward transport of 5-6 km, post-dates the Central Elba fault (PERTUSATI *et alii*, 1993).

THE WESTERN-CENTRAL ELBA INTRUSIVE COMPLEX

The Christmas-tree laccolith complex of the Island of Elba is part of the larger western-central Elba intrusive complex that consists of intrusive bodies that crop out within a stacked tectonic pile (Fig. 3). Field, petrographic and chemical data, along with intrusive relationships, define the different units and allow their correlation between exposures in western and central Elba (DINI *et alii*, 2002). A summary of petrographic characteristics and ages is given in Tab. 1, while average chemical compositions are shown in Tab. 2.

The western-central Elba intrusive complex consists of hypabyssal and plutonic rocks with porphyritic, volcanic-like textures and plutonic-like textures, respectively. For each unit the geographic names were joined to a textural term, "porphyry", "aplite" or "microgranite" for the hypabyssal rocks, and the comprehensive term "pluton" for the main intrusive body. In describing the rock type for each unit (Tab. 1), names were derived from the Q'-ANOR plutonic classification diagram (Fig. 4), to take into account the overall intrusive context. Furthermore, the plutonic rock nomenclature and use of textural terms such as "porphyry" and "aplite" follows the regional geological tradition (MARINELLI, 1955; MARINELLI, 1959). The relative intrusive chronology has been firmly established on the basis of crosscutting relationships. Isotope chronology points out that magmatism in western and central Elba occurred during two main pulses, the first around 8 Ma (Capo Bianco aplite, Nasuto microgranite and Portoferraio porphyry), and the second around 7 Ma (San Martino porphyry, Monte Capanne pluton, and Orano porphyry (DINI *et alii*, 2002).

The Capo Bianco Aplite

The Capo Bianco Aplite is a white porphyritic rock with alkali-feldspar granite compositions (Fig. 5a). It crops out in western Elba on a ridge, structurally above ultramafic rocks and below an argillaceous unit of Complex IV, constituting five adjacent but isolated caps that were likely emplaced as a single sill and subsequently dismembered by younger intrusions. In central Elba, a tourmaline-rich layer of Capo Bianco Aplite (Fig. 5b) intruded higher within the pre-intrusive sequence and was subsequently encased within later intrusions.

The Nasuto Microgranite

The Nasuto Microgranite, (Figs. 5d, e) of syenogranite composition (Fig. 4), crops out over an area of 0.5 km² along the northern shore of western Elba. It is entirely surrounded, as well as intruded, by the younger Portoferraio porphyry, so that its primary intrusive contacts are lost.

The Portoferraio Porphyry

The Portoferraio Porphyry (Fig. 5f) contains prominent phenocrysts of sanidine (Figs. 5g, h) is of monzogranite to syenogranite composition (Fig. 4). It occurs as four major layers up to 700 m thick, commonly interconnected and accompanied by minor dykes and sills. Three major layers occur in western Elba. The lowest two layers, with maximum thicknesses of about 75 m, intruded Complex IV parallel to the ENE-striking tectonic fabric. A higher layer of Portoferraio porphyry, emplaced between hornfelsed ophiolitic rocks and their metasedimentary cover, encases and crosscuts the

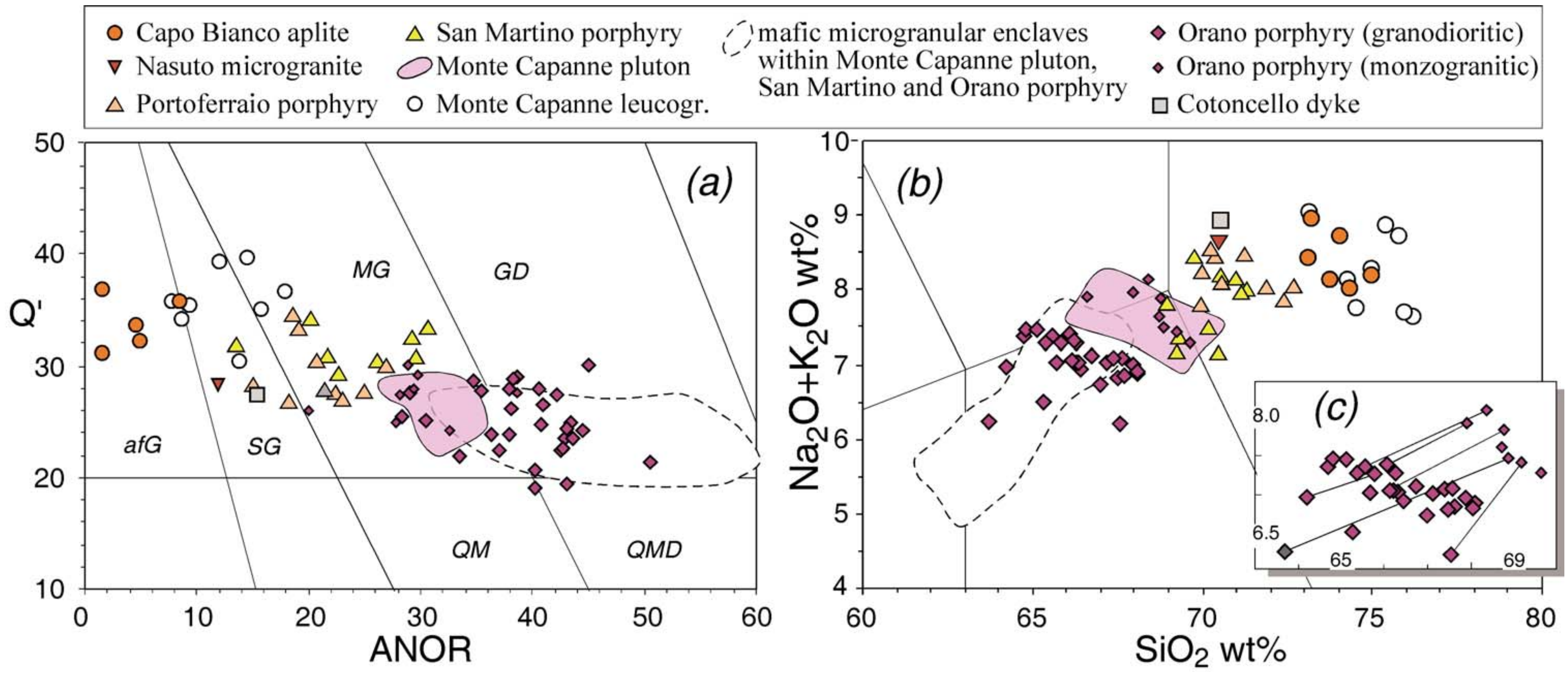


Fig. 4 - *a)* Q'-ANOR *classification diagram. Abbreviations of rock names:* afG, *alkali feldspar granite;* SG, *syenogranite;* MG, *monzogranite;* GD, *granodiorite;* QM, *quartz monzonite;* QMD, *quartz monzodiorite.*
b) Total alkali vs. silica (TAS) *classification diagram.*
c) TAS *enlargement for Orano dykes; tie-lines connect cores (larger symbol) and rims (smaller symbol) of individual dykes. Modified after* DINI et alii *(2002).*

Capo Bianco Aplite and the Nasuto Microgranite. This layer terminates to the SW against the Monte Capanne pluton where it is strongly mylonitised. It continues south-west of the Monte Capanne pluton (Chiessi area), suggesting the original length of this layer to have been over 9 km. The fourth layer of Portoferraio porphyry occurs in central Elba between Cretaceous Flysch above and Eocene Flysch below. The upper surface of this NNW-striking layer is generally subparallel to bedding in the overlying Flysch that dips moderately WSW. Along the southern edge, this laccolith bifurcates into five layers connected by E-W trending feeder dykes.

The San Martino Porphyry

The monzogranitic San Martino Porphyry (Fig. 5j), characterised by prominent megacrysts of sanidine set in a very fine-grained groundmass (Figs. 5k, l), occurs as subhorizontal layers and steeply-dipping dykes; megacrysts are often aligned subparallel to intrusive contacts. In western Elba, only WNW-striking dykes occur, cutting Complex IV and the older intrusive units; the largest dyke extends over 2.5 km with a thickness of 25 to 50 m. In central Elba, dykes of San Martino Porphyry cut the fabric of the sedimentary host as well as layers of the older intrusive units, while the main bodies are four, parallel, gently westward-dipping layers. These were emplaced above the layers of Portoferraio Porphyry, concordant to the fabric of the folded and faulted strata of the host Flysch. Bifurcation along the upper surface forms branches, and, at Monte San Martino, a large septum of Flysch maintains a simple planar geometry over a map distance of 1.5 km. These igneous layers, with maximum thicknesses ranging from 100 and 700 m, taper out towards both northern and southern ends. Lengths measured in the N-S direction range between 2.4 and 8.3 km, with the thickest and largest layer exposed over more than 18 km^2.

The Monte Capanne Pluton

*The Monte Capanne Pluton in western Elba has a roughly circular plan (Figs. 1 and 3) and is mainly composed of monzogranite (Fig. 4), with prominent K-feldspar megacrysts. On the basis of dimension, morphology and modal abundance of K-feldspars, as well as the geochemical variations within the pluton, three internal facies have been distinguished (*DINI et alii*, 2002; *ROCCHI et alii*, 2002). Contacts with surrounding country rock are mostly intrusive in nature and dip away from the pluton. Host rocks, belonging to the ophiolitic-sedimentary tectonic Complex IV (Fig. 1), and exhibiting shear fabric acquired during the Apenninic compressive phase, were overprinted by thermal metamorphism and deformed by emplacement of the pluton itself. The contact metamorphic reactions suggest peak conditions with temperatures in excess of 600°C at a pressure of 0.1-0.2 GPa (*DINI et alii*, 2002). The pluton is cut by several leucosyenogranite dykes, commonly of thicknesses up to tens of m, occurring within both the pluton and its thermometamorphic aureole, mainly close to the pluton's contact.*

The Orano Porphyry

*The Orano Porphyry unit comprises a swarm of nearly 100 dark-coloured quartz, monzodioritic to monzogranite dykes (Fig. 4) crosscutting all the other intrusive units of the sequence (Figs. 5m, n, o). Contacts with host rocks are sharp and planar, commonly exhibiting abrupt changes in orientation; thicknesses range from less than 1 m to up to 50 m. In western Elba, Orano dykes are restricted to the north-western portion of the Monte Capanne pluton and its contact aureole (6 Ma dykes/km^2). Orano dykes crop out only in the northern half of central Elba. In both areas, strikes cluster around the E/W direction. Some dykes are internally zoned, testifying to exploitation of the same conduit by succeeding magma pulses (*DINI et alii*, 2002).*

GEOCHEMICAL EVOLUTION OF THE WESTERN-CENTRAL ELBA INTRUSIVE COMPLEX

The sequence of intrusions described above consists of magmas of various origins, developed in the time interval between ca. 8 and 6.8 Ma (Tab. 1). The petrogeneses of these magmas have been discussed in detail by DINI *et alii* (2002) and WESTERMAN *et alii*, (2003). The first phase of the magmatic activity was dominated by pure anatectic melts which are considered to have been generated via muscovite- (Capo Bianco Aplite) or biotite- (Nasuto Microgranite and Portoferraio Porphyry) dehydration melting of a metasedimentary source (label C1 in Fig. 6). The genesis and ascent of anatectic magmas were linked to late Miocene lithospheric thinning and decompression following earlier Oligocene-Miocene orogenic overthickening.

The second phase of igneous activity is volumetrically more important, and involved hybrid magmas produced by the interaction of mantle-derived mafic melts (M1) and peraluminous crustal melts (C2). This crustal component was derived from a different crustal source than C1, and is directly represented only by the Cotoncello syenogranite dyke within the Monte Capanne pluton. The M1 mantle magma, thought to be similar to the nearby coeval Capraia K-andesites, is not directly represented, but rather occurs within hybrid products, i.e. mafic microgranular enclaves. The San Martino Porphyry is the first voluminous intrusion of hybrid magma during this second phase, marking the culmination of the construction of laccolith complex.

At this stage, the competing processes of (1) hybridism of mafic and felsic melts and (2) fractional crystallisation, operated to generate the Monte Capanne Pluton. In this scenario, the different internal facies primarily represent emplacement pulses of hybrid varieties, whereas the late leucogranite dykes are the end-products of fractional crystallisation.

Finally, the last igneous intrusions are represented by the Orano dykes. This magma has a primary composition differing from that of the mafic melt involved in the earlier main hybridisation process, and is thought, therefore, to be derived from a distinct, strongly modified mantle (M2).

During their ascent, the Orano melts were first variably hybridised with a unique crustal material (C3), and then further modified at a shallower level by capturing crystals and/or melt from the Monte Capanne system.

In summary, the igneous activity between ca. 8 and 6.8 Ma at Elba recorded an evolution of the composition of intruding magma dominated initially by the crust, then by hybrid systems,

Capo Bianco aplite

Nasuto microgranite

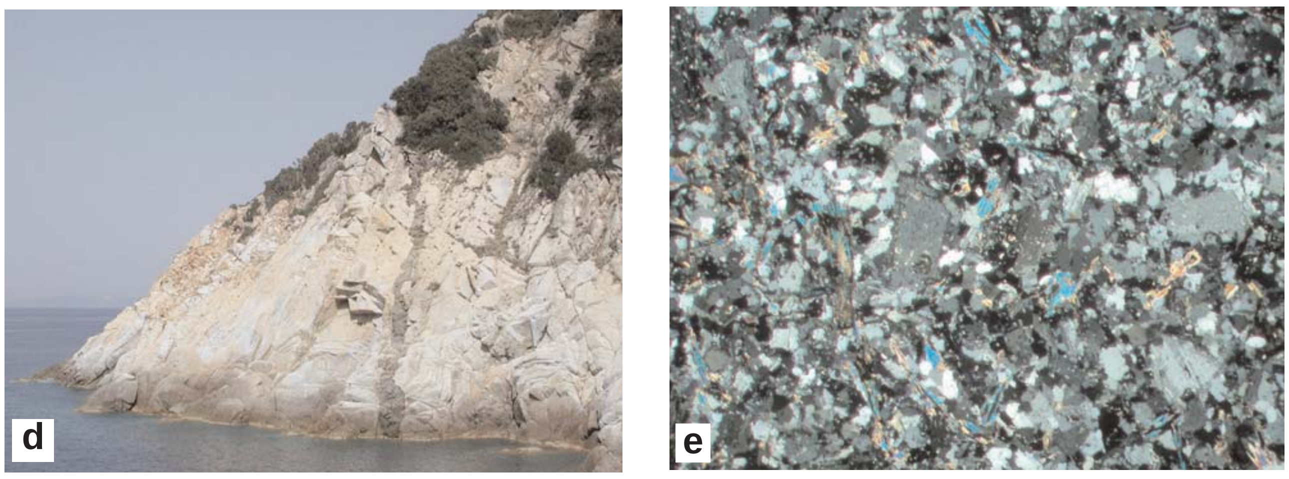


Fig. 5 -

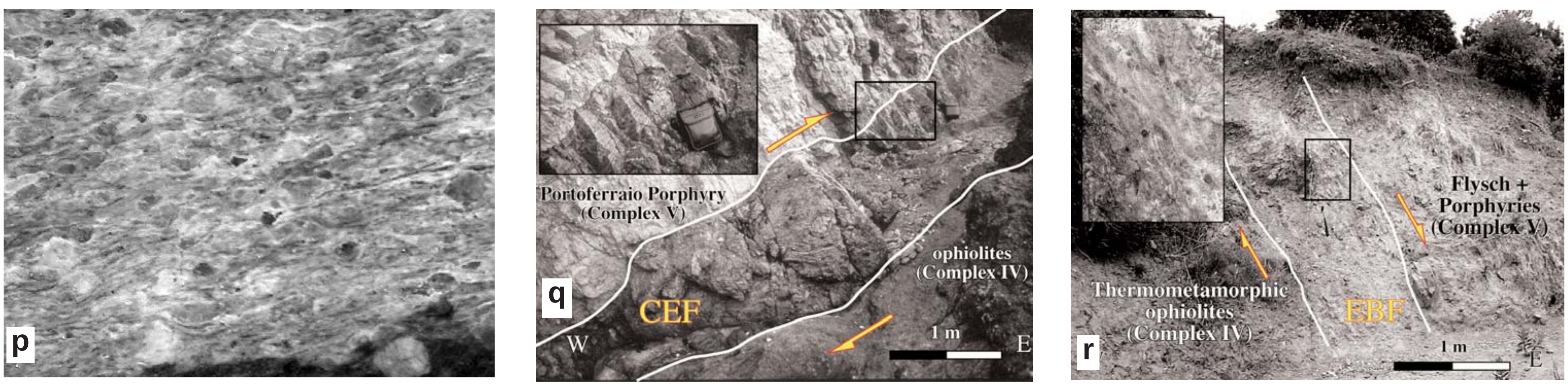
a - *Capo Bianco aplite - This exposure at the type locality in cen tral Elba shows the lower 60 m of the laccolith layer, visible here above the younger Portoferraio porphyry that intruded at the base.*

b - *Capo Bianco aplite - Mesoscopic textures of the Capo Bianco aplite, with abundant blue-black tourmaline orbicules defining a subhorizontal layering characteristic of the unit in central Elba.*

c - *Capo Bianco aplite - Microscopic texture with a neuhedral, primary, muscovite phenocryst in a holocrystalline trachytoid matrix defined by aligned albite microliths. Width of the photo is 2 mm.*

San Martino porphyry

Structural details



d - *Nasuto microgranite - Outcrop features at Punta del Nasuto show the homogeneous character of the microgranite, crosscut here by adark vertical Orano dyke varying from 2 to 3 m in thickness.*

e - *Nasuto microgranite - Photomicrograph of the monzogranitic Nasuto microgranite with 25-30 vol% small phenocrysts of quartz, plagioclase (andesine-oligoclase), K-feldspar and biotite. Width of the photo is 5 mm.*

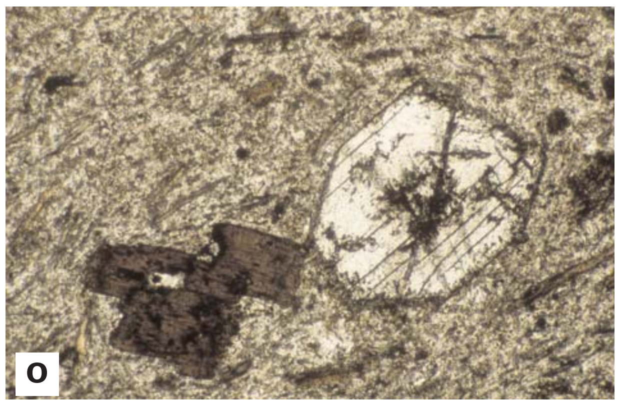
f - *Portoferraio porphyry - Outcrop features of laccolith layers intruded parallel to bedding along thesouthern shore of central Elba at Capo Fonza. Tapering terminations are well displayed.*

g - *Portoferraio porphyry - The mesoscopic texture of the Portoferraio porphyry near Punta del Nasuto shows typical abundance (25-50 vol%) of euhedral phenocrysts in an aphanitic matrix.*

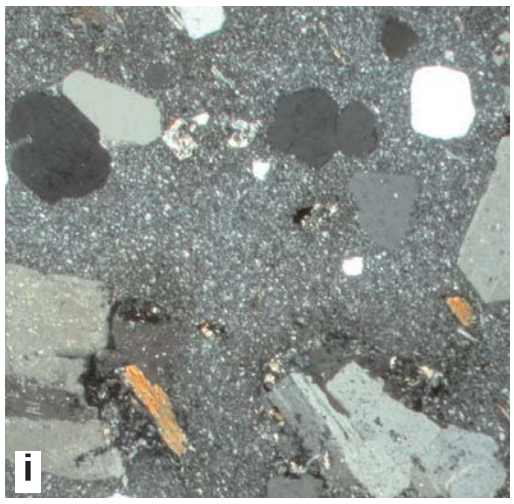
h - *Portoferraio porphyry - Close up view of Portoferraio porphyry near Punta del Nasuto, showing phenocrysts of euhedral, low-temperature sanidine and quartz in positive relief owing to differential weathering. Coin for scale.*

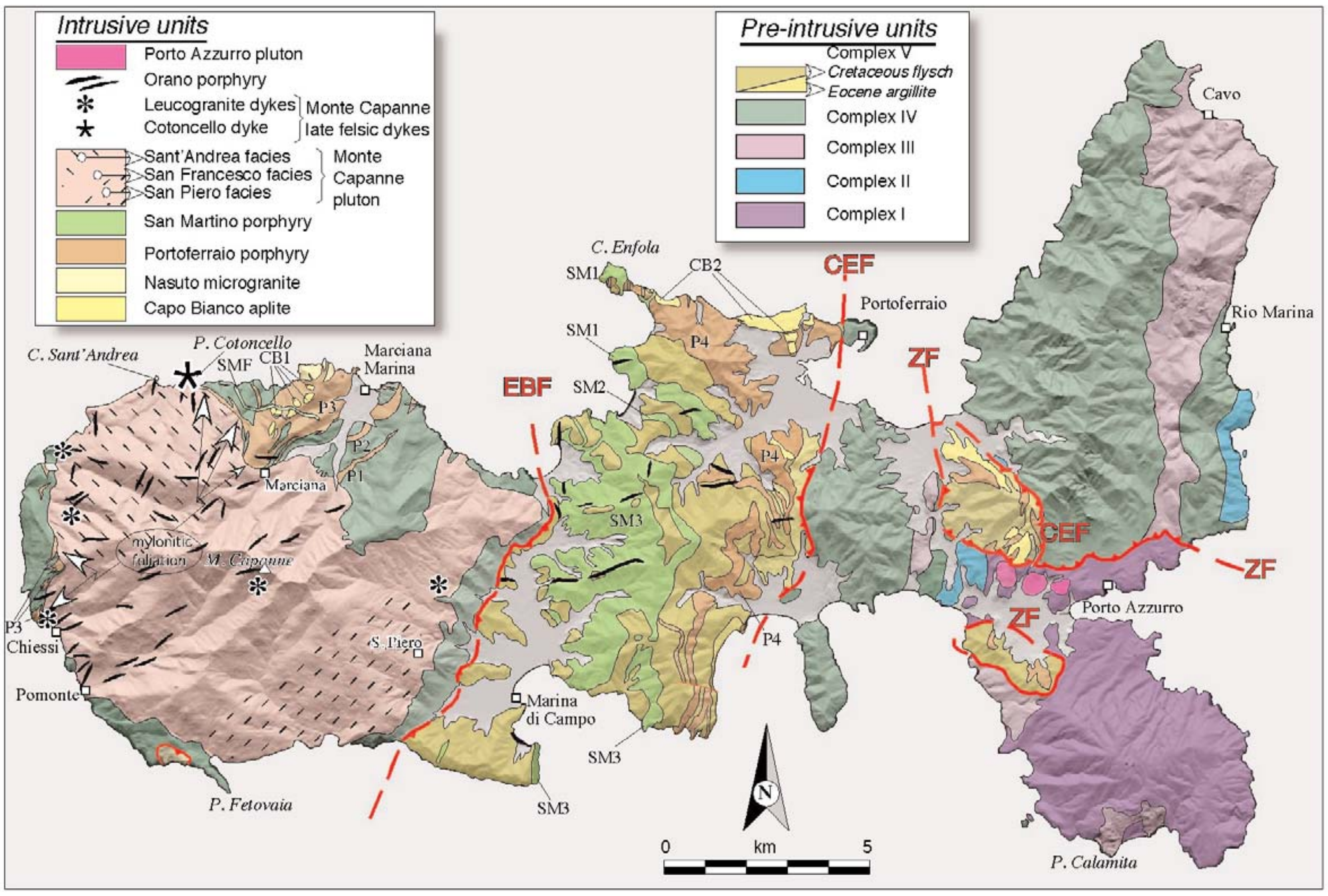
i - *Portoferraio porphyry - Holocrystalline texture with euhedral low-temperature sanidine (far right), plagioclase, biotite and rounded quartz phenocrysts in a fine-grained matrix. Width of the photo is 5 mm.*

Orano porphyry



Portoferraio porphyry





j - San Martino porphyry - Two branches of the San Martino Christmas-tree laccolith, exposed near the roof along the southwest shore of Golfo di Campo between Capo Poro and Punta Bardella.

k - San Martino porphyry - Mesoscopic texture of the San Martino Porphyry with low-temperature sanidine megacrysts, weakly aligned parallel to the intrusive contact against Cretaceous Flysch at Punta Bardella.

l - San Martino porphyry - Photomicrograph showing 40-50 vol% phenocrysts and megacrysts; the low-temperature sanidine megacryst (right) has quartz, biotite and concentrically zoned plagioclase inclusions. Width of the photo is 5 mm.

m - Orano porphyry - Outcrop features of an Orano dyke in Monte Capanne monzogranite at Colled' Orano. Note included K-feldsparxenocrysts, microgranular mafic enclaves, and granitic xenoliths.

n - Orano porphyry - Close up view of Orano dyke at Colle d'Orano showing the intrusion exploiting brittle fractures. Weakly-aligned xenocrysts, including rounded K-feldspar megacrysts, are abundant.

o - Orano porphyry - Photomicrograph of euhedral biotite and rare orthorhombic pyroxene phenocrysts in a matrix of biotite-phlogopite and oligoclase-andesine with quartz and K-feldspar. Width of the photo is 1.5 mm.

p - Foliated Portoferraio porphyry - Mylonite with fragmented and recrystallised quartz, plagioclase and K-feldspar in a schistose fine-grained groundmass. Purple colour from recrystallised biotite.

q - Central Elba Fault - Composite photo of tectonic breccia from Laguna. Clasts include western Elba lithologies, including Portoferraio porphyry, that constrain time of displacement.

r - Eastern Border Fault - Looking north at the chaotic breccia marking the high-angle normal fault separating western and central Elba. Outcrop northwest of La Pila.

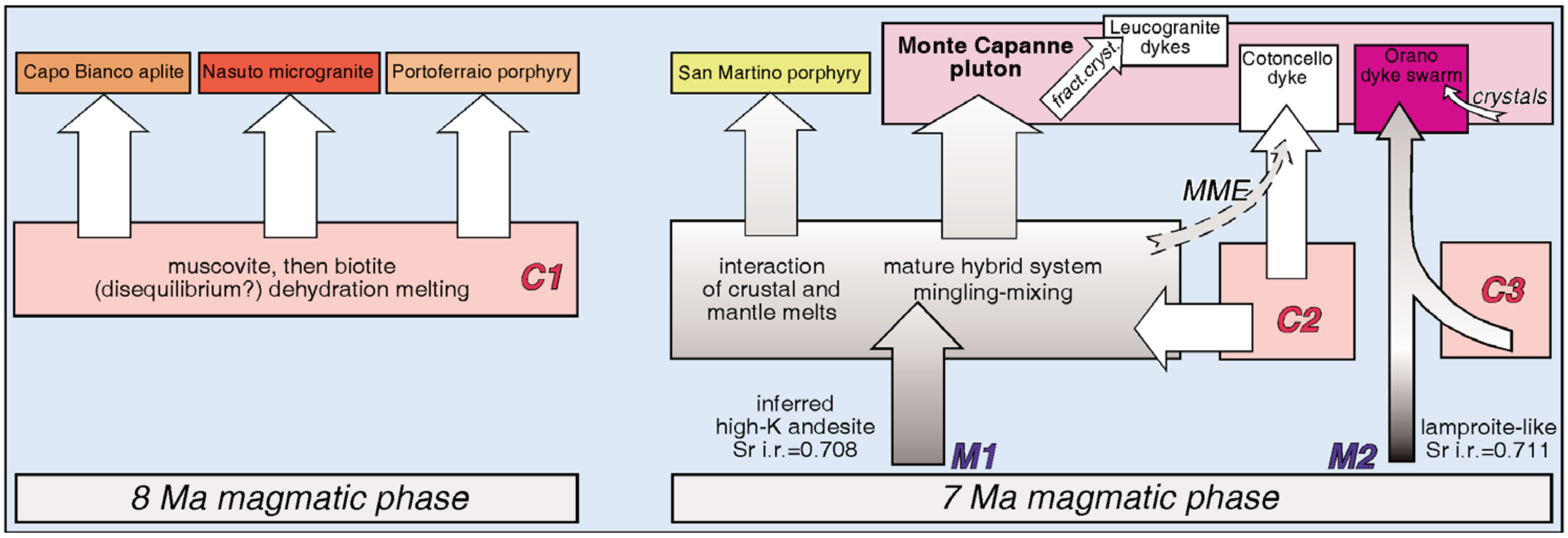


Fig. 6 - *Schematic model for the genesis of Elba magmatic products through time.* MME: *mafic microgranular enclaves;* i.r.: *initial isotopic ratio. Modified after* DINI et alii *(2002).*

and finally by a mantle component. This evolution paralleled the progressive thinning, heating and intrusion by mafic melts of the Apennine fold belt during the late Miocene. It is worth noting that peculiar melts generated at the beginning and at the end of the igneous activity were volumetrically modest and did not contribute to the generation of the main hybrid magmas.

GEOMETRY OF THE LACCOLITH COMPLEX

The western-central Elba igneous complex is composed primarily of several sheet-like intrusions with extensively known roofs and floors that make up the Christmas-tree laccolith complex, along with a larger pluton with a locally exposed roof but no known floor. The main bodies of the Capo Bianco Aplite, Portoferraio Porphyry, and San Martino Porphyry all occur subparallel to the planar structures of the host metaophiolite, metasediments, and Flysch. Feeder dykes occur beneath individual layers of both the Portoferraio Porphyry (e.g. on the W side of Golfo di Lacona) and the San Martino Porphyry (e.g. E-W trending San Martino dyke W of Marciana Marina). Therefore, each intrusive unit is interpreted as a multilayer laccolith, and the resulting geometry is that of a nested, multilayer, multipulse Christmas-tree laccolith complex (Fig. 7).
The thickness values of individual layers vary across an order of magnitude from 50 to 700 m (ROCCHI *et alii*, 2002). The layers of central Elba have N-S strikes with lengths between 2.4 to 10 km, while trends in western Elba are more variable and their length varies from 1.6 to 9.3 km. All the nine main Elba laccolith layers have large aspect ratios (diameter/thickness), varying from 12 to 33. The diameter for each layer was approximated from the maximum horizontal exposed length. Volumes were calculated assuming two end-member shapes: a laccolith approximated by a spherical bowl with height equal maximum thickness, and a sill approximated by a cylinder with height equal maximum thickness. Actual volume is likely between the two values; therefore, we assume the best volume estimate to be the average between the two calculations.
Volumes of individual layers vary more than an order of magnitude, from 1.3 to 30 km^3 (ROCCHI *et alii*, 2002). Emplacement depths for individual layers were evaluated by measuring overburden thickness in cross-sections, once the original tectonostratigraphic sequence was restored. Additionally, depths were corrected taking into account the emplacement sequence of intrusive layers and the likely amount of erosion (about 800 m based on the rough estimate of the present mean erosion rate for Italy of 0.1 mm/yr: BRANCA & VOLTAGGIO, 1993).
The Monte Capanne Pluton intruded the base of the laccolith complex. Its emplacement depth, however, is not simply the sum of laccolith layers and their host rock thicknesses, since the pluton punched through several layers of Portoferraio Porphyry in western Elba, as demonstrated by the strong mylonitic foliation developed in the Portoferraio Porphyry, close to the contact with the pluton on both its NE and SW sides (Fig. 5p).
After also taking erosion into account, the calculated emplacement depth for the pluton is about 4.5 km, a value in agreement with peak conditions of contact metamorphism produced by its intrusion. Fig. 7 schematically illustrates (to scale) the pluton-laccolith complex with its dome structure.

EMPLACEMENT MECHANISMS

Emplacement of the magmas was controlled by encountering crustal anisotropies (i.e. magma traps) rather than by reaching neutral buoyancy levels. On the basis of the quantitative relationships between dimensional parameters, growth of these sheet-like intrusions is thought to have been frozen during a vertical inflation stage; this hampered the possible coalescence of the distinct magma batches to form thicker tabular plutons.
Indeed, most of the laccolith layers at Elba were emplaced along strong crustal heterogeneities such as thrust surfaces between Complexes, secondary thrusts inside Complexes, and bedding in the Flysch. The collected data lend support to a model in which the main controlling factor on the switch from vertical to horizontal magma movement is the large availability of subhorizontal strength anisotropies that behaved as crustal magma traps (HOGAN *et alii*, 1998), rather than the attainment of the neutral buoyancy level for rising magma.
The relationships between the dimensional parameters of the layers constituting the Elba laccolith complex have been explored with the aim of better understanding the growth mechanisms of intrusions in the shallow crust (ROCCHI *et alii*, 2002). A significant power-law correlation has been found between thickness (T) and diameter (L). In the context of a two-stage filling process (lateral expansion first, followed by upward inflation: JOHNSON & POLLARD, 1973; MCCAFFREY & PETFORD, 1997; CRUDEN & MCCAFFREY, 2001), this has been interpreted as evidence of laccolith growth frozen in the vertical inflation stage (ROCCHI *et alii*, 2002).
These relationships suggest that the Portoferraio and San Martino Porphyries were emplaced as Christmas-tree laccoliths because the magma was not able to coalesce in a single reservoir, likely owing to the excess of crustal magma traps found in Elba.

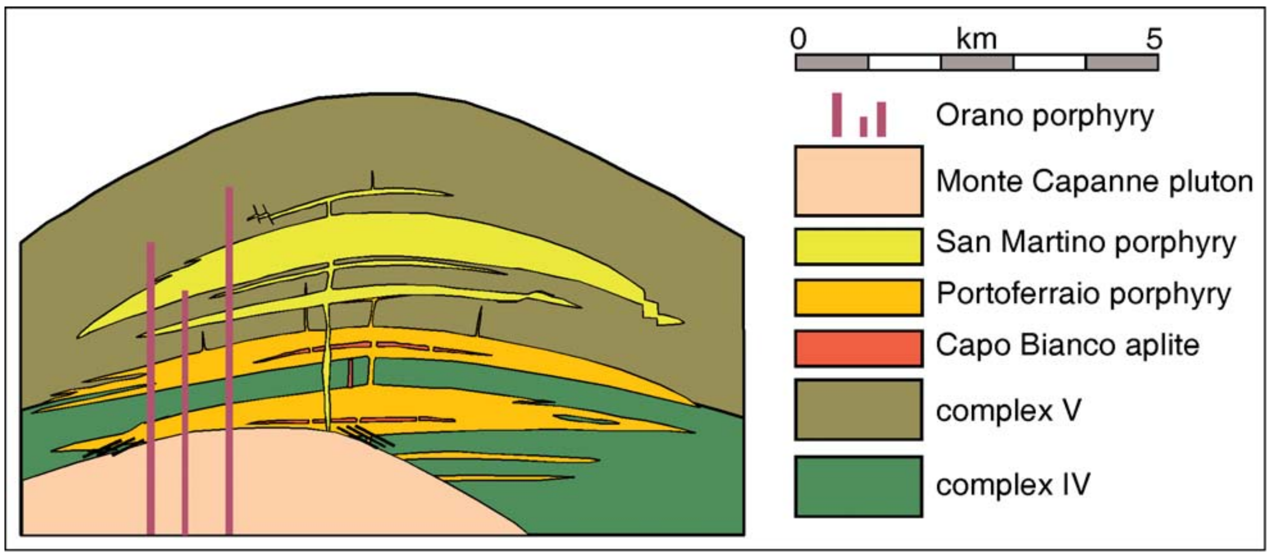


Fig. 7 - *Schematic cartoon of the nested Christmas-tree laccolith complex at the end of its construction.*

TECTONIC EVOLUTION OF THE LACCOLITH COMPLEX

Emplacement of the whole laccolith complex led to the formation of an oversteepened dome structure in western Elba, while the subsequent emplacement of the Monte Capanne Pluton into its basal portion triggered the decapitation of the structure, with eastward displacement of its upper part. Indeed, the present setting of the laccolith complex does not reflect the original emplacement geometry (WESTERMAN *et alii*, 2004). All the intrusive units were emplaced within tectonic Complexes IV and V when they were stacked above the present western Elba (Fig. 8a).

Then, shortly after the laccolith dome was constructed and intruded by the Monte Capanne Pluton and the Orano dykes, the upper part of the entire igneous-sedimentary complex was tectonically translated eastwards along the Central Elba fault (CEF, Fig. 5q; Fig. 8b). Following this eastward translation, a "west side up" movement occurred along the Eastern Border fault (Fig. 5r), with a throw of 2 to 3 km (Fig. 8b through d). The minimum amount of displacement along the Central Elba fault (CEF) is constrained to about 8 km by the distance from the pluton's aureole eastwards to its leading edge, where fragments of hornfels from that aureole occur in the fault mélange.

The timing of displacement on CEF is constrained by (1) the occurrence of fragments of Monte Capanne hornfels in the footwall mélange of CEF some 8 km east of the nearest outcrop of the thermal aureole, indicating that movement on the CEF occurred after contact metamorphism linked to the Monte Capanne Pluton (ca. 6.9 Ma), and (2) the matching distribution and orientation of Orano dykes in western and central Elba, suggesting that the Orano dykes were truncated and translated by the movement along the CEF (post 6.85 Ma). The timing in this scenario is further constrained by the occurrence, on mainland Tuscany (some 50 km to the east), of abundant cobbles and boulders of tourmaline-bearing Capo Bianco Aplite and Portoferraio Porphyry, in conglomerates deposited very close to the end of the Messinian (MARINELLI *et alii*, 1993; TESTA & LUGLI, 2000). Indeed, Capo Bianco Aplite and Portoferraio Porphyry layers were concentrated just above (and presumably below) the CEF, and the most logical mechanism to expose them without exposing the overlying San Martino Porphyry units was by erosion of tilted layers (today's tilt of laccolith layers is about 30°; Fig. 5f).

The eastward displacement of the upper part of the complex is at least partly linked to gravitational instability. For about 1 million years, a 2,700 m thick tectonostratigraphic section was inflated by the addition of at least 2,400 m of laccolithic intrusions, producing a new section of about 5,000 m of thickness. A dome with a diameter of 10 km and a height of 2.5 km was formed, with a surface slope of about 25° (assuming an originally flat surface). We envision that the emplacement of the Monte Capanne Pluton beneath this dome caused oversteepening and triggered the main eastward displacement of the upper section. Once significant movement began, transfer of the load from above Monte Capanne towards central Elba promoted movement on the east-dipping Eastern Border fault, as the unloaded pluton rose and the thickened central Elba section subsided.

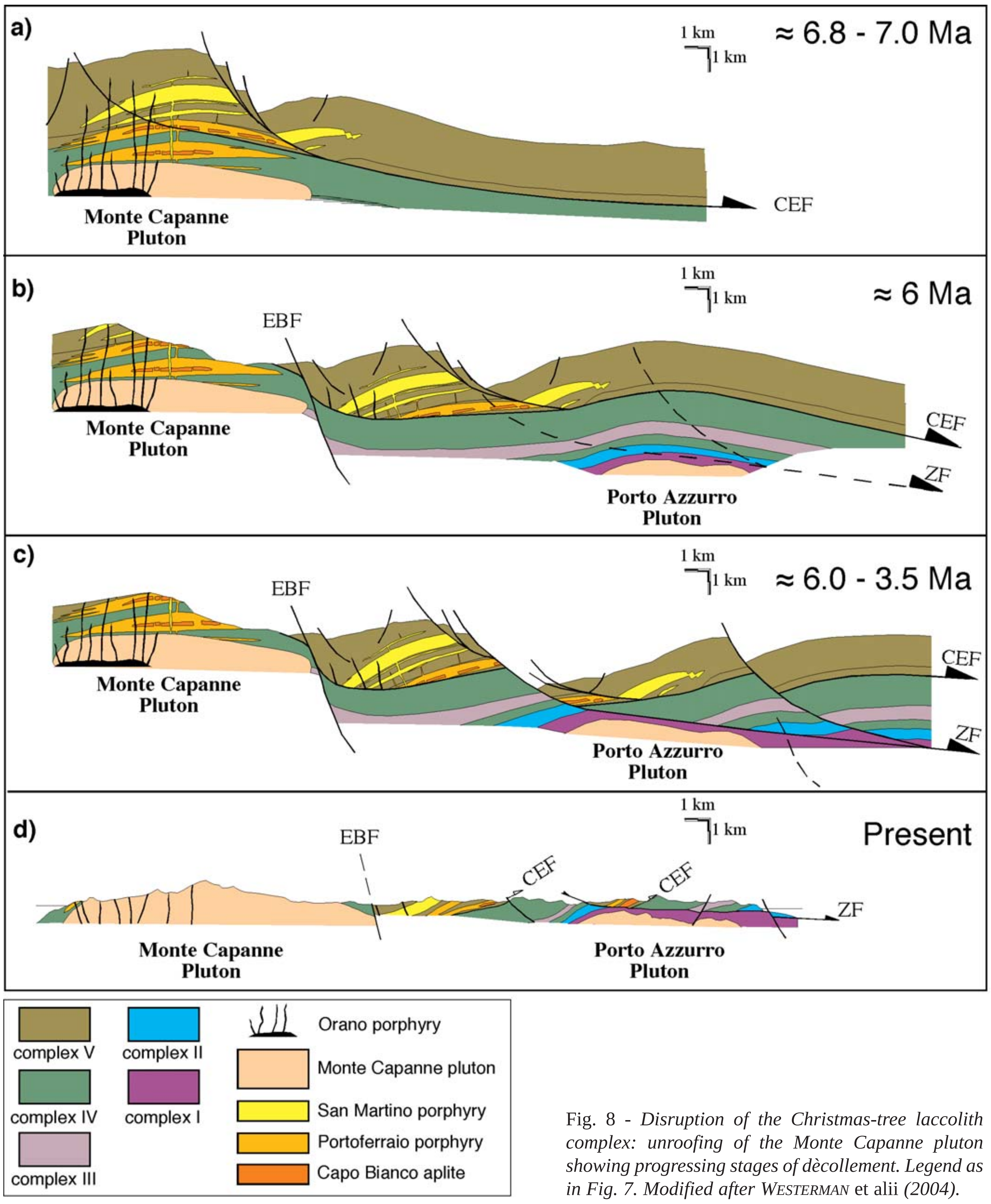


Fig. 8 - *Disruption of the Christmas-tree laccolith complex: unroofing of the Monte Capanne pluton showing progressing stages of dècollement. Legend as in Fig. 7. Modified after* WESTERMAN et alii *(2004).*

The final movement on the Eastern Border fault took place entirely in a brittle regime, truncating the Central Elba fault, that has since been eroded in western Elba and lies almost completely buried in central Elba.

Evidence from experimental analogue models (MERLE & VENDEVILLE, 1995; ROMAN-BERDIEL *et alii*, 1995) and structural observations of natural examples (GUCWA & KEHLE, 1978) show that laccolith-type magmatic intrusions can produce stresses great enough to induce thrusts and folds in the adjacent sedimentary rocks. In particular, the most efficient process seems to be gravity gliding, during which layer-parallel compression can result as rocks glide away from the topographic high created by laccolithic intrusion.

The rate of displacement for dismemberment of the Elba laccolith complex is constrained by the time between onset of the movement along the Central Elba fault (ca. 6.8 Ma) and the time when cobbles were deposited (end of Messinian, i.e. before 5.3 Ma). Allowing for erosion and transport, a maximum estimate for the time available for the main movement on the Central Elba fault is less than 1.5 million years. Thus the eastward translation of at least 8 km occurred at an average rate of over 5-6 mm/yr.

This rate of movement is higher than those reported for detachment faults (STOCKLI *et alii*, 2001), while it is consistent with rates associated with gravity gliding (FLETCHER & GAY, 1971), and thus compatible with displacement triggered by magma emplacement.

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