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Petrological and geological data of porphyritic dikes from the Capo Arco area (Eastern Elba Island, northern Tyrrhenian Sea)

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Abstract. — New geological surveying at a 1:10.000 scale (CARG Project) allowed to refine the stratigraphic, structural and magmatic setting of the Elba Island. This paper aims at characterizing two dikes of likely Late Miocene age (Casa Carpini dikes), previously defined as lamprophyres (i.e. kersantite), outcropping in eastern Elba, on the eastern and southern slopes of the Monte Arco, close to Porto Azzurro. The grey to light-grey Casa Carpini dikes, the phyllites and metasandstones of the Ligurian-Piedmontese Acquadolce Unit, are quartz-diorites in composition with a maximum of 23% of mafic minerals (biotite). They show a microcrystalline porphyritic texture consisting of plagioclase, biotite, quartz, K-feldspar, and rare muscovite with scattered xenocrysts of quartz, plagioclase and K-feldspar. Plagioclase phenocrysts display normal zoning with An% = 9-23; the variability of An in the plagioclase microcrysts is wider (5-34%). The REE patterns are characterised by fractionated LREE and MREE and negative anomaly of Eu. The mantle-normalized trace element patterns show high content of the most incompatible elements with a positive spike of Th and Pb, and high LILE/HFSE ratios. Negative spikes of Nb, P and Ti are also observable. No negative anomalies of Sr are present, and Ce/Sr ratios are much lower than other magmatic rocks from Elba. A depletion in K, Rb and Cs is also observed in the studies rocks, possibly a result of secondary processes. Sr-Nd isotopic ratios for the two outcrops of the studied dikes show significant differences, with $^{87}Sr/^{86}Sr$ = 0.711845 and 0.711769 and $^{143}Nd/^{144}Nd$ = 0.512223 and 0.512246. The Casa Carpini dikes are petrographically different from most of the dike rocks associated to the granitoid plutons and laccoliths of the Elba Island. Instead, analogies can be found with the granodiorites to quartz-monzodiorite Orano porphyries, the last magmatic products of western Elba. The petrological and geochemical characteristics of the studied dikes are typical of the intermediate-acidic rocks of the Elba Island. As other rocks from Elba, they show petrographic and geochemical evidence of mixing between a calcalkaline mafic-intermediate magma similar to that of Capraia and a crustal anatectic melt. The geochemical signatures of the studied dikes suggest a more important role of mafic magmas with respect to the bulk of the Elba magmatism.

Riassunto. — Il nuovo rilevamento geologico a scala 1:10000 (CARG Project) dell'isola d'Elba ha permesso di meglio definirne le caratteristiche stratigrafiche, strutturali e magmatiche. In questo contesto, il presente lavoro ha lo scopo di caratterizzare due particolari dicchi (cartografati come Dicchi di Casa Carpini), precedentemente definiti come lamprofiri (i.e. kersantiti), affioranti nel settore orientale dell'isola d'Elba, lungo i versanti orientale e meridionale di Monte Arco, nelle vicinanze di Porto Azzurro.

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I dicchi di Casa Carpini, di colore grigio e grigio chiaro che tagliano le filladi e le meta-arenarie dell'Unità Ligure-Piedemontese-Acquadolce, sono delle quarzo-dioriti contenenti fino al 23% di minerali femici (biotite). Essi presentano una tessitura microcristallina porfirica costituita da plagioclasio, biotite, quarzo, K-feldspato, e rara muscovite in cui sono dispersi xenocristalli di quarzo, plagioclasio e K-feldspato. I fenocristalli di plagioclasio presentano un contenuto di Anortite (An) variabile nell'intervallo 9-23% e deboli zonature normali; la variabilità del contenuto di An è più ampia nei microcristalli (5-34%). I pattern delle REE sono caratterizzati da LREE e MREE frazionate e anomalia negativa di Eu. Il pattern degli elementi in tracce mostra arricchimento negli elementi più incompatibili e alti rapporti LILE/HFSE; sono osservabili, inoltre, arricchimento in Th e Pb, impoverimento in Nb, P e Ti. Non è presente anomalia negativa di Sr ed i rapporti Ce/Sr sono più bassi che in molte altre rocce dell'isola d'Elba. Un impoverimento in K, Rb e Cs, forse legato a processi di alterazione secondaria, caratterizza le rocce studiate. Fra i due dicchi di Casa Carpini esistono modeste ma significative differenze dei rapporti isotopici dello Sr (0,711845 e 0,711769) e del Nd (0,512223 and 0,512246). Essi sono petrograficamente diversi da molti dei dicchi associati ai plutoni granitici e alle laccoliti dell'isola d'Elba. Analogie si osservano, invece, con: porfidi di Orano a composizione granodioritica e quarzo-monzonitica, gli ultimi prodotti magmatici dell'Elba occidentale. Le caratteristiche petrologiche e geochimiche dei dicchi di Casa Carpini sono tipiche delle rocce intermedio-acide dell'isola d'Elba. Come altre rocce dell'isola, mostrano evidenze petrografiche e geochimiche di mixing fra un magma calcalcalino, intermedio-femico, del tipo Capraia e un fuso crostale anatettico. Tuttavia, le loro caratteristiche geochimiche suggeriscono un ruolo dei magmi femici più importante rispetto al resto del magmatismo elbano.

KEY WORDS: *Elba Island, Magmatism, Porphyritic dikes, Miocene.*

PAROLE CHIAVE: *Isola d'Elba, Magmatismo, Dicchi porfirici, Miocene.*

INTRODUCTION

New geological surveying carried out in the Elba Island both for the CARG Project (new geological mapping of Italy at 1:50.000 scale) and the 1:10.000 Geological Mapping Project of Regione Toscana, add new data in the stratigraphic-structural and magmatic framework of the eastern part of the Island recently defined by Bortolotti *et al.* (2001) and Babbini *et al.* (2001).

This work deals with the setting and composition of two magmatic dikes (Casa Carpini dikes in Bortolotti *et al.*, 2001 and Babbini *et al.*, 2001), previously defined as lamprophyres by Debenedetti (1953) and outcropping on the eastern and southern slopes of the Monte Arco (NE of Porto Azzurro, Fig. 1), and their significance in the magmatic and tectonic evolution of the Elba Island and, more in general, of the Northern Tyrrhenian area.

GEOLOGICAL OUTLINE

Elba Island has a key role in the reconstructions of the stratigraphic, tectonic, metamorphic and magmatic evolution of the Northern Tyrrhenian Sea and the inner part of the Northern Apennines chain (Barberi *et al.*, 1967, 1969a,b; Bartole, 1995; Pertusati *et al.*, 1993; Bortolotti *et al.*, 2001 and references therein). In particular, the complex Elba stack of nappes, which is considered the innermost outcrop of the Northern Apennines Chain, is also well known for its Fe-ore bodies (Tanelli *et al.*, 2001) and the relationships between the emplacement of the Mio-Pliocene magmatic bodies and tectonics (Trevisan, 1950; Barberi *et al.*, 1969a; Pertusati *et al.*, 1993; Bouillin *et al.*, 1994, Daniel & Jolivet , 1995; Bortolotti *et al.*, 2001; Babbini *et al.*, 2001; Maineri *et al.*, 2003; Westerman *et al.*, 2004).

The new geological CARG surveying at the 1:10.000 scale of Elba Island (Project) allowed a revision of its stratigraphic, structural and magmatic setting (see Bortolotti *et al.*, 2001; Babbini *et al.*, 2001). Bortolotti *et al.* (2001) suggest an architecture of the Elba tectonic stack more complex than suggested previously (Trevisan, 1950; Barberi *et al.*, 1969 a,b). In particular, the former authors defined the piling up of nine main tectonic units (Figs. 1 and 2) which pertain to the Adriatic paleo-continental margin (e.g. Tuscan Units: PU, OU, MU, TN see below) and to the Ligurian-Piedmontese paleo-oceanic realm of the Western Tethys (e.g. Ligurian units: OU, EU, CU; Ligurian-Piedmontese units: AU, GU see

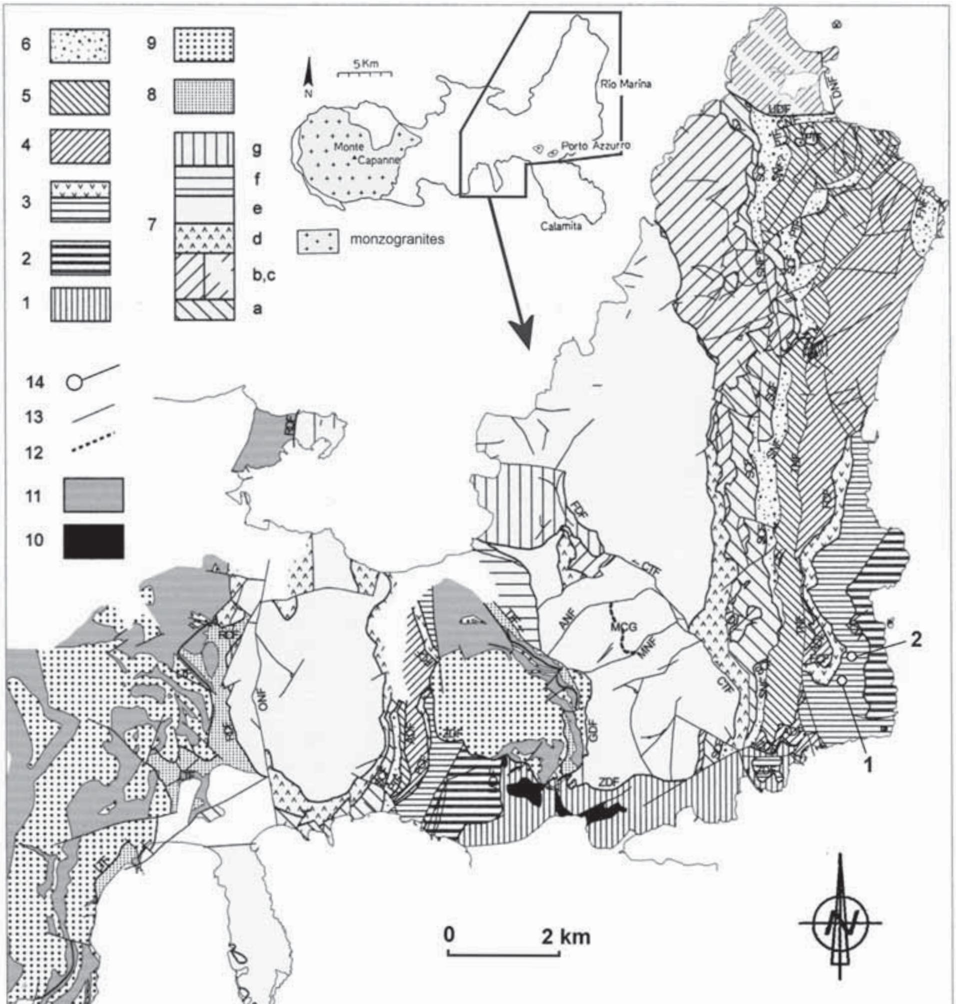


Fig. 1 – Structural map of central and eastern Elba Island. 1- **PU** – Porto Azzurro Unit (Tuscan Domain=TD); 2- **UO** – Ortano U. (TD); 3- **AU** – Acquadolce Unit (a- **PSU** – Porticciolo Subunit; b- **FSU** – Santa Filomena S.) (Ligurian-Piedmontese Unit=PD); 4- **MU** – Monticiano-Roccastrada U. (T.D.); 5- **TN** – Tuscan Nappe (T.D.); 6- **GU** – Gràssera U. (P.D.); 7- **OU** – Ophiolitic U. (a- **ASU** – Acquaviva S.; b- **SSU** – Monte Serra S.; c- **CSU** – Capo Vita S.; d- **TSU** – Sassi Turchini S.; e- **VSU** – Volterraio S.; f- **MSU** – Magazzini S. g- **BSU** – Bagnaia S.) (Ligurian Domain=LD); 8- **EU** – Paleogene Flysch U. (L.D.); 9- **CU** – Cretaceous Flysch U. (L.D.), 10- La Serra – Porto Azzurro monzogranite; 11- Neogene aplites and porphyries; 12- Mt. Castello shoshonitic dike; 13- Faults, 14- location of the studied dikes. **LTF**- Madonna della Lacona Thrust Fault **CU/EU**; **PTF**- La Parata Thrust Fault **GU/TN**; **ADF**- Mt. Arco Detachment Fault **TN/MU**; **GDF**- Casa Galletti Detachment Fault **EU/UO**; **ZDF**- Zuccale Detachment Fault All Units/**PU**; **UDF**- Casa Unginotti Detachment Fault **CSS/SSU** and **GU**; **RDF**- Colle Reciso Detachment Fault **VSU/EU**; **FDF**- Fosso dell'Acqua Detachment Fault **BSU/SSU**, **TSU** and **VSU**; **VCF**- Valdana Complex Fault **AU/UO**; **FCT**- Mt. Fico Complex Fault **MU/AU**; *SCF*- St. Felo Complex Fault **OU/GU**; **CTF**- Cima del Monte Transfer Fault; **TTF**- Casa Totano Transfer Fault; **MNF**- Monte Castello Normal Fault; ANF- Acquacavalla Creek Normal Fault; **TNF**- Terranera Normal Fault; **SNF**- St. Caterina Normal Fault; **ONF**; Mt. Orello Normal Fault; **CNF**- Cavo Normal Fault; **DNF**- Cala dell'Alga Normal Fault; **FNF**- Punta del Fiammingo Normal Fault; **MCG**- Mt. Castello graben. (modified from Bortolotti *et al.*, 2001).

below). Before their final emplacement in the Elba's tectonic pile during the 8.5 to 5.1 Ma time interval, some of these units were intruded by two acidic plutons (Mt. Capanne and La Serra-Porto Azzurro monzogranites), and by dikes of variable composition (Marinelli, 1959; Ferrara & Tonarini, 1993; Saupé *et al.*, 1982; Juteau *et al.*, 1984; Serri *et al.*, 1993; Conticelli *et al.*, 2001; Rocchi *et al.*, 2002; Dini *et al.*, 2002; Maineri *et al.*, 2003; Poli, 2004). From bottom to top of the tectonic pile, the units are (Fig. 2):

– **Porto Azzurro Unit** (**PU**). It is made up of phyllites, quartzites and micaschists (Mt. Calamita Fm.), probably of Paleozoic age, with a local Mesozoic cover consisting of metasiliciclastics and crystalline dolostones and dolomitic marbles. PU rocks show a strong static recrystallisation due to the La Serra-Porto Azzurro intrusion and the related aplitic and microgranitic dike network (5.1-5.3 Ma: Saupé *et al.*, 1982; Maineri *et al.*, 2003). The aplitic dikes are cut along the low-angle tectonic contact (Zuccale Fault in Fig. 2) with the overlying embricated stack of units described below.

– **Ortano Unit** (**UO**). It includes metavolcanites (Porphyroids) and quartzitic-phyllitic metasediments (Capo d'Arco Schists) of probably Ordovician age locally intruded by rare aplitic dikes.

– **Acquadolce Unit** (**AU**). It is composed of marbles, grading upwards into calcschists and, finally, into phyllites, metasiltstones and metasandstones with intercalations of calcschists which contain fossils of Early Cretaceous age. At the top of the unit, a metaserpentinite body occurs. The studied Casa Carpini dikes are intercalated in AU in the Monte Arco-Capo d'Arco area.

– **Monticiano-Roccastrada Unit** (**MU**). It largely consists of Upper Carboniferous-Triassic metasiliciclastic rocks (the Permian-Carboniferous Rio Marina Fm. and the Triassic "Verrucano" Group) and locally also of a Jurassic to Oligocene epimetamorphic succession (from the calcschists and cherty limestones to the Pseudomacigno).

– **Tuscan Nappe** (**TN**). South of the locality La Parata, this unit is composed only of calcareous-dolomitic, at times vacuolar, breccias ("Calcare Cavernoso"), while northwards these rocks are overlain by Upper Triassic to Hettangian shallow marine carbonates, and Sinemurian to Dogger carbonatic, siliceous and marly pelagic sediments.

– **Gràssera Unit** (**GU**). This anchimetamorphic unit, possibly of Cretaceous age, mostly consists

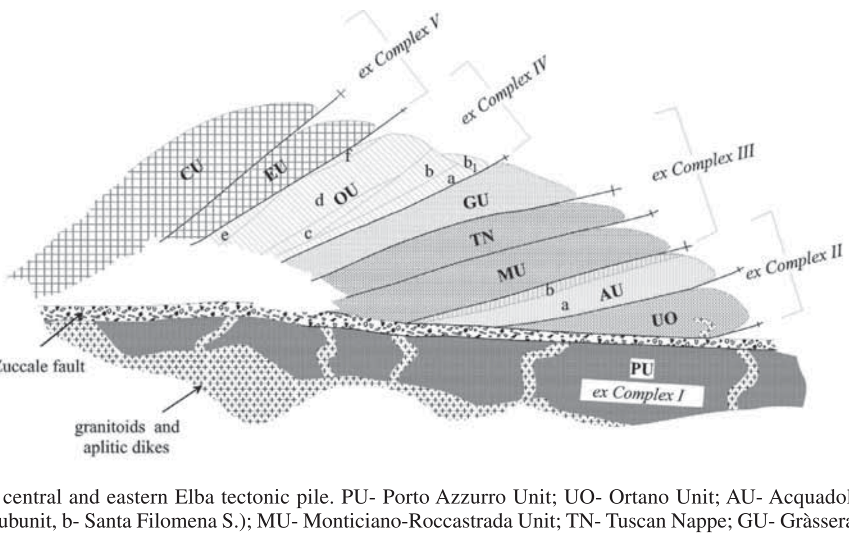


Fig. 2 – The central and eastern Elba tectonic pile. PU- Porto Azzurro Unit; UO- Ortano Unit; AU- Acquadolce Unit (a. Porticciolo Subunit, b- Santa Filomena S.); MU- Monticiano-Roccastrada Unit; TN- Tuscan Nappe; GU- Gràssera Unit; OU- Ophiolitic Unit (a- Acquaviva Subunit; b- Mt. Serra S.; b_1- Capo Vita S.; c- Sassi Turchini S.; d- Volterraio S.; e- Magazzini S.; f- Bagnaia S.); EU- Paleogene Flysch Unit; CU- Cretaceous Flysch Unit (after Bortolotti *et al.*, 2001).

of varicoloured slates with rare carbonate-siliceous and radiolarian cherts intercalations (Cavo Fm.) and a basal Calcschist Member.

– **Ophiolitic Unit** (**OU**). This Ligurian Unit is composed of seven tectonic subunits including serpentinites, ophicalcites, Mg-gabbros, and their Jurassic to Lower Cretaceous volcanic-sedimentary cover (Basalts, Mt. Alpe Cherts, Nisportino Fm., Calpionella Limestones and Palombini Shales). A shoshonitic dike (Mt. Castello Dike: 5.8 Ma, Conticelli *et al.*, 2001) fills ENE-WSW-trending normal faults within OU in the Porto Azzurro area; similar dikes were also present in the Capo Stella promontory, in the central-southern part of the islando (Mt. Capo Stella dikes).

– **Paleogene Flysch Unit** (**EU**). It is constituted by an Eocene succession including shales with calcareous-marly, calcarenitic and arenaceous intercalations and, locally, by ophiolitic-carbonate breccias (Colle Reciso Fm.). Acidic dikes and laccoliths intrude EU and CU (Rocchi *et al.*, 2002; Dini *et al.*, 2002): Aplites (Capo Bianco Aplites: 7.9 Ma), locally sericitised (the so-called “Eurite”: Maineri *et al.*, 2003), and porphyries (Portoferraio Porphyries: 8.2 Ma and San Martino Porphyries: 7.4-7.2 Ma) intrude the sedimentary succession, but do not crosscut the basal contact with the underlying Ophiolitic Unit.

– **Cretaceous Flysch Unit** (**CU**). It consists of a basal tectonised complex, similar to **OU** (ophiolites, basalts and Jurassic-Cretaceous sedimentary cover slices), and of a sedimentary succession formed by Cretaceous Palombini Shales and Varicoloured Shales, which grade upwards into an arenaceous-conglomeratic (Ghiaieto Sandstones) and then to a calcareous-marly-arenaceous Helminthoid-type flysch (Marina di Campo Fm.) of Late Cretaceous Age. Similarly to the EU, this unit is frequently intruded by locally thick acidic dikes and laccoliths (see EU).

This complex stack of oceanic and continental units was originated mainly during the Late Oligocene-Middle Miocene syn-collisional and serrage events of the Apenninic tectogenesis, but it was strongly modified by the following extensional stages (Bortolotti *et al.*, 2001 and references therein). First, it was affected by low-angle normal faulting since? Middle/Late Miocene and continued during Messinian-Pliocene times through detachments (e.g. the Zuccale Fault) due to the intrusion and uplift of the magmatic bodies. High-angle faulting also occurred since the Messinian (e.g. the NW-SE trending transfer fault systems in the OU) and finally dissected the tectonic pile during the Pliocene (e.g. the WSW-NNE and N-S- trending systems locally sealed by hematite ores: Lippolt *et al.*, 1995).

Field data

The two studied outcrops of magmatic rocks are located on the eastern and south-eastern slopes of the Monte Arco (north-east of Porto Azzurro, see location in Fig. 1). These rocks were described for the first time by Trevisan (1950) in the Terra Nera (Casa Carpini)-Monte Arco area and classified as kersantites by Debenedetti (1953). Recently, both dikes were mapped by Morelli (2000) and named Casa Carpini Dikes in the geological map of Babbini *et al.* (2001). Instead Trevisan (1950) and Debenedetti (1953) suggested that these rocks belong to a single dike.

In both outcrops, the dikes display a grey to light-grey colour and a fine-grained-porphyritic texture, and show a strike about E-W and a dip to the south. They fill fractures within the grey-greenish phyllites and metasiltstones with local grey calcschist intercalations of the Acquadolce Unit, generally at middle-high angle respect to the main foliation (S1). The first outcrop (1 in Fig. 1) is about 125 m a.s.l. on the right of the road from Porto Azzurro to Capo Arco, just about 50 meters after the “Capo Arco” residence entrance. Here the magmatic rock appears altered by weathering and Fe-mineralizations and affected by brittle deformations; the second outcrop (2 in Fig. 1) crops out at about 175 m a.s.l. north-eastward of the previous one, for about 15m along a track on the eastern slope of the Monte Arco. In particolar, here the sub-volcanic rock is exposed twice along the track and are moderately altered. The thickness of the dike is variable from 50 cm to about 2 m. The intrusive relationships with the phyllitic-quartzitic country rocks of the Acquadolce Unit are outlined by a light gray, about 20 cm-thick thermometamorphic margin.

PETROGRAPHY AND MINERAL CHEMISTRY

The studied rocks display a microcrystalline porphyritic texture (Fig. 3). The microcrystalline framework consists of plagioclase, biotite, quartz, K-feldspar, and rare muscovite where the mafic mineral phase makes up15 to 23% of the whole rock volume. The feldspar crystals are generally sub-idiomorphic whereas quartz is intercrystalline. K-feldspar is sometimes included in quartz. Fe-Ti oxide and apatite occur as magmatic accessory mineral phases. In this microcrystalline framework, large crystals of quartz and plagioclase, up to 4.5 mm in size, are scattered. The plagioclase crystals are generally subhedral to rounded and show albite-carlsbad and albite twinning; rare plagioclase glomerocrysts with decussate texture are also present. Quartz is represented by rounded, multiple-fractured crystals sometimes showing embayments. Mineral phases appear often altered and, in some cases, replaced by secondary minerals. In particular, feldspars exhibit sericitic alteration and biotite is often altered and chloritized. Moreover, the petrographic observations and the electron microprobe analyses locally reveal also rare zeolites and epidote as alteration minerals.

The composition of the main mineral phases is reported in Tab. 1. Cores of plagioclase phenocrysts display low Anorthite (An) content, in the range 9-23%. Zoning is slight, generally normal. An variability in the plagioclase microcrysts is wider (5-34%), pointing to a less evolved composition (Fig. 4). K-feldspar crystals are represented by orthoclase (Or % = 80-94); biotite has a Mg# in the range 0.54-0.64. Host rocks (see also Elter & Pandeli, 2001) are granolepidoblastic, often quartzitic phyllites with intercalations of granoblastic quartzitic metasandstones and rare calcschists. Their main continuous to millimetric spaced foliation (S1) is made up of quartz+ sericite+chlorite±acidic plagioclase, and apatite, FeTi-oxides, pyrite and graphite as accessory minerals. S1, including intrafoliar muscovite±quartz fishes (pre-S1 foliation), is affected by millimetric-spaced zonal crenulations (S2) which are outlined by the alignment of opaque minerals. Post-tectonic epidote+quartz+chlorite veins are also present. Particularly close to the contacts with the dikes, the metasiliciclastic rocks show evidence of contact metamorphism by blastesis of static, often mimetic biotite. A locally strong, final mineralization of Fe-oxides and hydroxides (veins and infiltrations) is also recognizable.

GEOCHEMISTRY

The studied dikes have been analysed for major, trace element and Sr and Nd isotopic composition;

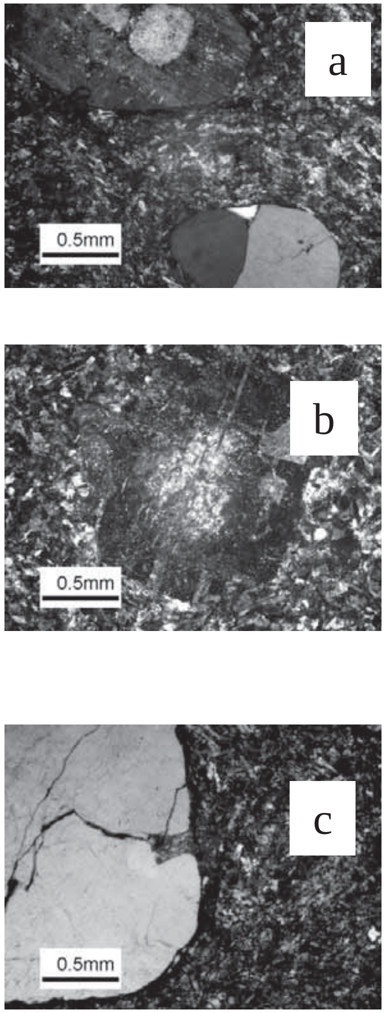


Fig. 3 – a) Cross-polarized light image of the microcrystalline texture; b) Cross-polarized light image of a plagioclase phenocryst; c) Cross-polarized light image of au embayed quartz phenocryst.

TABLE 1 – *Representative chemical analyses of the mineral phases.*

	plagioclase								
	microph	microph	microph	pheno rim	pheno core	pheno rim	pheno inner rim	pheno rim	pheno core
SiO_2	61.8	66.0	68.4	65.7	65.3	70.6	60.8	67.1	67.1
Al_2O_3	24.7	22.2	20.5	22.7	23.1	19.4	25.9	22.0	22.1
Fe_2O_3	0.16	0.05	0.43	0.06	0.10	0.06	–	–	0.02
CaO	5.4	2.4	4.7	3.2	1.9	2.8	7.1	1.6	2.0
Na_2O	8.1	9.8	6.3	9.7	7.6	7.3	7.1	10.7	10.4
K_2O	0.94	0.17	0.36	0.29	1.16	0.83	0.34	0.12	0.17
Sum	101.1	100.6	100.7	101.5	99.2	101.0	101.2	101.5	101.8
An	25.6	11.6	28.7	15.0	11.0	16.2	34.9	7.6	9.5
Ab	69.2	87.4	68.7	83.4	80.9	78.0	63.1	91.8	89.6
Or	5.3	1.0	2.6	1.6	8.1	5.8	2.0	0.7	1.0

	K-feldspar		
	microph	microph	pheno core
SiO_2	64.7	65.2	65.8
Al_2O_3	19.9	19.9	19.2
Fe_2O_3	0.14	0.03	0.03
CaO	0.04	0.77	–
Na_2O	0.56	1.5	0.68
K_2O	14.3	13.1	14.7
Sum	99.6	100.5	100.4
An	0.2	4.0	–
Ab	5.6	14.3	6.6
Or	94.2	81.7	93.4

	phyllosilicate			
	microph	microph	pheno core	microph
SiO_2	37.9	36.6	39.3	35.4
TiO2	0.10	0.32	0.28	0.1
Al_2O_3	19.0	16.7	16.3	18.6
FeO	15.0	17.0	15.2	16.2
MnO	0.40	0.54	0.33	0.63
MgO	13.0	14.8	15.2	15.4
CaO	0.84	0.22	0.38	0.18
Na_2O	1.56	0.09	0.20	0.22
K_2O	2.5	5.5	6.5	3.7
Cr_2O_3	0.01	0.64	0.09	0.07
Sum	90.2	91.7	93.6	90.4
Mg #	60.7	60.8	64.0	62.8

microph = microcrystals; pheno = phenocryst; An = anorthite; Ab = albite; Or = orthoclase.

results are reported in Tables 2 and 3. According to the alkalies-silica classification diagram of Cox *et al.* (1979), the studied rocks can be classified as quartz-diorites (Fig. 5).

The two Casa Carpini dikes are compositionally similar. Only small differences, probably reflecting variable content of quartz and plagioclase phenocrysts, have been observed, both for major and trace elements. Overall, the major composition of these rocks resemble closely intermediate-acid rocks from Elba (Poli, 2004); however, Al_2O_3 is higher, and K_2O is lower. The REE patterns (Fig. 6a) are characterised by fractionated LREE, MREE, and HREE and by negative anomalies of Eu, as observed in several Elba igneous rocks (Dini *et al.*, 2002; Poli, 2004). In Fig. 6a are also

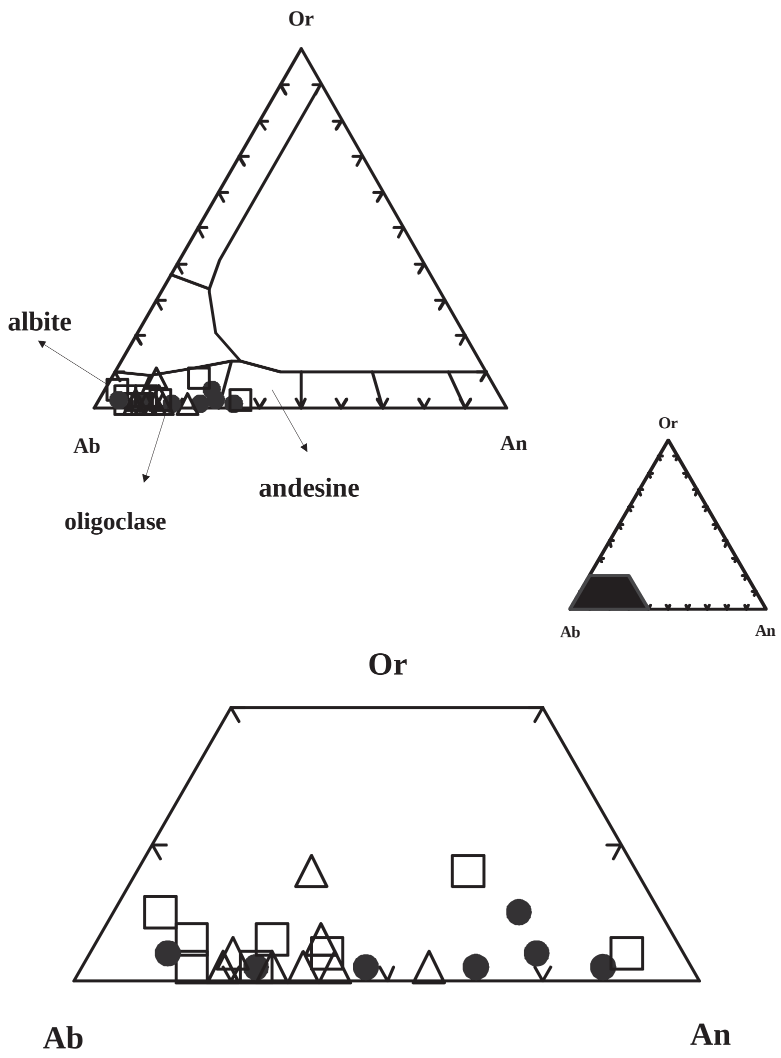


Fig. 4 – Or-Ab-An classification diagram of plagioclase. Open square = rim of phenocrysts, open triangle = core of phenocrysts; filled circle = core of microcrysts.

TABLE 2 – *Major element composition and CIPW norm (wt %).*

Sample	E1	E2
SiO_2	65.83	67.69
TiO_2	0.61	0.50
Al_2O_3	17.27	16.71
Fe_2O_3	2.13	1.62
FeO	1.35	1.35
MnO	0.10	0.08
MgO	1.93	1.90
CaO	2.21	1.98
Na_2O	3.32	3.37
K_2O	2.49	2.05
P_2O_5	0.14	0.14
L.O.I.	2.61	2.62
Quartz	29.77	33.35
Orthoclase	14.71	12.11
Albite	28.09	28.52
Anorthite	10.05	8.91
Corundum	5.43	5.68
Hypersthene	4.81	5.2
Magnetite	2.91	2.35
Hematite	0.12	0.00
Ilmenite	1.16	0.95
Apatite	0.33	0.33

TABLE 3 – *Trace element (ppm) and isotopic (Sr, Nd) composition of Casa Carpini dikes.*

Sample	E1	E2
Be	9	8
V	60	57
Cr	73	69
Co	3.0	1.6
Ni	29	27
Cu	44	40
Rb	109	91
Sr	691	705
Y	19	17
Nb	11	11
Cs	4.8	3.5
Ba	560	392
La	45	42
Ce	87	81
Pr	10	9
Nd	39	36
Sm	7.3	6.7
Eu	1.62	1.27
Gd	6.0	5.5
Tb	0.77	0.71
Dy	4.43	5.74
Ho	0.69	0.61
Er	1.72	1.56
Yb	2.7	2.6
Lu	0.23	0.29
Pb	31	42
Hf	4.0	4.0
Ta	2.6	2.4
Th	23	22
U	10	9
$^{87}Sr/^{86}Sr$	0.711845	0.711769
$^{143}Nd/^{144}Nd$	0.512223	0.512246

shown for comparison the compositions of the Orano porphyries (data from Dini *et al.*, 2002) which display, among the Elba intrusive rocks, some similarities with the Casa Carpini dikes (cfr. their patterns in Fig. 6a) and have a relatively low SiO_2 content. In particular, the Casa Carpini dike patterns in Fig. 6a fall close to the lower boundary of the LREE Orano area. Comparison (not shown) with other Elba magmatic rocks (Mt.Capanne, Capo Bianco, Portoferraio, San Martino; cfr. Dini *et al.*, 2002) reveals a higher LREE and MREE content of the Casa Carpini rocks whereas the HREE content of these latter generally are lower or fall in the range of values found in the compared rocks. The trace element composition of the studied dikes is reported as mantle normalised (Sun and McDonough, 1989) trace element patterns (Fig. 6b). The patterns show high content of the most incompatible elements with a positive spike of Th and Pb, and high LILE/HFSE ratios. Negative spikes of Nb, P and Ti are also observable. Together with the Casa Carpini rocks in Fig. 6b are also reported the compositions of the Orano dikes and Capraia volcanics (data from Dini *et al.*, 2002 and Peccerillo, 2005). Some similarities are observable between the patterns of Casa Carpini dikes and Capraia rocks even if these latter are more enriched in Sr, P, Ti and Y. The analysed dikes, however, display lower K, Rb and Cs than Capraia and especially than Orano, most probably because of the strongest alteration of our rocks, as testified by high LOI. In any case, Ce/Sr ratios are much lower than other magmatic rocks outcropping in the Elba Island (cfr. Dini *et al.*, 2002).

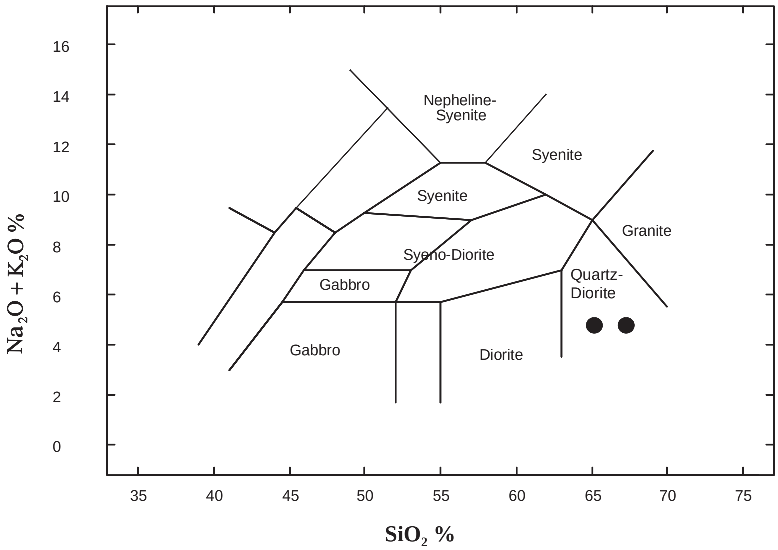


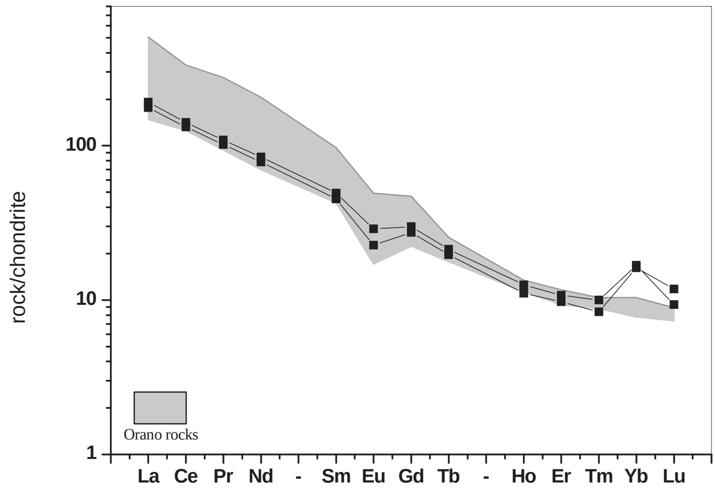
Fig. 5 – Alkalies-SiO_2 classification diagram (Cox *et al.*, 1979) of the studied rocks.

Small but significant differences between the two Casa Carpini rocks exist in the isotopic ratios. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios are respectively 0.711845 and 0.711769 and 0.512223 and 0.512246; these values plot along a hyperbolic curve (not shown) between Capraia calcalkaline rock and crustal anatectic magmas, suggesting a genesis by mixing between these two endmembers. Sr isotopic ratios are slightly lower and Nd isotopic ratios are higher than the bulk of the Elba rocks and plot with the Orano dikes (e.g. Dini *et al.*, 2002).

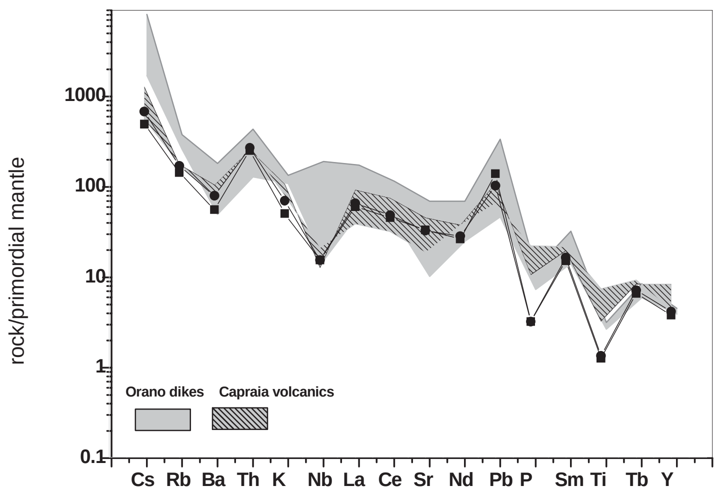
DISCUSSION

The data reported in the previous paragraphs allow the refinement of the magmatic evolution of the eastern Elba Island. First, the term lamphrophyre (i.e. kersantite in Debenedetti, 1953) is not suitable for the Casa Carpini dikes whose mafic content is up to 23% of the whole rock. In fact, according to the IUGS recommendation (Le Maitre, 2002), lamprophyres are porphyritic, mesocratic to melanocratic rocks containing at least 35% of mafic (biotite and/or amphibole, clinopyroxene and olivine) minerals. The Casa Carpini dikes are petrographically different from the dike swarm associated to the Serra - Porto Azzurro Monzogranite (5.1-5.3 5.9 Ma, Saupe *et al.*, 1982; Maineri *et al.*, 2003) which intruded the underlying tectonic units (i.e. the Porto Azzurro Unit and locally the overlying Ortano Unit; Marinelli, 1959; Barberi *et al.*, 1969a,b; Saupe *et al.*, 1982; Bortolotti *et al.*, 2001). The latter dikes consist of whitish K-feldspar-rich aplites and microgranites whereas the Casa Carpini dikes are plagioclase-rich. Also the aplites and particularly the monzogranitic to syenogranitic porphyries, intruded in the EU and CU units show an evident higher content in K-feldspar and quartz and a minor content in biotite (cfr. Dini *et al.*, 2002). Stronger compositional differences can be observed with the mafic shoshonitic Monte Castello dike (5.8 M.a) which was recognized by Conticelli *et al.* (2001) in the Ophiolitic Unit of the Porto Azzurro area. In fact, the Monte Castello dike displays clinopyroxene and olivine phenocrysts set in a groundmass containing clinopyroxene, plagioclase, sanidine and oxides (Conticelli *et al.*, 2001).

On the contrary, Casa Carpini dikes show similarities with other subvolcanic rocks of the western and central Elba island. In particular, the studied dikes resemble the petrographic and geochemical characteristics of the granodiorite to



a)



b)

Fig. 6 – a) Chondrite-normalised REE patterns for Casa Carpini rocks. Normalisation values from McDonough and Sun (1995); b) Mantle-normalised trace element patterns for Casa Carpini rocks. Normalisation values from Sun and McDonough (1989). Source of data: Orano from Dini *et al.*, 2002; Capraia from Peccerillo (2005).

quartz-monzodiorite Orano porphyries (6.85 Ma, Dini and Laurenzi, 1999), the late products of the Mt. Capanne magmatic system (cfr. Dini *et al.*, 2002). Furthermore they show some similiarities also with the Capraia island rocks.

More in general, the petrographic and geochemical characteristics of the studied dikes put them within the intermediate-acid Elba magmatic rocks and other rocks of the Tuscan Magmatic Province (TMP). The TMP is characterised by a large variety of intrusive and effusive rock types closely associated in space and time. This complex rock association has been divided into three main groups (Poli, 2004): 1) mafic rocks, dikes and mafic-intermediate enclaves; 2) intermediate-acid rocks and 3) silicic rocks. The first group is compositionally complex and consists of calcalkaline, shoshonitic to lamproitic types (Peccerillo, 2005 with references). The second group of rocks generally displays evidence of mixing processes whereas the silicic rocks exhibit typical characteristics of crustal derived melts without mixing evidence. The composition and texture of quartz, plagioclase and K-feldspar phenocrysts contained in the Casa Carpini rocks allow to hypothesize a xenocrystic origin for these crystals which, thus, represent evidence of interaction between mafic and silicic magmas, a process that affected the bulk of Elba and Tuscany acid-intermediate magmatism (Poli *et al.*, 1989; Dini *et al.*, 2002; Rocchi *et al.*, 2002; Poli, 2004). Crystals of quartz and feldspars possibly have been "included" in the magma in a solid state by a mingling mechanism. The rounded edges of the quartz crystals are thus the effect of reaction between crystals and molten magma.

The Elba magmatism emplaced, between about 8 and 6.5 Ma, magmas from crust- to hybrid- to mantle-dominated. The Casa Carpini porphyritic dikes closely resemble the composition of the Orano products, interpreted as strongly modified mantle magmas, variably hybridized by mixing with crustal material, during their ascent to the surface. These magmas represent some of the least contaminated by crustal anatectic melts, displaying relatively low Sr and high Nd isotopic signatures (Dini *et al.*, 2002). The composition of the mantle magma has been hypothesised similar to the Capraia island K-andesites (Dini *et al.*, 2002). The petrographic and geochemical similarities between the Casa Carpini dikes and the Orano dikes could suggest a similar magmatic history by mixing-mingling, with an important role of mafic end-members.

A still unresolved problem is the age of the Casa Carpini dikes. Unfortunately, the high alteration degree of the studied dikes made impossible a radiometric dating. The studied rocks do not show any evidence of foliation but they crosscut the main foliation of the Acquadolce phyllites and metagreywackes which was dated 19 Ma by Deino *et al.*, 1992. Is not clear if these dikes end or crosscut the basal contact with the Ortano Unit and the underlying Zuccale Fault due to the lack of outcrops of such peculiar dikes in the lower part of the Acquadolce Unit in the Capo Arco-Terranera area. In the former case they could represent, as the Monte Castello dike, the evidence of a post - 19 Ma/ ?pre – 5.9 Ma intrusion event which was later unrooted by the detachements connected to the emplacement and the uplift of the Serra - Porto Azzurro magmatic body. In any case, the Fe alterations of the Casa Carpini dikes suggest that their emplacement occurred pre-5.3 Ma (age of the Fe ores of the Terranera area, Lippolt *et al.*, 1995).

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Our beloved colleague and friend Filippo Olmi gave us help and suggestions during the electron microprobe analyses. He passed away still in a very young age, leaving us with deep sadness. We will ever remember him.

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Appendix

Phase compositions were determined by a Jeol JXA-8600 electron microprobe operating at 15 kV and 15 nA and equipped with a Series II Tracor Northern system. Corrections for matric effects were made according to the method of Bence and Albee (1968). Major element composition was obtained by combined wet chemical technique (Na_2O, MgO, FeO, L.O.I.) and X-Ray Fluorescence.

Trace element analyses were determined by ICP-OES and ICP-MS at the SGS laboratory, Toronto, Canada, using the following procedure: 0.10 g of crushed and pulverized rock samples are fused by Sodium peroxide in graphite crucibles and dissolved using dilute HNO_3. During digestion the sample is split into 2 and half is given to ICP-OES and the other half is given to ICP-MS. The digested sample solution is aspirated into the inductively coupled plasma Mass Spectrometer (ICP-MS) where the ions are measured and quantified according to their unique mass and the other half aspirated into the inductively coupled plasma Optical Emission Spectrometer (ICP-OES) where the atoms in the plasma emit light (photons) with characteristic wavelengths for each element. This light is recorded by optical spectrometers and calibrated against standards. Precision is better than 10%.

Sr and Nd isotope analyses were performed at the Department of Earth Sciences, University of Firenze. Sample powder (20mg) was dissolved in a HF–HNO_3–HCl mixture. Sr and Nd fractions were separated following standard chromatographic techniques using AG50x8 and PTFE–HDEHP resins with HCl as eluent. The total procedural blank was < 200 pg for Sr and < 100 pg for Nd, making blank correction negligible. Mass spectrometric analyses were performed on a Thermo Finnigan Triton-Ti thermal ionization mass spectrometer equipped with nine movable collectors. Sr and Nd isotope compositions were measured in dynamic mode and are reported normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, respectively. Exponential-law mass fractionation correction was used for all Sr and Nd isotopic data. Uncertainties in measured (m) and initial (0) isotopic ratios refer to the least significant digits and represent ±2σ run precision and ±2σ propagated error, respectively. The external precision of NIST SRM987 was $^{87}Sr/^{86}Sr = 0.710250 \pm 6$ (2σ, n =5), and that of the La Jolla standard was $^{143}Nd/^{144}Nd = 0.511847 \pm 5$ (2σ, n = 6).