Field Trip Guide Book - P61

Volume n° 6 - from P55 to PW06

ITALIA 2004

32nd INTERNATIONAL GEOLOGICAL CONGRESS

MONTE ARGENTARIO AND ISOLA DEL GIGLIO (SOUTHERN TUSCANY, ITALY): A RECORD FROM CONTINENTAL BREAK-UP TO SUBDUCTION, OROGENIC WEDGE FORMATION, AND POST-OROGENIC EXTENSION

Leaders: J. Reinhardt, F. Rossetti

Florence - Italy
August 20-28, 2004

Post-Congress **P61**

The scientific content of this guide is under the total responsibility of the Authors

Published by:
APAT – Italian Agency for the Environmental Protection and Technical Services - Via Vitaliano Brancati, 48 - 00144 Roma - Italy

APAT
Italian Agency for Environment
Protection and Technical Services

Series Editors:
Luca Guerrieri, Irene Rischia and Leonello Serva (APAT, Roma)

English Desk-copy Editors:
Paul Mazza (Università di Firenze), Jessica Ann Thonn (Università di Firenze), Nathalie Marléne Adams (Università di Firenze), Miriam Friedman (Università di Firenze), Kate Eadie (Freelance indipendent professional)

Field Trip Committee:
Leonello Serva (APAT, Roma), Alessandro Michetti (Università dell'Insubria, Como), Giulio Pavia (Università di Torino), Raffaele Pignone (Servizio Geologico Regione Emilia-Romagna, Bologna) and Riccardo Polino (CNR, Torino)

Acknowledgments:
The 32nd IGC Organizing Committee is grateful to Roberto Pompili and Elisa Brustia (APAT, Roma) for their collaboration in editing.

Graphic project:
Full snc - Firenze

Layout and press:
Lito Terrazzi srl - Firenze

Volume n° 6 - from P55 to PW06

32nd INTERNATIONAL GEOLOGICAL CONGRESS

MONTE ARGENTARIO AND ISOLA DEL GIGLIO (SOUTHERN TUSCANY, ITALY): A RECORD FROM CONTINENTAL BREAK-UP TO SUBDUCTION, OROGENIC WEDGE FORMATION, AND POST-OROGENIC EXTENSION

AUTHORS:
J. Reinhardt (University of Natal - South Africa)
F. Rossetti (Università di Roma Tre - Italy)

Florence - Italy
August 20-28, 2004

Post-Congress

P61

Front Cover:
Extensional shear zone in layered marble at Cala Moresca. Asymmetrical shear bands and sigmoidal structures indicate sinistral sense of shear (top of the east)

Leaders: J. Reinhardt, F. Rossetti

Introduction

Blueschist-facies mineral assemblages have been known for a long time from metabasites of the Monte Argentario promontory and from two islands of the Tuscan Archipelago, Giglio and Gorgona. The presence of blue amphiboles had been recorded more than a hundred years ago, even though the implications in terms of pressure-temperature conditions were obviously recognised only much later (e.g., Ricci, 1972). As the classic Ligurian ophiolites on the Italian mainland do not contain such assemblages, the high-pressure rocks had been considered a curiosity.

Since then, a much improved understanding of mineral assemblages and mineral reactions as well as a systematic approach in characterising the metamorphism of continental-derived sedimentary rocks has contributed to establish a more comprehensive picture of orogenic regional metamorphism in the Northern Apennines. Findings of ferro-magnesian carpholite in particular (Theye et al., 1997; Jolivet et al., 1998; Rossetti, 1999) demonstrated that high-pressure, low-temperature metamorphism is by no means a matter of rare local occurrences, but, apart from metabasites, is rather widespread in continental-derived units such as the Triassic Verrucano Group.

Furthermore, detailed structural and geochronological studies have paved the path for larger-scale correlations and tectonic modelling of the Northern Tyrrhenian region. It was recognised that the high-pressure units have a protracted history of deformation (prograde and retrograde) and that some of the prominent structures seen in outcrop relate to exhumation and crustal stretching rather than the preceding subduction and crustal thickening events (Jolivet et al., 1998). It was also recognised that the extension-related structures can be traced into the young felsic intrusives such as the Giglio monzogranite (Rossetti et al., 1999).

Thus, since the first extensive field study carried out on the Monte Argentario and the island of Giglio by Lazzarotto et al. (1964) - which is still an essential basis for any new studies - the Cainozoic tectono-metamorphic history has become much more transparent. The present data of these and related areas add important constraints on the reconstruction of the geodynamic evolution of the Tyrrhenian-Northern Apennine region. More generally, they provide valuable insight into the compression-extension dynamics of orogens, and how this is reflected in the rock record.

The field trip visits two locations, Monte Argentario and Isola del Giglio. These areas played a pivotal role in the more recent re-investigations of the tectono-metamorphic history of the Northern Apennines - Tyrrhenian Sea - Corsica region, not least by being a geological link between Alpine Corsica to the west and the main Northern Apennines belt to the east. The focus of the excursion will be on petrological and structural aspects of a variety of rock types, including Triassic continental to marine rocks, Jurassic ophiolites, and Tertiary intrusives. The particular significance of mineral assemblages, prograde and retrograde, and of related structures will be emphasized, and their contribution to the understanding of the larger-scale crustal dynamics will be discussed.

Logistical note: General access to the areas by road is good as these are popular tourist destinations. The unfortunate consequence of this popularity and of the exceptional beauty of these places is that access to specific sites has become increasingly difficult in recent years due to housing development and the establishment of numerous luxurious private holiday mansions along the coast, particularly at the Monte Argentario. The fact that Giglio Island is a nature reserve will hopefully prevent this type of development, not just for the benefit of geological field work.

Literature references: see end of guide

Map reference:
Gianniello, G., Lazzarotto, A. and Mazzanti, R. (1964). Carta geologica del Monte Argentario e del Promontorio del Franco (Isola del Giglio) 1: 25000 (supplement in: Lazzarotto, A., Mazzanti, R. and Mazzoncini, F. (1964). Geologia del Promontorio Argentario (Grosseto) e del Promontorio del Franco (Isola del Giglio - Grosseto). *Boll. Soc. Geol. Ital.* 83 (2), 1-124)

The following section gives an overview on the geological evolution of the region and presents a synthesis of data in form of a regional-scale geodynamic model.

Regional geological setting

This summary is to a large extent based on the review by Rossetti et al. (2002) and the paper of Jolivet et al. (1998). Please consult these publications for further references.

The overprinting of tectonically thickened crust by extensional processes characterises the Cainozoic history of many Alpine belts in the Mediterranean region. As lateral crustal movements are still active today in some of the belts, the present distribution of zones of compression versus zones of extension in conjunction with the late Cainozoic tectonic history of these terrains can provide clues to the coupling of, and inversions between, compressional and extensional processes as the orogen evolves.

A common feature on the neo-tectonic map of the Mediterranean (being essentially a snapshot of nothing more than a transient state of late Alpine tectonics) is extension in the back-arc domain of subduction zones (Figure 1). In such back-arc domains, remnants of high-pressure (HP) metamorphic complexes show HP ages only marginally older than their extensional overprint (typically 10-20 Ma for the Tyrrhenian-Tuscan region; see also below). As subduction zones progressively migrate towards external parts of orogens, the back-arc domain shifts into the previously thickened orogenic zones leading to post-orogenic extension. In such circumstances, crustal thinning will be to a large extent tectonically controlled, and the development of major extensional detachments may contribute to the rapid exhumation of previously deeply buried parts of these orogens.

Accordingly, the present Tyrrhenian-Apennine system (Figure 2) developed as a consequence of Tertiary post-orogenic processes located at the back of the growing and eastward migrating Apennine compressional belt (Faccenna et al., 2001). Extensional reworking of the compressional architecture led to extensive thinning of the previously thickened crustal section and omission of large parts of the tectono-stratigraphic sequence, from the Late Miocene onwards. Extension and crustal thinning are characterised by the development of spaced crustal shear zones, sedimentary basins and magmatic activity.

There is a distinct west-to-east younging trend in felsic magmatism and in the onset of basin sedimentation (Figure 3). Magmatic bodies have been dated from 14 Ma in Corsica to 2 Ma in Tuscany, and even younger further east). The centres of extensional basins as well as magmatic centres shifted eastwards at an average velocity of 1.5 - 2 cm/a. Structural and seismic data indicate eastward-dipping extensional shear zones, both brittle and ductile.

The tectono-stratigraphic units most strongly affected in terms of reworking by the late extensional processes are those originally deeply buried and later exhumed.

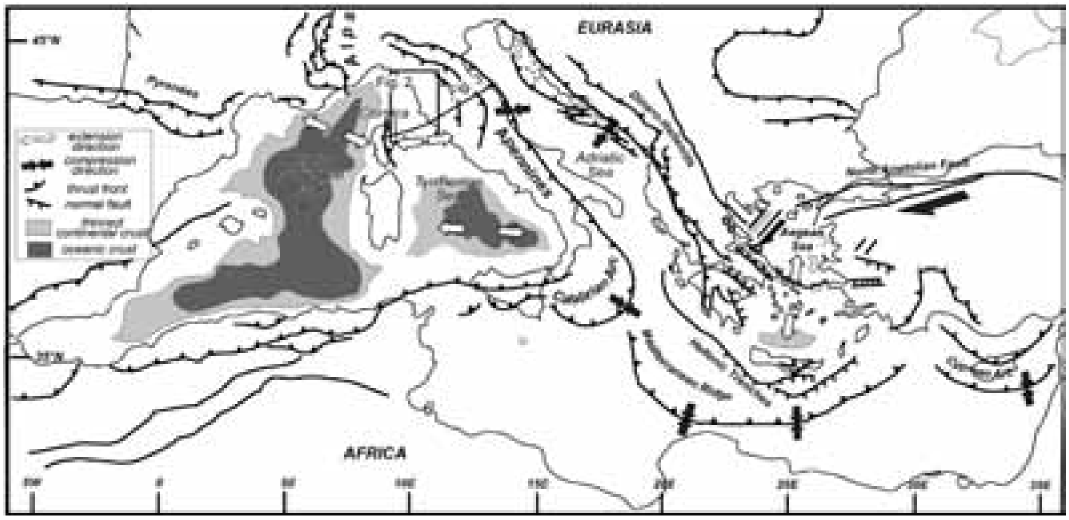

Figure 1 - Simplified tectonic map of the Mediterranean area (from Jolivet et al., 1998). Box shows area of Figure 2.

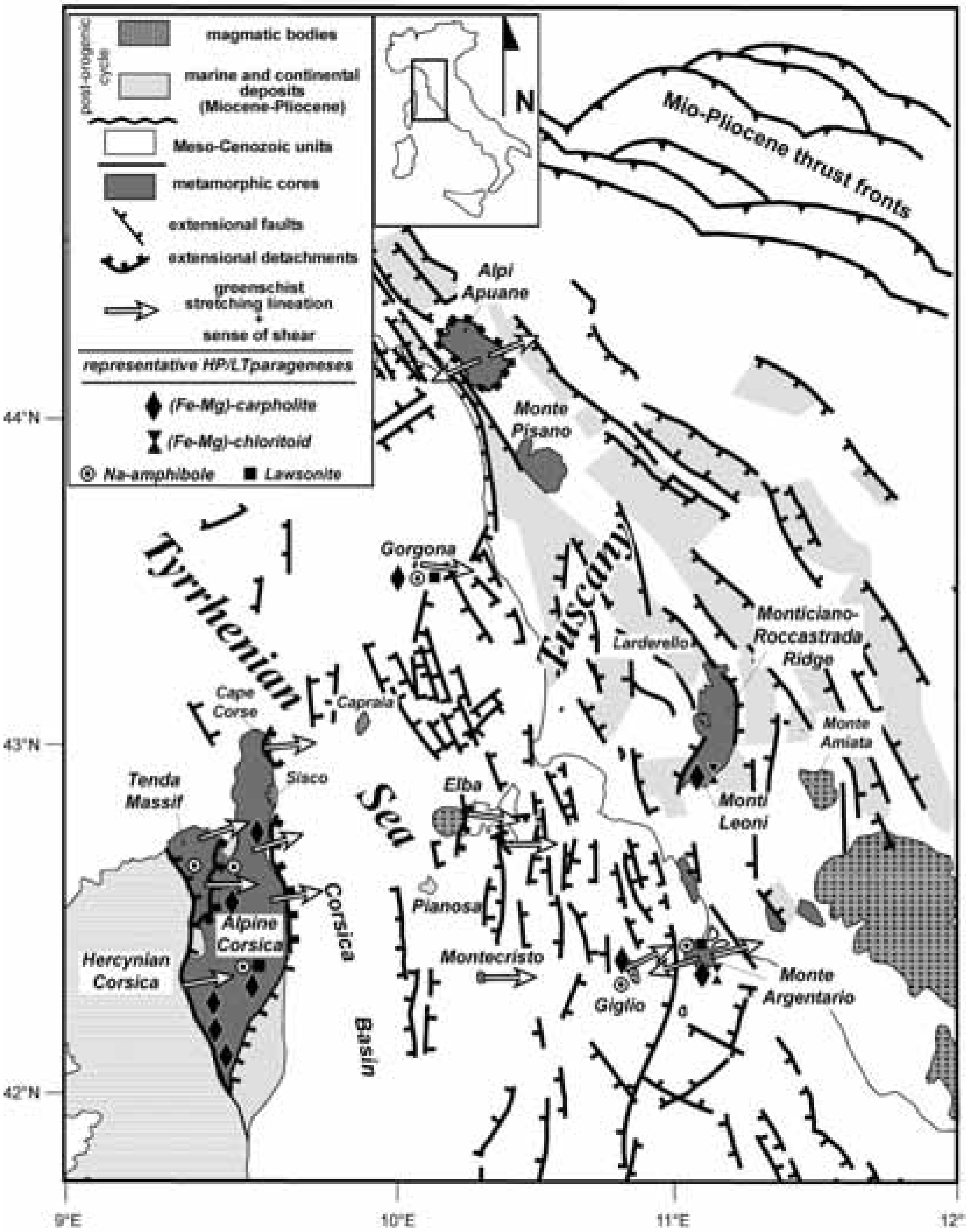

Figure 2 - Tectonic map of the northern Tyrrhenian area with occurrences of high-pressure, low-temperature minerals (from Rossetti et al., 2002, after Jolivet et al., 1998). Arrows show the direction of stretching and sense of shear within the major extensional shear zones (hanging-wall movement).

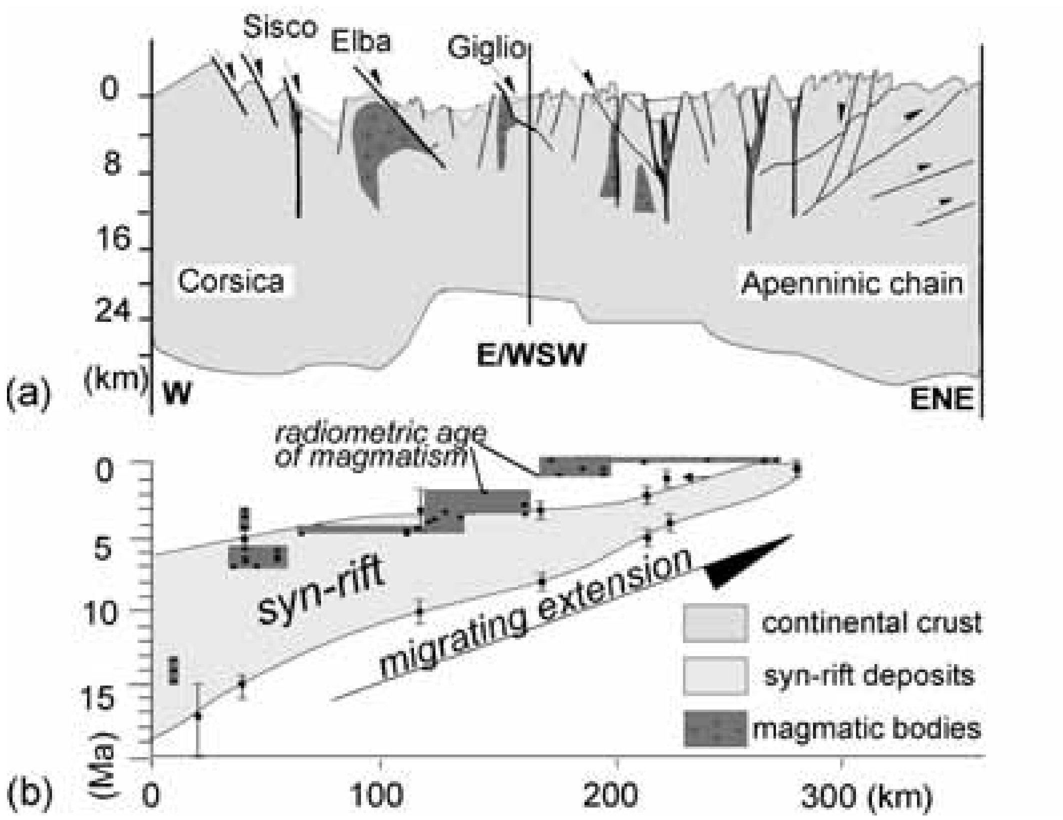

Figure 3 - (a) Crustal-scale cross-section and (b) age-distance diagram of magmatic activity and syn-rift deposits along the transect shown in Figure 1 (from Rossetti et al., 2002).

Occurrences of high-pressure meta morphic rocks are distributed between north-eastern Corsica and western Tuscany, and represent the interior part of the original orogen predating the opening of the Tyrrhenian Sea. These remnants of early subduction and accretion include the eclogite and blueschist terrain of Alpine Corsica, Gorgona Island, western Giglio, Monte Argentario as well as mainland occurrences of HP-LT rocks (such as Monticiano-Roccastrada and Monti Leoni). The structural-metamorphic record of these units provide crucial data for the reconstruction of the geodynamic processes shaping the Apennines-Tyrrhenian region, and in particular for the transition from crustal thickening to subsequent extension.

On the Tuscan side, these metamorphic complexes consists mainly of Triassic and Jurassic continental- to oceanic-derived rocks. Their metamorphic histories are characterised by a greenschist to sub-greenschist facies overprint on early high-pressure assemblages, with some oceanic rocks preserving an even earlier record of syn-rifting sub-seafloor metamorphism. Peak P-T conditions and exhumation paths for a range of localities are shown in Figure 4. Decompression paths generally remain on the low-temperature side, thus favouring the preservation of the HP/LT mineral Fe-Mg-carpholite. From northeastern Corsica to Southern Tuscany, two trends in metamorphism can be observed: the age of HP metamorphism becomes progressively younger (from about 60 Ma in Corsica to about 20 Ma in Tuscany), indicating an eastward migration of the subduction suture, while the peak pressures decrease from west to east (Figure 4).

The significance of tectonic processes following the stage of deep burial is expressed by the fact that the dominant planar and linear structures seen in many localities are exhumation-related. Early foliations and lineations are preserved, but strongly overprinted. The retrograde stretching lineations are on average roughly east-west oriented (Figure 2). The dominant sense of shear in rocks of bulk non-coaxial deformation, in

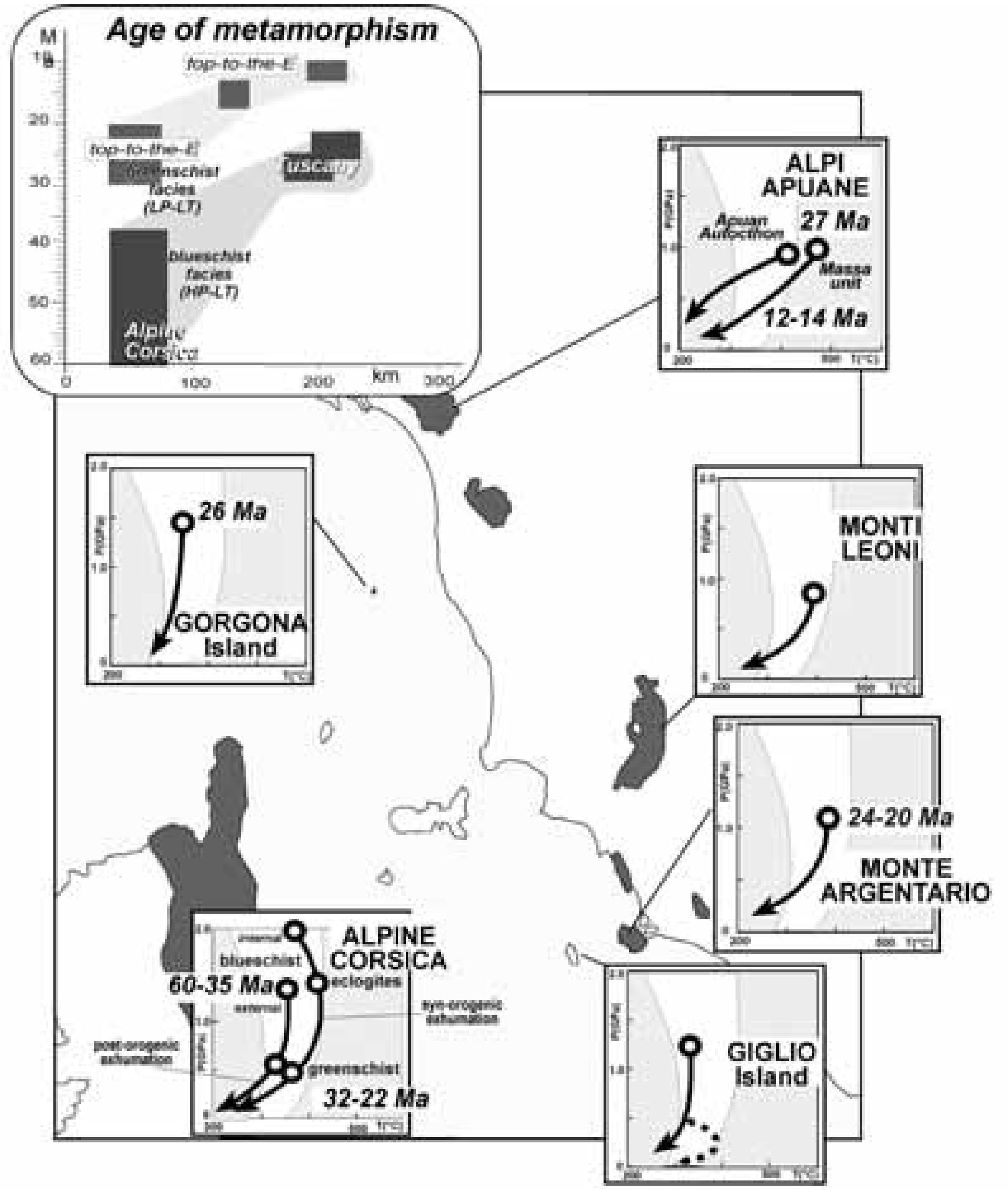

Figure 4 - P-T exhumation paths for metapelites in the northern Tyrrhenian region (from Rossetti et al., 2002; after Jolivet et al., 1998, and references therein). The insert shows an age-distance diagram for the main metamorphic events along the transect shown in Figure 1 (after Brunet et al., 2000).

shear zones and on extensional detachments is top-to the-east.

A critical point in the tectonic interpretation of the stratigraphic, structural and metamorphic record is the mode of closure of the Ligurian ocean. Earlier models suggested a flip of subduction zones, mainly to explain the westward verging structures of Alpine Corsica and the eastward verging structures of the Apennines, and to account for the fact that remnants of the Ligurian oceanic crust are found on both sides of the Tyrrhenian Sea (cf. Figure 5). It was further assumed that the HP-metamorphic complexes formed during the earlier Alpine event (i.e., eastward subduction), thus correlating with the HP complexes of the Western Alps. The non-HP-metamorphic ophiolites of the Northern Apennines (i.e., the Ligurides) were then obducted and incorporated in the nappe pile created during westward subduction and final closure of the Ligurian-Piemontese ocean.

However, a simpler plate-tectonic model appears to be better suited to explain the continuity of the structural-metamorphic evolution, the present distribution of high-pressure rocks in the Tyrrhenian-Apennine region, the record of late Cainozoic felsic magmatism, and the sedimentary record from the Late Cretaceous to the Lower Pleistocene (Figs. 5, 6). This model proposes continuous westward subduction since the Palaeocene, with the subduction suture originally placed at the European continental margin (i.e., Corsica; Figure 6A). The subduction process started with the oceanic crust, and, once the Ligurian-Piemontese oceanic basin had closed, continued with underthrusting of the Adria margin beneath the European continental margin (Figure 6B).

During continent-to-ocean orogenesis, a double-verging orogenic wedge formed at the Sardinia-Corsica continental margin. As the two continental

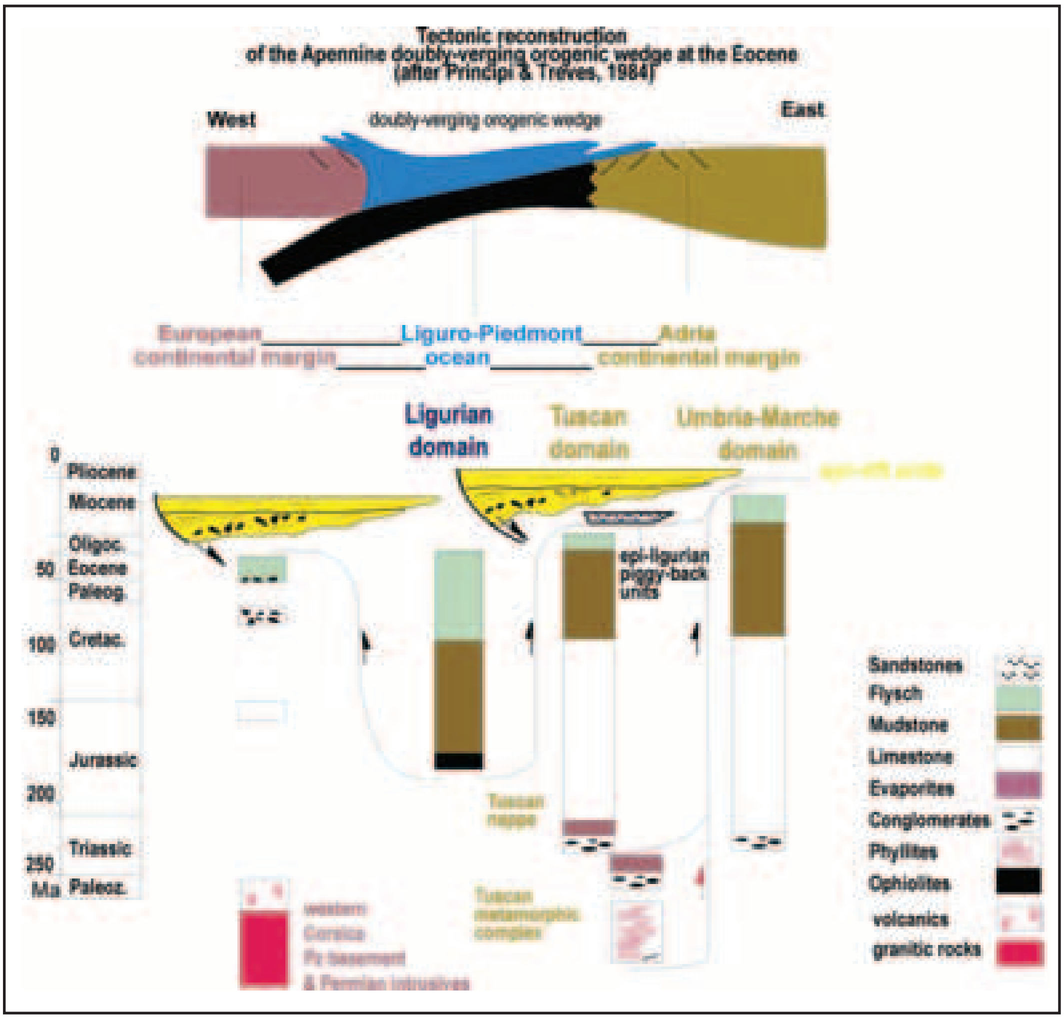

Figure 5 - Diagrammatic stratigraphic columns of the Corsica-Apennines area with tectonic transport directions indicated, and reconstruction of the early-stage orogenic wedge between Corsica and Northern Apennines (from Jolivet et al., 1998).

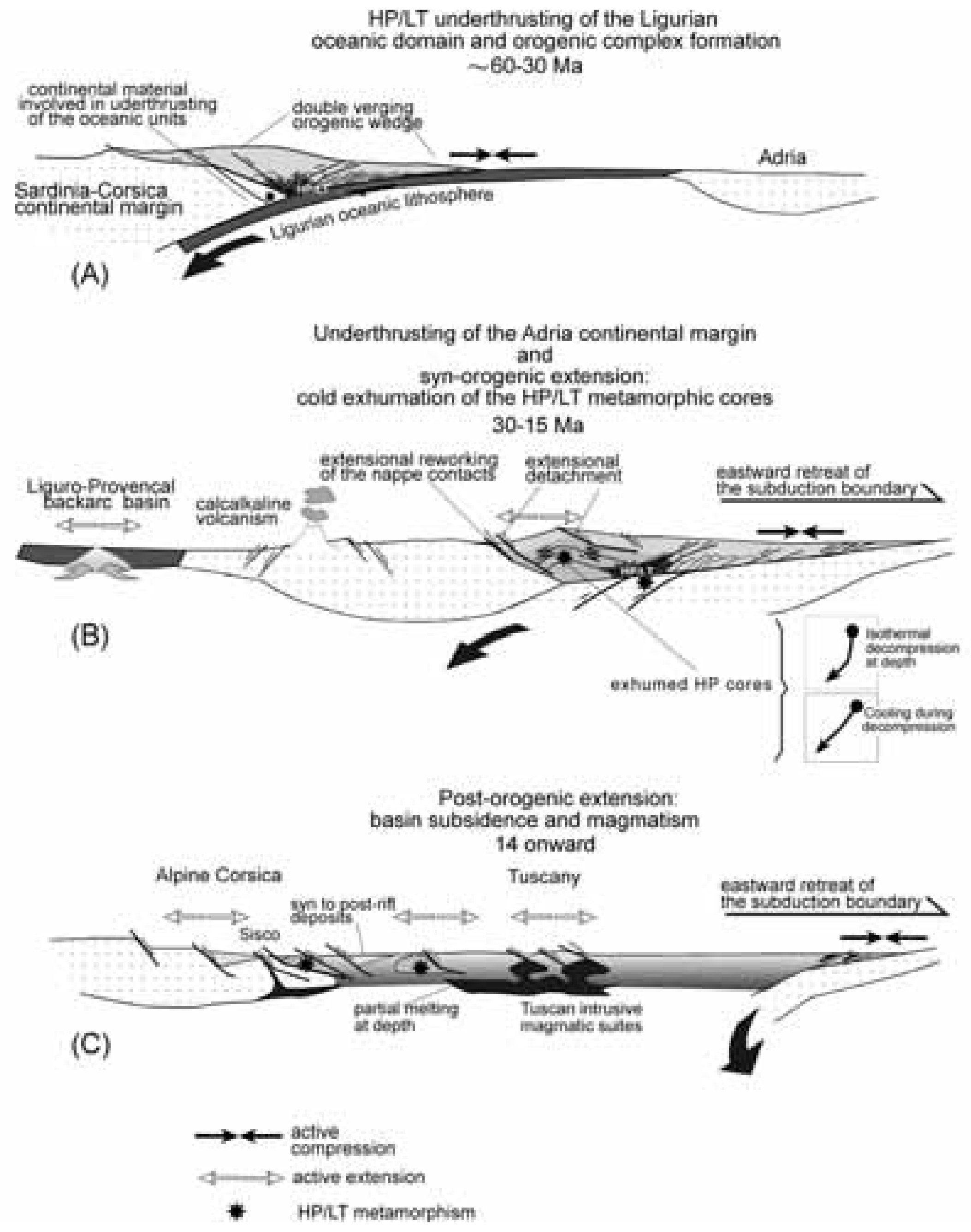

Figure 6 - Schematic three-stage 2-D geodynamic model summarising the Tertiary tectonic evolution of the region between Sardinia-Corsica and the Adria continental margin (from Rossetti et al., 2002; modified after Jolivet et al., 1998). The position of the deep-seated metamorphic rocks exposed in the interior of the Northern Apennines is indicated. (A) Formation of the thick-skinned, doubly-vergent orogenic wedge during the consumption of the Ligurian-Piemontese oceanic domain beneath the European margin. (B) Underthrusting of cold Adria continental margin; syn-orogenic extension and exhumation in the interior domain of the orogen. (C) Post-orogenic back-arc extension caused by the progressive eastward retreat of the Apennine subduction boundary; crustal thinning and magmatism.

margins collided, the overthickened orogenic wedge started to collapse with the effect of progressively exhuming HP-LT units, while HP-metamorphism was still active in more external domains (Adria margin). Continued underthrusting prevented thermal relaxation in the overlying rocks, thus promoting relatively cold exhumation paths. Exhumation during active convergence resulted in reworking and tectonic mixing of the various metamorphic and non-metamorphic units in the orogenic wedge, leading to juxtaposition of units with very different structural-metamorphic signatures, as we see it in the field today.

The onset of back-arc extension behind the externally migrating compressional front affected the orogenic pile from Mid- to Late Miocene onwards (Figure 6C). This period is characterised by crustal thinning and subsidence of the peri-Tyrrhenian basins. In the internal parts of the back-arc domain, thermal relaxation set in which caused local partial melting. Such anatectic melts, mixed with sub-crustal magmas, provided the source for the igneous rocks of the Tuscan Magmatic Province. Crustal thinning and magmatism were controlled by east-dipping ductile to brittle extensional faults and shear zones.

The exhumation of HP rocks is therefore a two-stage process, the first stage being syn-orogenic (i.e., orogenic wedge collapse), and the second being post-orogenic back-arc extension. Due to tectonic transport in opposite directions during formation of the double-verging orogen and due to the subsequent opening of the Tyrrhenian Sea, the rock complexes originating from the deep parts of the orogenic wedge are now widely spread between eastern Corsica and the Apennines.

Field itinerary

General note

Please be aware that some outcrops are on private

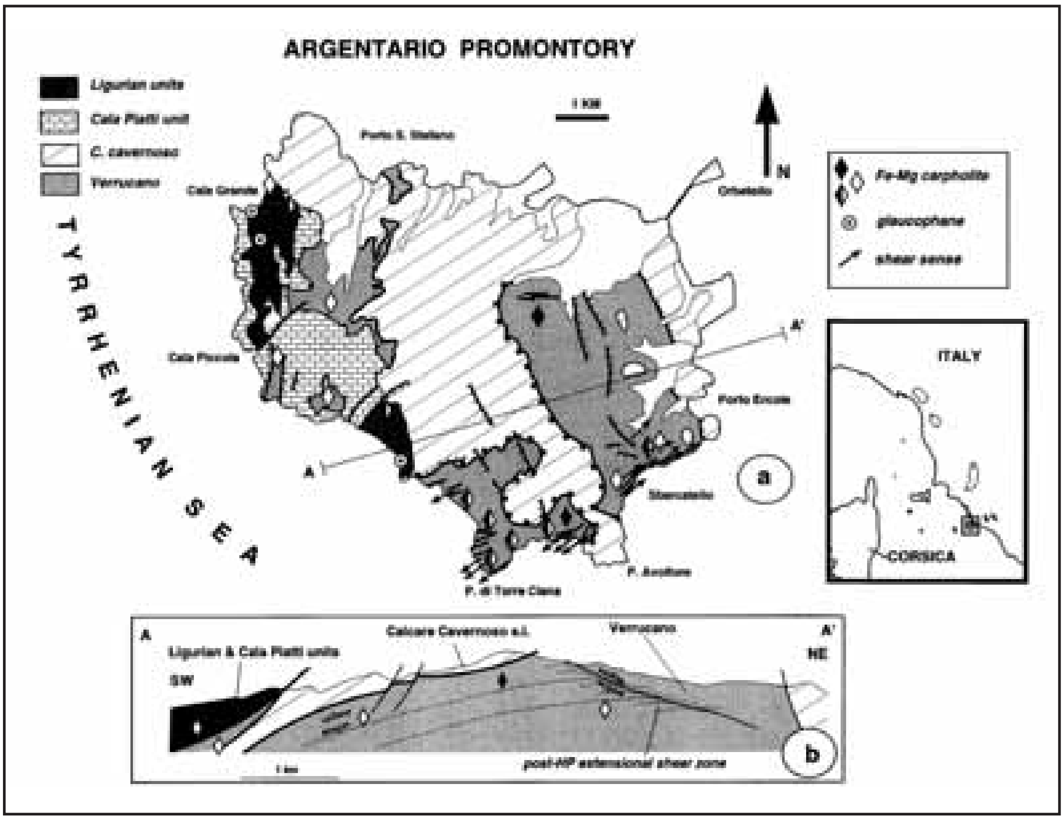

Figure 7 - (a) Structural map of the Monte Argentario and (b) cross-section (from Jolivet et al. (1998). Occurrences of high-pressure minerals are indicated.

property for which an explicit permission to enter is required. Hammering and sampling may be restricted in such cases. Sampling is not permitted in general on the Island of Giglio as it is a nature reserve. We will try to get a special permission, though, for the members of the field trip.

DAY 1

South-eastern Monte Argentario

General overview and program of day 1:

- Introduction to the geological setting and tectonic evolution of the Northern Apennines
- Verrucano outcrops: petrological evidence for HP/LT metamorphism; structural overprinting during late- and post-orogenic processes

Two geological units, Verrucano and Calcare Cavernoso, dominate the geological map of the central and eastern part of the Monte Argentario Promontory (Figure 7; Lazzarotto et al. 1964). In addition, there are minor occurrences of Palaeozoic metasediments. The term "Verrucano" describes a terrestrial to coastal-marine facies which is characteristic for the base of the Alpine sedimentary cycle. In the Northern Apennines, the Verrucano has a Mid-Triassic age. The Calcare Cavernoso is essentially a "pitted" calcarous rock of grey colour that lacks primary bedding structures. Its origin has been a matter of debate - sedimentary (representing Late Triassic evaporites) versus tectonic - and perhaps both is true. Its tectonic significance lies in the fact that it forms the detachment zone of the Tuscan Nappe, which overrides the Tuscan "basement" units, including the Verrucano (Figure 5).

Whereas the rocks of the Tuscan Nappe are very low-grade metamorphic to non-metamorphic, the Verrucano Group rocks contain low-grade metamorphic minerals such as pyrophyllite, sudoite, chloritoid, and Fe-Mg-carpholite (Theye et al., 1997; Jolivet et al., 1998). In conjunction with observations on reaction textures, these minerals have been used to characterise metamorphism and constrain P-T paths. The discovery of ferro-magnesian carpholite in particular (X_{Mg} = Mg/(Mg+Mn+Fe^{2+}) = 0.36 - 0.70) demonstrated that the Verrucano Group of the east-central Monte Argentario had experienced HP-LT conditions similar to those derived from metabasites in the west (Theye et al., 1997). The P-T path shows peak conditions of at least 8 kbar and about 350°C, followed by isothermal decompression to less than 5 kbar at about 350°C, before major cooling set in. This reflects the transition from maximum tectonic thickening (orogenic wedge) to fast decompression (extensional low-angle shear zones and faults).

Itinerary for day 1: Drive from Florence to Orbetello and Monte Argentario. Arrive at Porto Ercole late in the morning. Drive on Via Panoramica to Forte Filippo on La Rocca. Continue on Via Panoramica to a lunch stop at the Bar Le Viste (Stop 1.1) for a geological introduction. Drive southwest on Via Panoramica to examine road cuts near Fortino Stella (Stop 1.2). Continue along Via Panoramica towards Torre dell Avoltore. Take downhill footpath from Via Panoramica to outcrops on hillside (Stop 1.3).

Stop 1.1:

Bar Le Viste, Via Panoramica, opposite the small island of Isolotto.

General introduction to the geological setting and tectonic evolution of the Northern Apennines. Geological significance of the Monte Argentario - Giglio region in the Northern Apennines tectono-metamorphic framework.

Stop 1.2:

Road cuttings on Via Panoramica, southeast of Fortino Stella

The outcrops show meta-conglomerates ("anageniti") and psammo-pelitic rocks typical of the Mid-Triassic Verrucano Group. The strata are steeply dipping, forming part of a large F_2 fold structure. The S_2 axial planar cleavage is at a low angle to S_0 in the pelitic layers, but is strongly refracted as it cuts across more competent psammitic beds. Typical metamorphic mineral assemblages of this locality are muscovite-pyrophyllite-paragonite-quartz ± chlorite ± sudoite in Al-rich rich phyllites, locally with chloritoid, and muscovite-quartz ± chlorite ± sudoite ± chloritoid in Al-poorer varieties (Costantini et al., 1995). As in so many other localities, the high-pressure indicator mineral carpholite had escaped everyone's notice until recent years. However, in this particular outcrop, carpholite occurs only locally as remains. Retrograde breakdown products now replace much of it.

Stop 1.3:

Hillside outcrops below Via Panoramica, west of Torre dell' Avoltore

Exposed are psammopelitic rocks of the Verrucano Group. Colourless to green carpholite fibres can be observed in Verrucano beds as well as in quartz veins. The fibres define a distinct mineral lineation

L_1. Subsequent D_2 overprinting, characterised by tight folds with an S_2 axial planar foliation resulted in transposition of the early carpholite fabric. As can be seen in outcrop-scale D_2 fold structures, carpholite fibres are folded around the F_2 fold hinges.

DAY 2

Isola del Giglio

General overview and program of day 2:

- High-pressure, low-temperature metamorphism and subsequent retrogression in Verrucano rocks; overprinting of peak-metamorphic fabrics by exhumation-related fabrics
- Giglio Monzogranite Intrusion: from late magmatic fabrics to solid-state deformation

The larger part of Giglio Island consists of Pliocene monzogranite intrusions. Metamorphic and sedimentary rocks of Jurassic to Triassic age form the small Franco Promontory on the western side (Lazzarotto et al. 1964) (Figure 8). The island is a unique site to study the link between the syn- and the post-orogenic processes that affected the internal portions of the northern Apennine orogenic wedge in the Tyrrhenian region. Fe-Mg-carpholite-bearing rocks representing the exhumed deep root of the orogenic wedge are in fact in tectonic contact with Pliocene intrusives, which in turn are products of thermal relaxation processes that accompanied the late extensional attenuation of the previously thickened orogenic crust (Rossetti et al., 1999).

At the Franco Promontory, similar to the nearby Monte Argentario, the stacking of different tectono-stratigraphic units can be recognized (Figure 8). Unit V consists of Fe-Mg-carpholite-bearing metasediments (predominately quartz-rich phyllites and schists), belonging to the Tuscan Verrucano Group. This unit, with a thickness of around 100 meters, crops out extensively along the western part of the promontory and constitutes the lowermost unit of the whole nappe complex. Unit M is a tectonic melange dominantly composed of metapelites (Vc) at least in part belonging to the uppermost part of the Verrucano sequence, and by fragments of high-pressure metamorphic basic rocks (Oph) and Ligurian calcschists. Unit M underlies most of the central part of the promontory with a thickness of almost 150 meters. Upper Triassic massive and stratified dolomites and bedded limestones in association with tectonic and solution breccias of the Calcare Cavernoso

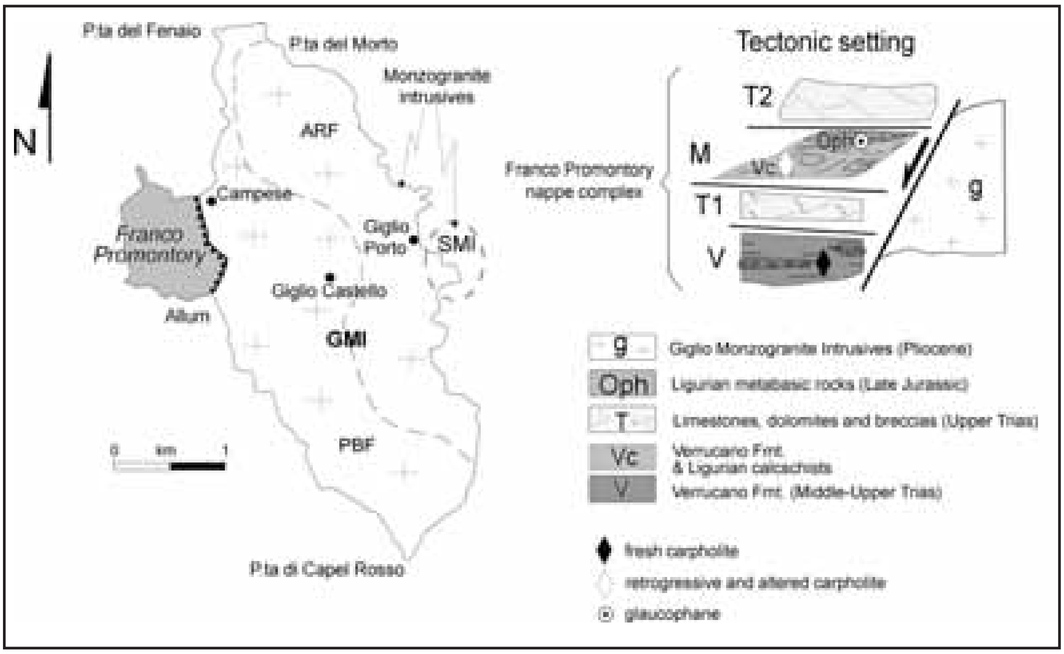

Figure 8 - Geological map of Giglio Island (after Lazzarotto et al., 1964; Westerman et al., 1993; Rossetti et al., 1999), with the stop localities indicated.

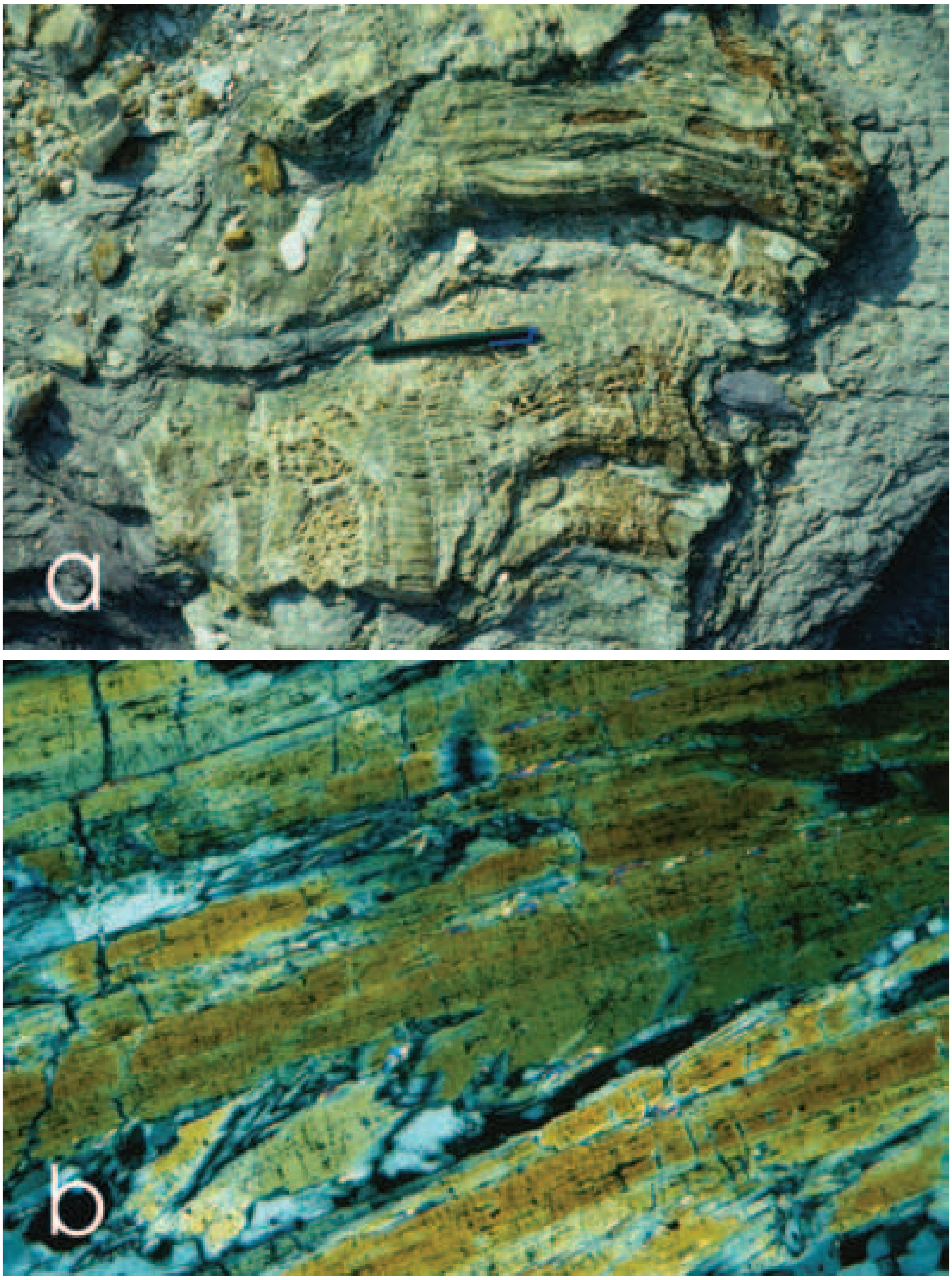

Figure 9 - (a) Fe-carpholite - quartz composite fibrous association in Verrucano metapelites. (b) Thin section of Verrucano metapelite from Giglio Island showing the blueschist peak equilibrium association of Fe-carpholite, quartz and phengite.

Formation, cropping out along the Gulf of Campese and at Cala dell' Allume, constitute unit T. This unit is found between the two high-pressre units (T1) and also at the top of the nappe complex (T2) (Figure 1).

The Giglio Monzogranite Intrusion (GMI) comprises two different monzogranitic intrusions of an overall S-type peraluminous and sub-alkaline composition, with an average Rb/Sr radiometric cooling age of 5.0 Ma (Westerman et al., 1993). The main intrusive body is characterised by an outer zone that is strongly foliated and locally layered (Pietrabona Facies, PBF) and an inner zone that is porphyritic and homogeneously textured (Arenella Facies, ARF; Figure 8). The latter facies has preserved the magmatic, concentric structures and it may be considered the core of the pluton (Burrelli and Papini 1992) (Figure 11). Transitions to solid-state structures are mostly localised in the north-western part of the island, an area that may represent the original plutonic rim. Stops 2 and 3 illustrate the development of solid-state structures along the rim of the GMI, including progressive ductile to brittle top-to-the-east shear features.

Itinerary for day 2: Ferry from Porto Santo Stefano to Giglio Porto. Drive from Giglio Porto on the eastern side of the island across the Giglio monzogranite to Campese on the westcoast, and further southwards along the contact between the monzogranite and the nappe pile of the Franco Promontory. Walk 1.5 km across the Franco Promontory nappe pile to reach Stop 2.1. Back to Campese to examine granite pavements around Torre del Campese (Stop 2.2). Drive towards the northern tip of the island on the road to Giglio Porto. Walk 2 km on footpath to the lighthouse at Punta Fenaio (Stop 2.3).

Stop 2.1:

Mugni beach, Promontorio del Franco

The Mugni beach locality is a spectacular outcrop that illustrates the succession of two main deformation and metamorphic episodes, which are characteristic of the early Apennine orogenic history. The first episode is related to the HP/LT stage, the second to the retrogressive stage with a final re-equilibration in the low-grade greenschist facies during eastward-directed shearing.

Petrography

Verrucano rocks exposed at the Mugni beach consist of Fe-Mg-carpholite, phengite, chlorite, quartz and minor ankerite. Late, static formation of green biotite is locally observed. Fibrous carpholite crystals are commonly observed on quartz-rich segregations lying parallel to the foliation planes (Figure 9). Textural relationships, such as folding of the carpholite + quartz + phengite aggregates, sub-grain formation and undulose extinction in quartz, indicate that the formation of the carpholite-bearing segregations is an early event in the metamorphic history.

Carpholite compositions range from X_{Mg}= 0.37 to 0.41, with a low fluorine content between 0 and 0.13 wt%. Peak pressure estimates obtained from the phengite-substitution in white micas (Si^{4+} = 3.19-3.24 p.f.u.) in equilibrium with carpholite indicate pressure values ranging from 10 to 12 kbar for temperatures between 250° and 350°C (Rossetti et al., 1999). Carpholite phenoblasts are locally replaced by fine-grained aggregates of phyllosilicates (white mica + chlorite). Further alteration of carpholite produced kaolinite. The absence of chloritoid indicates that the exhumation path did not cross the chloritoid-producing carpholite breakdown reaction, and hence, the P-T gradient must have remained relatively cool. Replacement of carpholite by late kaolinite suggests cooling during decom-pression within the kaolinite + quartz stability field. Finally, the presence of static green biotite in some samples reflects a late influence by the nearby pluton and a short-lived temperature increase to about 400°C.

The derived (pre-intrusive) peak P-T conditions define a higher P/T metamorphic ratio than those reconstructed by Theye et al. (1997) for the Monte Argentario samples where chloritoid is present and the celadonite substitution in muscovite is lower.

Structures

HP/LT (Fe-Mg)-carpholite bearing assemblages define a relic S_1 schistosity that occurs within a retrograde greenschist D_2 fabric. The extensive reworking caused by the D_2 event means that no conclusive structural data are available to reconstruct the earlier D_1 deformation episode.

The D_2 event, from syn- to post-kinematic relative to the retrograde greenschist metamorphism, resulted in a penetrative L-S tectonic fabric, which constitutes the main structural feature in the Verrucano rocks. The S_2 schistosity is almost flat-lying and defined by a retrogressive assemblage of chlorite + white mica. S_2 schistosity is associated with a pervasive strain-slip crenulation cleavage and is axial planar to mesoscopic, eastward asymmetric F_2 folds

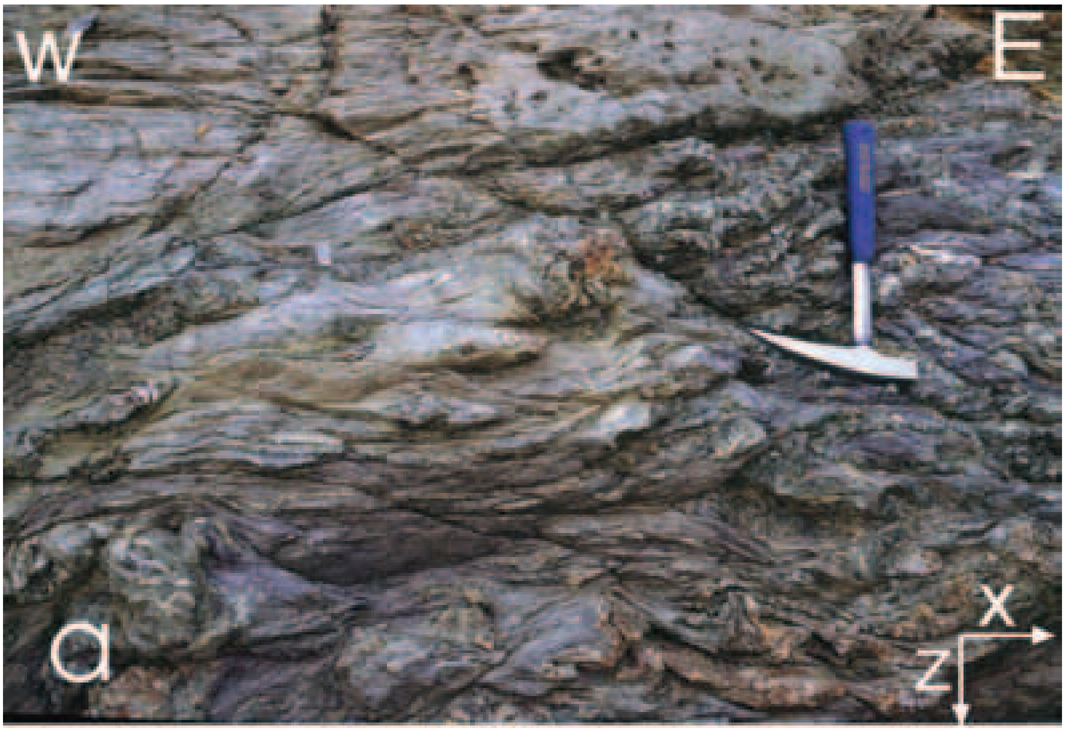

Figure 10a - Second-phase vertical coaxial shortening (D_2) in Verrucano metasediments reworking the early HP plano-linear fabric.

refolding the early HP/LT assemblages (Figure 10a). L_2 stretching lineations trend roughly E-W and are defined by quartz and mica-chlorite aggregates. Similarly oriented stretching is also indicated by vein-filling quartz fibres accompanying D_2 boudinage.

Carpholite fibres in metapelites are boudinaged and sheared along the L_2 direction, with retrograde quartz-chlorite-micas associations filling the gaps. Quartz fibres formed after carpholite retrogression are folded with the same geometry, attesting the post-HP character of this deformation. Sections parallel to L_2 stretching lineations and perpendicular to the S_2 foliation, generally show a non-coaxial shear fabric. Shear criteria, such as σ-type porphyroclasts, asymmetric boudins, pressure shadows and S-C structures are synkinematic relative to the retrogressive greenschist metamorphism and indicate a constant top-to-the east sense of shear (Figure 10b). D_2 flattening features, S_2 foliation and strain-slip crenulation cleavage, are re-oriented and cut along D_2 shear bands. Further deformation features include semi-brittle low-angle and brittle high-angle conjugate extensional faults, accommodating a general maximum extension direction ranging from N60°E to E-W.

Stop 2.2:

Torre del Campese, monzogranite pavements

This stop shows solid-state deformation structures that developed while the pluton cooled down. Ductile shearing deformation is localised on low-angle east-dipping aplitic dykes. Stretching directions (provided mostly by quartz and tourmaline aggregates) strike N120°E and the sense of shear, as deduced from the offset of pre-existing dykes and S-C relationships, is always top-to-the-east (Figs. 11, 12). Locally, late cataclasites and ultracataclasites developed along the C-surfaces accompanying a late, eastward-directed, extensional faulting. This is consistent with continuing shear deformation as temperature decreases.

Stop 2.3:

Punta del Fenaio (coastal outcrop)

At Punta del Fenaio, the monzogranite is seen in primary contact with its wall rocks. The monzogranite contains zones of low-grade mylonite overprinting the primary igneous structure (Figure 11). Along the coast, formation

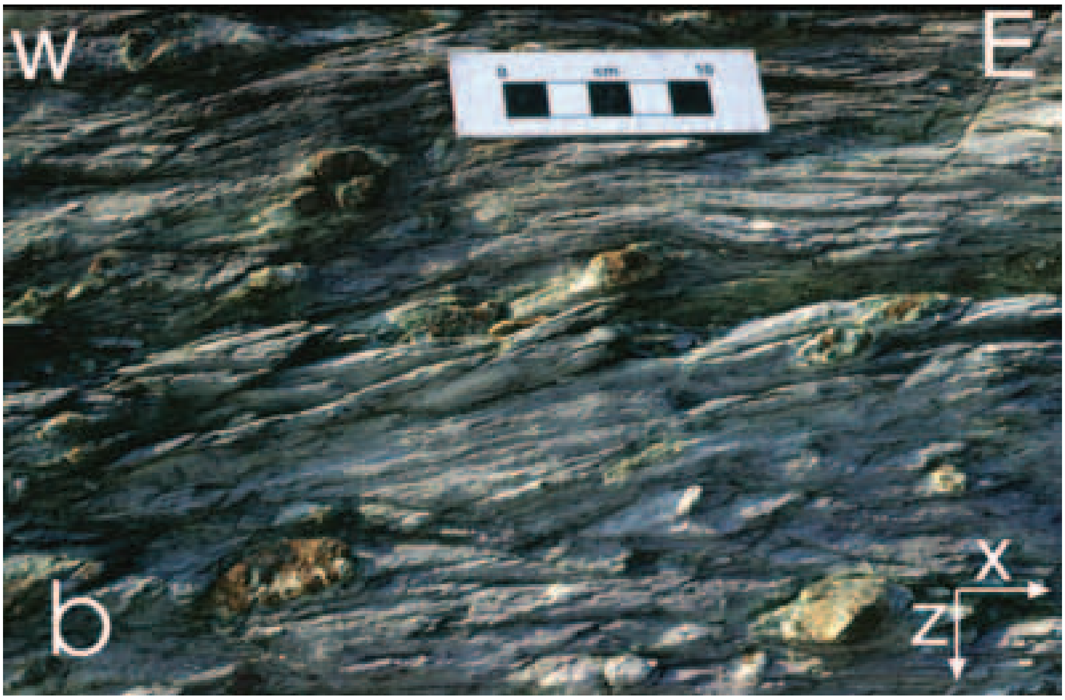

Figure 10b - Top-to-the-east greenschist ductile shear bands in Verrucano metapelites.

of S-C tectonites can be also observed. C surfaces are defined by zones rich in mica and fine-grained recrystallised quartz. Stretching lineations on C-surfaces, mostly marked by quartz and tourmaline crystals, trend N120°E and the sense of shear is top-to-the-east, as derived from S-C relationships and other kinematic indicators.

DAY 3

Western Monte Argentario

General overview and program of day 3:

- Ophiolite unit: petrological aspects and metamorphic history
- Ductile and brittle deformation in calcitic-dolomitic marble

In contrast to the east-central Argentario, the western part of the promontory forms a tectonic melange comprising a large variety of rock types, many of which are not found further east. This melange displays more affinity with the tectonic pile of the Franco promontory on the island of Giglio.

The Triassic sequence is represented by psammo-pelitic Verrucano, dolomitic marble (“grezzoni”) and gypsum (equiv. to Burano Anhydrite). In addition, abundant calcite marble is present (Stop 3.2), dated with microfossils as Mid-Triassic to lowermost Carnian (Gelmini & Mantovani, 1980). Hence, this marble is an age equivalent of the clastic Verrucano facies (the latter being far more common throughout the Northern Apennines). The marble sequence has been given the local name “Cala Piatti unit” (Decandia & Lazzarotto, 1980) Interlayered calcareous beds and phyllites are considered as being transitional in facies between pelitic Verrucano and the calcite marble unit (Reinhardt, 1982; Stünitz, 1982, unpubl. theses).

Similar to the Franco tectonic stack on Giglio, a strongly fragmented ophiolite unit forms a substantial part of the western Argentario melange (Lazzarotto et al., 1964, Ricci, 1968). Rock types of this unit include ultramafic rocks (mainly serpentinite, locally talc-tremolite rock and pyroxenite), metagabbro (Stop 3.3) and metabasalt (largely dykes in metagabbros; pillow structures have not been observed) with a MORB geochemical signature (Ricci & Serri, 1975), and a variety of

metasedimentary rocks of oceanic provenance (see Stop 3.1). Even though no geochronological studies have been undertaken yet to determine the age of the ophiolite, it appears most likely that these are fragments of the Ligurian oceanic crust, and hence have a Jurassic age (cf. Figure 5).
Further to the units described here, there are minor occurrences of metasedimentary rocks (siliceous-calcareous rocks, greywacke, etc.) whose age and provenance are still obscure. Nevertheless, their presence emphasizes the complex tectonic character of this terrain. The tectonic melange of the Western Argentario has a hanging-wall position with respect to the east-central complex. Calcare Cavernoso and carbonate-dominated tectonic breccia separate the two, but are also found at higher structural levels in the west.

Itinerary for day 3: Drive along Via Panoramica from Porto Santo Stefano to Cala Grande (Stop 3.1; on private property). Continue along Via Panoramica to the entrance of the Cala Moresca private holiday complex. Walk or drive down to the coast. Take footpath along coastal cliffs to the north (Stop 3.2). Back to the Via Panoramica and to the roadcuttings opposite the Ristorante "Il Moresco" (Stop 3.3). Return to Florence or Rome in the afternoon.

Stop 3.1:
Cala Grande, below Via Panoramica
This area shows a variety of metasedimentary rocks in association with metabasites, all belonging to the ophiolite unit. The metasediments include pelitic material, hematitic chert, radiolarite, calcareous beds, graded beds of mafic detritus, and breccias containing a mixture of sedimentary and mafic fragments.

Blueschist facies metamorphism is evident from mineral assemblages observed in the clastic rocks that contain gabbro-derived detritus, and from calcareous beds containing sodic amphibole ("blue marble"), and locally lawsonite. The range of metamorphic minerals in the gabbro-derived clastic beds is largely the same as in the metagabbros proper (cf. Stop 3.3).

Stop 3.2:
Cala Moresca (coastal cliffs)
Exposed is laminated to thick-bedded calcite marble, with interlayers of dolomitic marble towards the top of the sequence. Most of the marble is relatively pure, with rare intercalations of thin quartzitic beds. The structural inventory includes small-scale intrafolial folds, shear bands and a strong fragmentation of bedding due to boudinage (Figure on front cover). Part of the calcite marble shows a strongly developed macroscopic L-S tectonite fabric typical of mylonites. Related microstructures are largely obscured, though, due to pervasive post-deformational recrystallization of calcite. Only quartzitic layers retain evidence for ductile shearing (dynamic recrystallization, SPO, CPO). In contrast to the calcite marble, the dolomitic beds show little evidence for ductile flow, but are intensely fractured instead. Where both are interlayered, boudinage of dolomite marble is

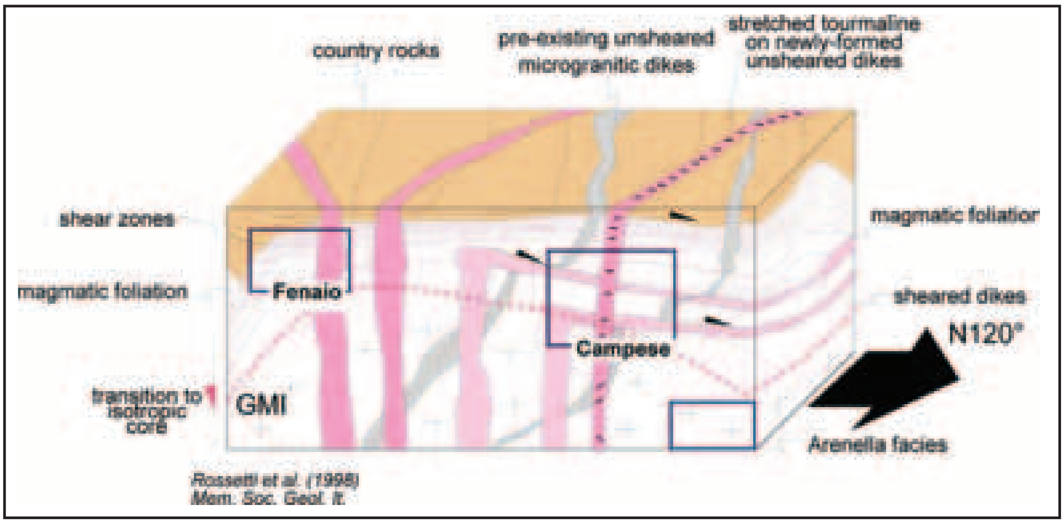

Figure 11 - Schematic block diagram illustrating the structural pattern of the Giglio Monzogranite Intrusion.

Figure 12 - Semibrittle eastward-dipping extensional fault in monzogranite at Torre del Campese. Note the offset of the aplitic dyke.

common. The overall sense of shear in this outcrop is top-to-the-east.

There is (as yet) no direct evidence for high-pressure metamorphism of this sequence. Peak P-T conditions derived from rocks in the Western Argentario tectonic complex are close to (above or below) the calcite-aragonite equilibrium curve, taking into consideration the uncertainly ranges of this reaction and of the P-T estimates for the Western Argentario. So far, no remains of aragonite have been found, neither in the Triassic marbles, nor in the marbles of the ophiolite units which did experience HP metamorphism (cf. Stop 3.1).

Stop 3.3:

Roadcuts on Via Panoramica, above Cala Moresca

The dominant rock type is metagabbro, occurring as strongly defomed to entirely undeformed varieties. Associated is minor metabasalt, plus phyllite and fine-grained siliceous metasediments. The mafic rocks provided the original evidence for high-pressure metamorphism in this region (Ricci, 1972), due to their conspicuous blue amphiboles. However, beyond this particular aspect, the metagabbros preserve a multiphase metamorphic history. Igneous textures and minerals can still be identified (notably the large clinopyroxene crystals visible in outcrop).

Hydrothermal overprinting in the sub-seafloor environment, from amphibolite facies conditions to sub-greenschist facies conditions is documented by the presence of minerals such as hornblende, actinolite, epidote, chlorite, and pumpellyite. High-pressure assemblages containing Na-amphiboles, lawsonite and, rarely, Na-pyroxene, in turn overprint the LP-HT and LP-LT assemblages (Reinhardt, 1982; Stünitz, 1982, unpubl. data). For the HP-LT mineral assemblage, P-T conditions of 340°C and 7 kbar have been calculated (Theye et al., 1997). The extent of equilibration at the different stages of metamorphism varies a lot between samples, from incipient reaction to complete overprinting. Furthermore, not all stages of metamorphism may be evident in each single sample of partially equilibrated metagabbro. Thus, reaction rims of blue amphibole on igneous clinopyroxene are not uncommon.

This variation in mineral assemblages and reactions reflects the varying degree of water access and infiltration throughout the metamorphic history, plus the feedback effects between deformation, infiltration and reaction softening. Those rocks completely converted to blueschists are typically fine-grained and strongly foliated.

Acknowledgements

We would like to thank our colleagues from Italy, France, Germany and Switzerland (C. Faccenna, R. Funiciello, B. Goffé, L. Jolivet, M. Mattei, F. Storti, H. Stünitz, T. Theye, and others) who have contributed in many ways to the present state of knowledge on this area, and with whom we have co-operated for years. It is to be hoped that international co-operation will continue and that new ideas keep evolving from that.

We would also like to thank those who have supported our cause by granting access to outcrops on their properties, during previous periods of field work (Cala Grande and Franco in particular), and for this international field trip.

References cited

Brunet, C., Monié, L., Jolivet, L. and Cadet, J.P. (2000). Migration of compression and extension in the Tyrrhenian Sea, insights from $^{40}Ar/^{39}Ar$ ages on micas along a transect from Corsica to Tuscany. *Tectonophysics* 321, 127-155.

Burrelli, F. and Papini, P. (1992). Structural analysis of Giglio island pluton. *In* "Contribution to the Geology of Italy with Special Regard to the Palaeozoic Basements" (L. Carmignani and P. Sassi, Eds.). IGCP 276, Newsletters vol. 15, 449-452.

Costantini, A., Decandia, F.A., Elter, F.M., Franceschelli, M., Giorgetti, G., Lazzarotto, A., Liotta, D., Memmi, I., Sandrelli, F. and Tavernelli, E. (1995). Low-temperature metamorphism in Southern Tuscany: P-T indicators and geodynamic implications. Guide-book to the field excursion, University of Siena.

Decandia, F.A. and Lazzarotto, A. (1980). Le unità tettoniche del Monte Argentario (Toscana meridionale). *In* "L'evoluzione tettonico-sedimentaria dell'Appennino settentrionale". Libretto guida, pp. 91-103. 70° Congresso, Società Geologica Italiana, Siena 1980.

Faccenna, C., Becker, T.W., Lucente, F.P. and Rossetti, F. (2001). History of subduction and back-arc extension in the central Mediterranean. *Geophys. J. Int.* 145, 1-21.

Gelmini, R. and Mantovani, M.P. (1980). Ritrovamento di fossili triassici nel calcare cristallino stratificato nero dell'Argentario (Toscana meridionale). *In* "L'evoluzione tettonico-sedimentaria dell'Appennino settentrionale". Libretto guida, pp. 105-107, 70° Congresso, Società Geologica Italiana, Siena 1980.

Jolivet, L., Faccenna, C., Goffé, B., Mattei, M., Rossetti, F., Brunet, C., Storti, F., Funiciello, R., Cadet, J.P., d'Agostino, N. and Parra, T. (1998). Mid-crustal shear zones in postorogenic extension: Example from the northern Tyrrhenian Sea. *J. Geophys. Res.* 103, 12123-12160.

Lazzarotto, A., Mazzanti, R. and Mazzoncini, F. (1964). Geologia del Promontorio Argentario (Grosseto) e del Promontorio del Franco (Isola del Giglio - Grosseto). *Boll. Soc. Geol. Ital.* 83 (2), 1-124

Principi, G. and Treves, B. (1984). Il sistema corso-appenninico come prisma d'accrezione. Rifflessi sul problema generale del limite Alpi-Appennino. *Mem. Soc. Geol. Ital.* 28, 529-576.

Ricci, C.A. (1968). Le rocce metamorfiche di natura basica e ultrabasica nelle serie a facies toscana. Studio chimico e petrografico. *Atti Soc. Tosc. Sci. Nat., Mem., Serie A* 75, 1-67.

Ricci, C.A. (1972). Geo-petrological features of the metamorphic formations of Tuscany. *Atti Soc. Tosc. Sci. Nat., Mem., Serie A* 79, 267-279.

Ricci, C.A. and Serri, G. (1975). Evidenze geochimichesulla diversa affinità petrogenetica delle roche basiche comprese nelle serie a facies toscana. *Boll. Soc. Geol. Ital*. 94, 1187-1198.

Rossetti, F., Faccenna, C., Jolivet, L., Funiciello, R., Tecce, F. and Brunet, C. (1999). Syn- versus post-orogenic extension: the case study of Giglio Island (northern Tyrrhenian Sea, Italy). *Tectonophysics* 304, 71-93.

Rossetti, F., Faccenna, C., Jolivet, L., Goffé, B. and Funiciello, R. (2002). Structural signature and exhumation P-T-t paths of the blueschist units exposed in the interior of the Northern Apennine chain, tectonic implications. *Boll. Soc. Geol. Ital.,* Spec Vol. 1. 829-842.

Theye, T., Reinhardt, J. Goffé, B., Jolivet, L. and

Brunet, C. (1997). Ferro- and magnesiocarpholite from the Monte Argentario (Italy): First evidence for high-pressure metamorphism of the metasedimentary Verrucano sequence, and significance for P-T path reconstruction. *Eur. J. Mineral.* 9, 859-873.

Westerman, D., Innocenti, F., Tonarini, S. and Ferrara, G. (1993). The Pliocene intrusions of the island of Giglio. *Mem. Soc. Geol. Ital.* 49, 345-363.

Back Cover:
field trip itinerary

FIELD TRIP MAP

Edited by APAT