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THE METASILICICLASTIC-CARBONATE SEQUENCE OF THE ACQUADOLCE UNIT (EASTERN ELBA ISLAND): NEW PETROGRAPHIC DATA AND PALEOGEOGRAPHIC INTERPRETATION

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ABSTRACT

The Acquadolce Unit (upper part of Trevisan’s Complex II) consists of a phyllitic-quartzitic succession with calcschist and metagraywacke intercalations and a serpentinite wedge at the top. This unit was generally correlated to the Dogger-Eocene metasediments of the Tuscan Paleozoic-Jurassic succession of the Apuan Alps but, more recently, has been attributed to the Ligurian or Piedmontese Domain (e.g. the “Schistes Lustrés” of the Gorgona Island). In this paper we present a detailed petrographic study of both the Acquadolce Unit and the Metasedimentary Unit of the Gorgona Island. In particular, we found significant mineralogical analogies between the lithotypes and tectono-metamorphic imprint of the two successions. The hypothesis that the Acquadolce Unit can be ascribed to a “Schistes Lustrés”-type succession is also supported by the relatively high-pressure (probably >8kbar) estimated for the D_1 deformation phase of the Acquadolce Unit from the K-white mica composition. The Acquadolce Unit is attributed to the metamorphic Ligurian-Piedmontese successions, allowing a redefinition of the main geological boundaries in the Tuscan Archipelago.

INTRODUCTION

The Elba Island, as a whole, is a precious source of geological data for the reconstruction of the deformations which built up the Alpine Corsica and the Northern Apennine pile of nappes and the subsequent extensional development of the Tyrrhenian Basin and Tuscan anatectic magmatism (Principi and Treves, 1984; Serri et al., 1991; Carmignani et al., 1995; Keller and Coward, 1996; Bartole et al., 1991; Jolivet et al., 1991; 1998 and references therein). High-pressure-low-temperature (HP-LT) metamorphic, continental (“Verrucano” Auctt.) and oceanic (Calcschists with ophiolites or “Schistes Lustrés” Auctt.) successions are present both in the Tyrrhenian area (e.g., Gorgona Island, Giglio Island, and Argentario Promontory: Jolivet et al., 1998 and references therein) and in Southern Tuscany (e.g. Monte Leoni and Monticiano-Roccastrada areas: Giorgetti et al., 1998; Roselle area: Ricci, 1972). According to some authors (Corti et al., 1996; Bortolotti et al., 2001a) “Schistes Lustrés”-type successions are also present within the Tuscan and Ligurian units of the Elba tectonic pile. In particular, in the central-eastern Elba, the uppermost part of the Trevisan’s Complex II (= Acquadolce Unit of Bortolotti et al., 2001a) shows lithological analogies with the oceanic metasedimentary cover cropping out in the Gorgona Island (Metasedimentary Unit in Capponi et al., 1990).

In order to test the previous correlation, we carried out a comparative petrographic study between the metasediments of the Acquadolce Unit and the Gorgona Metasedimentary Unit. In addition, approximate P-T estimates during the first tectonic phase in the Acquadolce Unit were obtained both from the chemical compositions of the K-white mica using the Massonne and Schreyer (1987) geobarometer, and from the mineral assemblages[1]. This pressure indication has been compared with the peak pressures estimated for different metamorphic complexes of Southern Tuscany and Tuscan Archipelago, and in particular with the pressure conditions proposed for the Gorgona Metasedimentary Unit by Jolivet et al. (1998).

GEOLOGICAL OUTLINE

In the geological framework of the northern Tyrrhenian Sea, the Elba (Figs. 1 and 2) and Gorgona (Fig. 3) Islands represent two pinning points for any attempt to locate the symmetry axis of the double vergent Northern Apennine-Alpine Corsica orogenic system (Abbate et al., 1970; Perrin, 1975; Reutter et al., 1980; Boccaletti et al., 1980; Principi and Treves, 1984). The northern prosecution of this geological boundary within the Liguria and Piedmont areas has been traditionally identified in the so-called Sestri-Voltaggio (Abbate et al., 1970; Sholle, 1970) or in the Villarvernia-Varzi-Levanto Lines (Elter and Pertusati, 1973). Farther north, the superposition of the Apennine Units onto the Alpine Units can be recognized by the Rio Freddo-Torino hill Line (Biella et al., 1992; Piana and Polino, 1995; Polino et al., 1995 and references therein). In the western part of the northern Tyrrhenian Sea, the Ligurian-Piedmont HP-LT metamorphic successions are well represented below the Oligocene Epiligurian and Miocene to Quaternary syn-/post-rift sedimentary covers and overlie the Ligurian Units (Bartole et al., 1991; Bartole, 1995). These oceanic HP-LT successions may be correlated with the blueschist facies rocks of the Gorgona Island (Capponi et al., 1990) and the “Schistes Lustrés” of the Alpine Corsica (Durand Delga et al., 1978; Durand Delga, 1984). The HP-LT metamorphism was acquired during Cretaceous to Eocene oceanic subduction and accretion stages and/or Upper Eocene to ?Oligocene continental collision between Europe (Sardinia-Corsica) and Adria Plates (Principi and Treves, 1984; Cohen et al., 1981; Caron, 1994; Egal, 1992; Abbate et

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[1] Contributions of the authors are as follows: geological surveys and structural data (E. Pandeli), petrography (E. Pandeli and M. Puxeddu), composition of the K-white mica (G. Ruggieri).

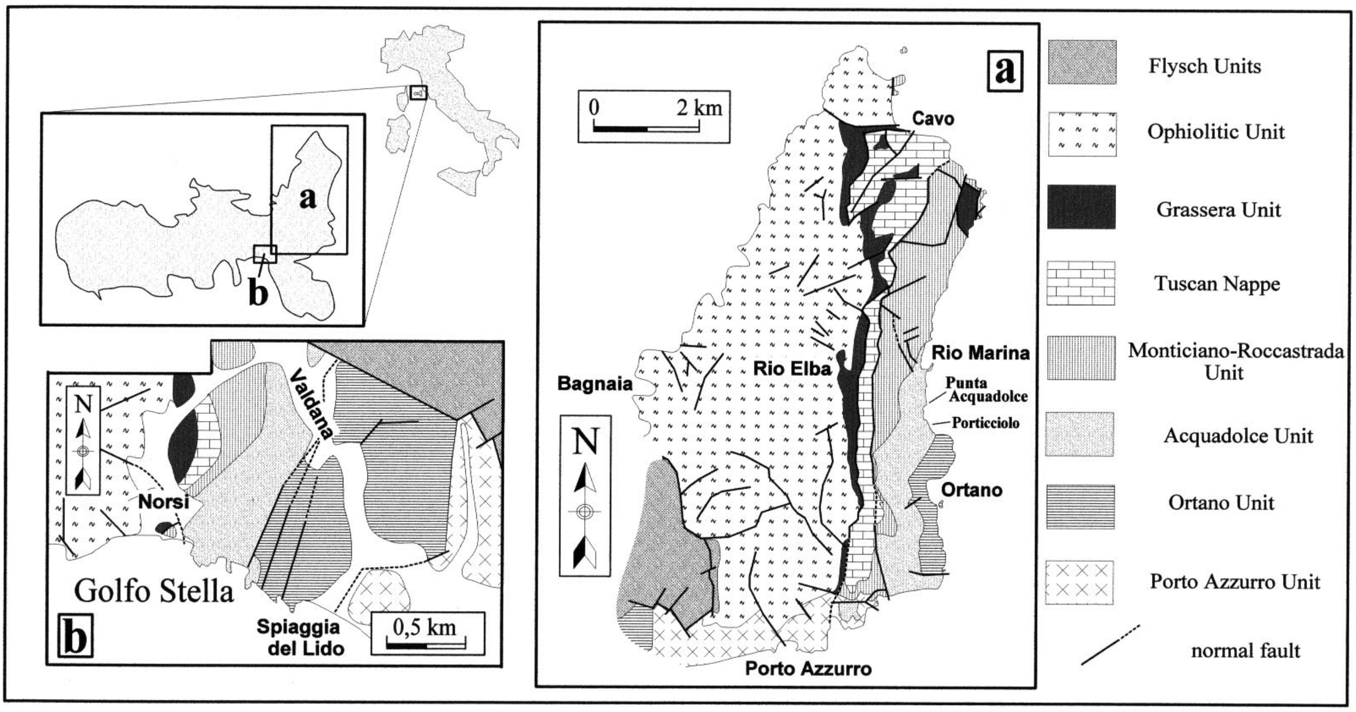

Fig. 1 - Geological sketch maps (according to Bortolotti et al., 2001a): a) Cavo-Rio Elba-Porto Azzurro area; b) Valdana-Norsi-Spiaggia del Lido area.

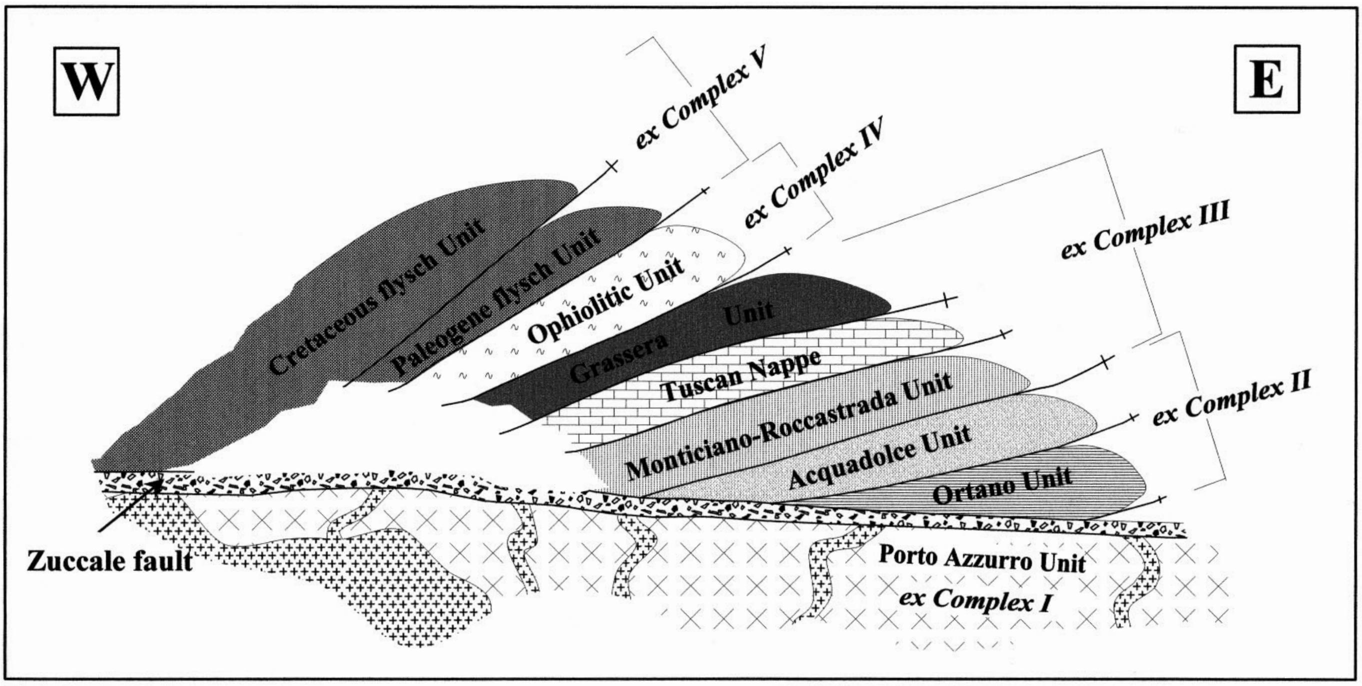

Fig. 2 - Sketch cross-section of the central-eastern Elba Island, not in scale.

al., 1994 and references therein). In the Oligocene-Early Miocene times at least part of these blueschist facies units were displaced eastwards onto the Ligurid nappes, and were incorporated in the Adria-vergent orogenic stack of the Northern Apennines, of which the Elba Island represents the more internal part (Bartole et al., 1991 and references therein).

A post-orogenic extension dissected this complex nappe stack by low- and high-angle normal faults. Faulting started in the Burdigalian in the areas close to the Sardinia-Corsica (Jolivet et al., 1991; Carmignani et al., 1995), and in the Middle?/Late Miocene in the Tuscan Archipelago and Maritime Tuscany (Elter et al., 1975; Channel and Mareschal, 1989; Bertini et al., 1994; Bartole, 1995; Keller et al., 1994; Keller and Coward, 1996). Extension and crustal thinning of the nappe stack was coupled with the opening of the Tyrrhenian Basin which is related to asthenospheric upwelling, and then followed by the development of the Tuscan anatectic magmatism with mantle contaminations (Boccaletti et al., 1985; Serri et al., 1991; Bartole, 1995 and references therein).

According to the classic Trevisan's model (see Trevisan, 1950, 1951; Barberi et al., 1969), the Elba Island may be described as a pile of five tectonic units (= Complexes) (Figs. 1 and 2). In particular, the lowermost three units were referred to the Tuscan metamorphic (Complex I and II) and

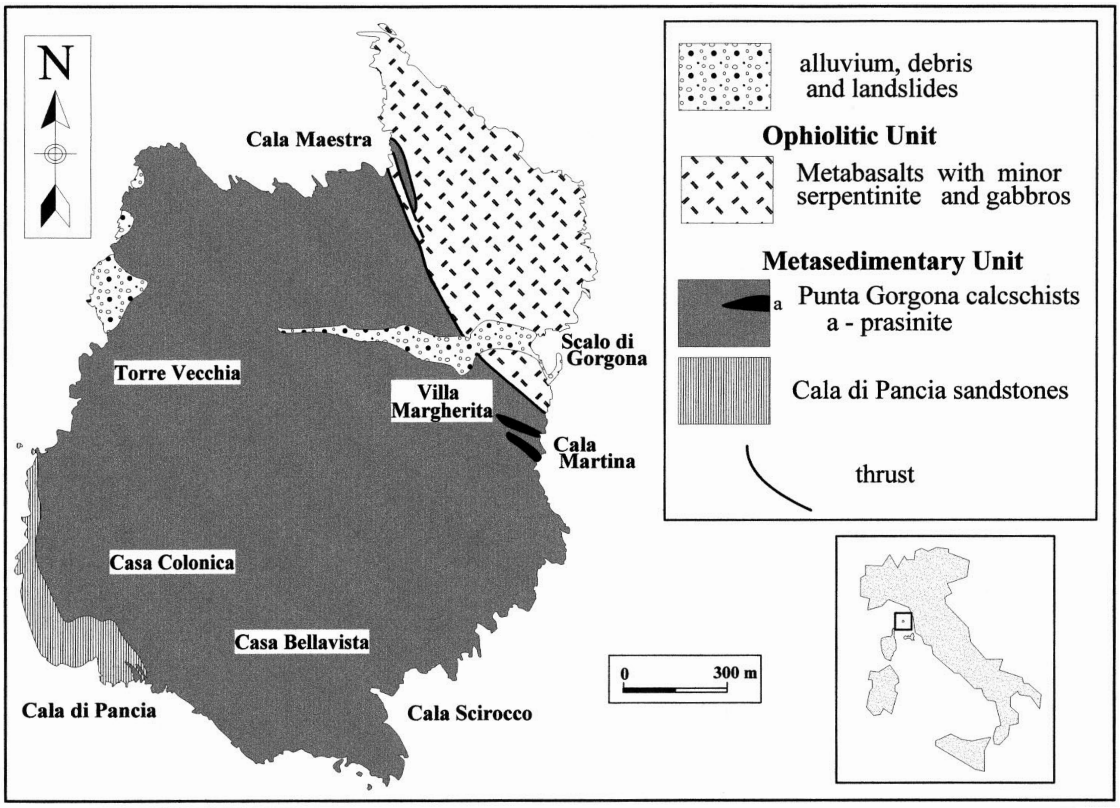

Fig. 3 - Geological sketch map of Gorgona Island (redrawn from Capponi et al., 1990).

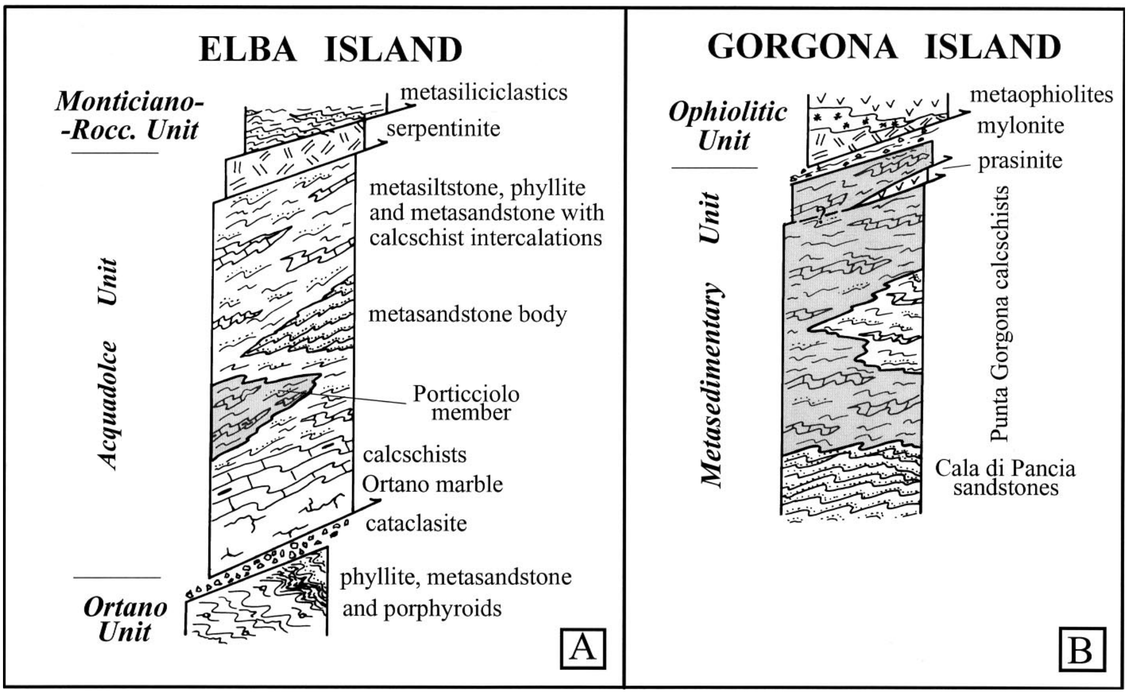

Fig. 4 - Columns of the geometric relationships of formations within the Elba Acquadolce Unit (A) and the Gorgona Metasedimentary Unit (B), not in scale.

non-metamorphic (Complex III) domains, while the overlying Complexes IV and V were attributed to the Ligurian realm, thus reproducing the classic tectonic framework of the Northern Apennines.

In the 7.6-4.9 Ma time interval the Elba nappe stack was sharply intruded by granitoids and aplitic-pegmatitic dyke swarms (Marinelli, 1959; Ferrara and Tonarini, 1993; Saupé et al., 1982 and references therein). Moreover, either during the intrusion or during the uplift of the cooled igneous bodies, important east-vergent detachments and thrustings of thick portions of the nappe stack occurred through low-angle normal faults (Trevisan, 1950; Barberi et al., 1969; Bouillin et al., 1994; Pertusati et al., 1993; Daniel and Jolivet, 1995). The final Elba I. evolution was characterized by block faulting (mainly north-south-trending) and generation of the famous hematite-rich ore bodies (Deschamps, 1980; Deschamps et al., 1983; Bortolotti et al., 2001a).

In the decades, the interest for the tectonic and stratigraphic setting of the Elba Trevisan's Complexes and, in particular, for the Complex II renewed (see in Bortolotti et al., 2000b for a review). Until the end of the '80, the Complex II has been considered as an Apuan-type Tuscan metamorphic succession (e.g Barberi et al., 1969), Paleozoic-Jurassic in age, consisting of the following units (see also

Fig. 4A), from the bottom: a) graphitic phyllites, quartzites and porphyroids (Carboniferous?-Permian?), b) recrystallized "Calcare Cavernoso"-type vacuolar dolomitic limestones (Late Trias?), c) marbles (Hettangian?), d) calcschists (Early-Middle Lias?), e) carbonate phyllite with calcschist levels (Dogger?); f) tectonized serpentinites.

On the basis of field and petrographic work, Pandeli and Puxeddu (1990) defined the unit b) as a cataclastic level related to the thrust of the Marbles on the underlying Paleozoic succession of likely Cambrian?-Ordovician age. Moreover, they rejected the attribution of the unit e) to the Dogger Tuscan metasediments, pointing out its analogy with some Paleozoic lithotypes (e.g., the Calamita Gneiss of the Complex I). The occurrence of Lower Cretaceous planctonic microfossils in the calcschist beds allowed Duranti et al. (1992) to attribute the unit e) to a Ligurian succession (Palombini Shales of the Complex IV), that have been recrystallized and deformed by the Mio-Pliocene granitoid intrusions. This hypothesis was ruled out by ^{40}Ar/^{39}Ar radiometric data (Deino et al., 1992: 19.68±0.5 Ma) on the main schistosity of the unit e). Finally, Corti et al. (1996) and Bortolotti et al. (2001a) -in agreement with Termier (1910)- attributed the Marble-Calcschist-Phyllite-Serpentinite association (Acquadolce Unit) to an ocean-derived Ligurian-Piedmontese metamorphic unit, as the "Schistes Lustrés" of the Gorgona Island.

The Gorgona Island is completely made up of HP-LT metamorphic units similar to the "Schistes Lustrés" of Corsica and Western Alps (Mazzoncini, 1965; Capponi et al., 1990). In particular, two tectonic units may be recognized, separated by a mylonitic horizon (Capponi et al., 1990) (Figs. 2 and 4b): a) "Metasedimentary Unit" with a Piedmontese affinity, includes a thick metasiliciclastic succession (Cala di Pancia metasandstone) capped by calcschist and phyllite with metasandstone intercalations (Punta Gorgona calcschists); b) the overlying Ligurian-Piedmontese "Ophiolitic Unit", consisting of metabasalts (locally with preserved dyke textures: Pandeli and Principi, in preparation) and minor gabbro and basal serpentinite bodies. According to Capponi et al. (1990), the tectonic superposition of the Ophiolitic Unit onto the Metasedimentary Unit strictly recalls a well-known geological setting of the Western Liguria (e.g., the thrusting of the ophiolitic Montenotte Unit onto the metasedimentary Voltri Group: Capponi et al., 1990).

The Acquadolce Unit (Elba I.) and the Metasedimentary Unit (Gorgona I.) show a similar polyphase ductile deformation history, characterized by two (D_1 and D_2) main tectono-metamorphic events (Capponi et al., 1990; Duranti et al., 1992; Elter and Pandeli, 2000). D_1 and D_2 are represented by tight to isoclinal folds with very pervasive and transpositive axial plane schistosities (S_1 and S_2). The D_1 folds can be rarely observed because of their strong transposition due to overlapping of the D_2 structures. The vergence of the latter folds suggest a syn-D_2 western sense of tectonic movement for the Gorgona Metasedimentary Unit (Capponi et al., 1990). In contrast, Jolivet et al. (1998) interpreted the syn-D_2 mylonitic contact between the Metasedimentary Unit and the overlying Ophiolitic Unit as "a detachment fault that moved the upper plate to ESE". In the Acquadolce Unit of Elba I., the kynematic indicators associated with S_2 display a complex pattern for the tectonic transport. In fact, even if they generally points to NE or SE (Duranti et al., 1992; Keller and Pialli, 1990), a top-to-SW sense of shear was locally recognized (Elter and Pandeli, 2001, this volume). Later close to open folds produced zonal or fracture cleavages (e.g., C_3 crenulations) in both islands.

LITHOLOGIC AND PETROGRAPHIC DATA

To verify the lithological analogy between the two metamorphic succession of the Tuscan Archipelago, a detailed petrographic study was performed on selected samples from the Gorgona "Metasedimentary Unit" and of the Elba "Acquadolce Unit". The phyllites and calcschists of the Acquadolce Unit were sampled in the best exposed outcrops between Porto Azzurro and Rio Marina areas (along the road to Capo Arco Residence in the Ortano Valley, and along the road and the coast from Rio Marina to Porticciolo) (Fig. 1a). Other samples were collected in the north-eastern coast of Golfo Stella (south of the Norsi beach) (Fig. 1b).

In this paper, we describe only the main features of the phyllitic-carbonate-quartzitic lithotypes of the Acquadolce Unit and the Metasedimentary Unit. Petrographic descriptions of other rocks cropping out in these two areas are reported in Pandeli and Puxeddu (1990), Mazzoncini (1965) and in Benvenuti and Pandeli (2001, in Benvenuti et al., 2001).

Acquadolce Unit (Fig. 4A). Most of the outcrops are represented by lead grey, grey-greenish to black phyllites and metasiltstones, locally with centimetric to metric, lens-shaped intercalations of whitish, grey and grey-greenish calcschists and grey metasandstones (Fig. 5a). In places (e.g., the coast south of Rio Marina), the calcschists predominate and may include whitish cherty nodules and levels. Locally, the calcschist horizons are strongly affected by contact metasomatism (due to the Miocene-Pliocene intrusions) and transformed into skarn bodies (e.g., the Torre di Rio skarn: Tanelli, 1977).

South of Rio Marina, between Porticciolo and Acquadolce, medium to coarse-grained, and at times graded, metasiliciclastic beds largely prevail over millimetric-centimetric black phyllitic intercalations, forming a ca. 15-20 m.-thick metarenaceous body (Fig. 5b). In the Porticciolo area, another peculiar lithofacies (20-30 metres-thick) is intercalated within the Acquadolce phyllites; it is represented by (from bottom to top): a) dark grey to black phyllites with millimetric-centimetric levels of grey to grey-greenish microquartzites and carbonate quartzites; b) alternations of 3-50 cm-thick beds of whitish to dark grey, at times cherty marbles, grey-greenish calcschists, and black to green phyllites and carbonate phyllites; c) a massive horizon of black phyllites (some metres-thick). The mineralogical composition of each lithotype is shown in Table 1.

Metasedimentary Unit (Fig. 4B). The widest lithological association exposed in the Gorgona Island is the "Punta Gorgona calcschists". It is mainly made up of alternating black, grey to greenish phyllites with centimetric to metric (up to 4-5 m), calcschists, metacalcarenites and marbles, dark grey to withish in colour (Fig. 5c). Centimetric (max 50 cm-thick) beds of grey to greenish metasandstone and metasiltstone are also common. In places, the calcschist beds disappear or the metasiliciclastic beds become dominant (e.g. SW of Villa Margherita), therefore the outcrops appear very similar to the typical Acquadolce lithofacies.

In the south-western side of the Gorgona Island, the "Cala di Pancia metasandstones" is a isoclinally folded, well-bedded arenaceous flysch succession, whose original thickness exceeds 60 m (Fig. 5d). It is mainly represented by decimetric to metric (max 4 m), coarse to fine-grained, grey metarenaceous beds, sometimes graded and characterized by basal microconglomeratic levels. The black metapelitic intercalations are thin (max 30 cm in thickness) or absent because of the amalgamation between the arenaceous beds.

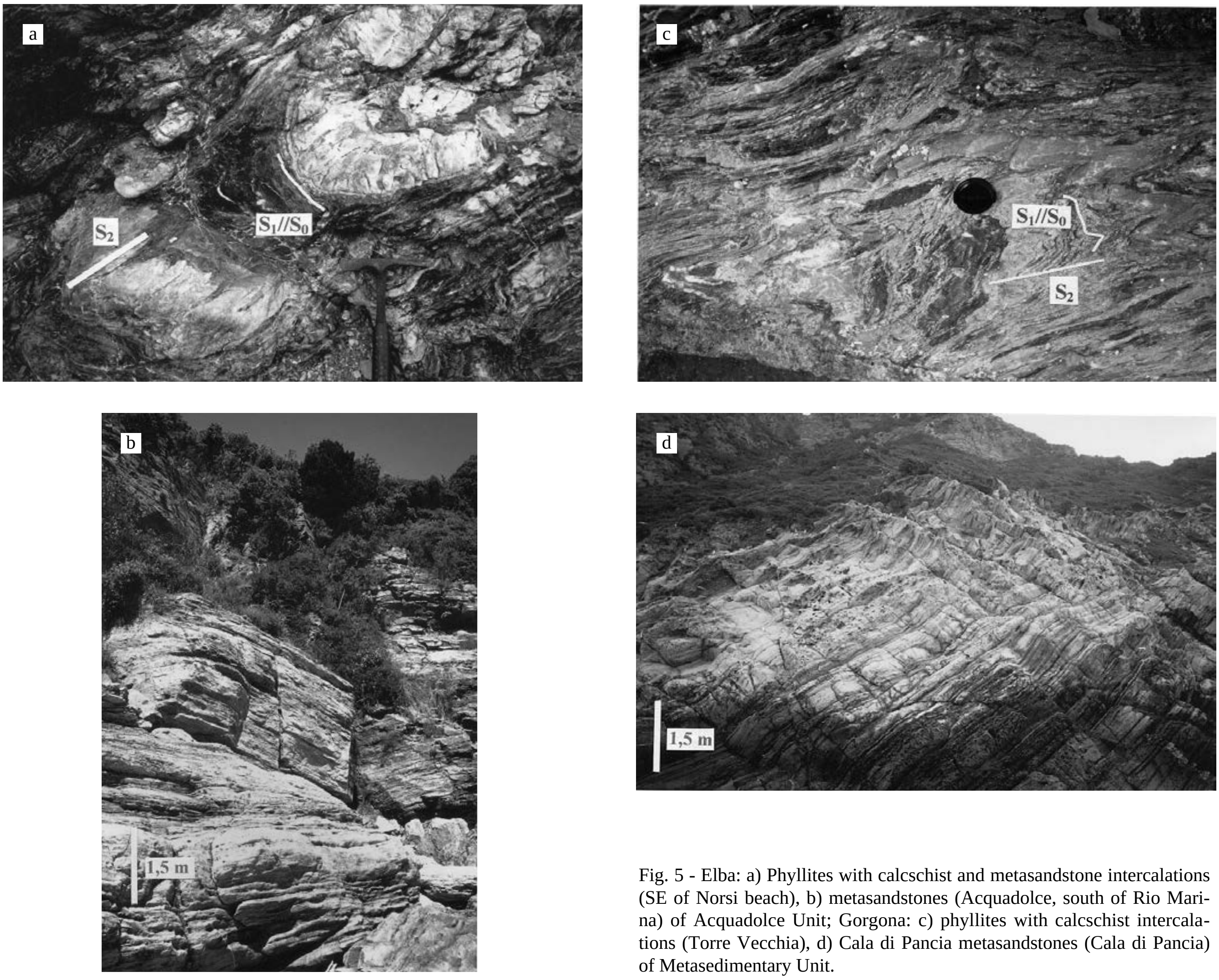

Fig. 5 - Elba: a) Phyllites with calcschist and metasandstone intercalations (SE of Norsi beach), b) metasandstones (Acquadolce, south of Rio Marina) of Acquadolce Unit; Gorgona: c) phyllites with calcschist intercalations (Torre Vecchia), d) Cala di Pancia metasandstones (Cala di Pancia) of Metasedimentary Unit.

Table 1 - Petrographic features of Acquadolce Unit (Central-Eastern Elba)

UNITS	LITHOLOGY	TEXTURE	MINERALOGIC ASSOCIATIONS			PARTICULAR REMARKS
			Main minerals	Accessories	Veins	
Phyllites with calcschist intercalations	phyllite and metasiltstone	lepidoblastic to granolepidoblastic	Ms+Chl+Qtz (±Ab±Cal)	Ep, Py, TiOp,Gr	Kfs+Ab±Tr-Act±Spn±Cal, Tr--Act, Ep+Cal, Ep+K-feld±FeOx±Cal, Py, Spn, Chl+Qtz+K-feld, Qtz+Ep+K-feld+Tr-Act	
	metasandstone	granolepidoblastic to granoblastic	- Qtz+Ms+Chl+Ab±Cal - Qtz± Mu±Chl (±Ab)	TiOp,Tur,Zrn, Spn,Gr,Ap,Py, Rt		Organic matter-rich levels
	calcschist	granolepidoblastic to granoblastic	Cal(±Dol)±Ms±Qtz±Chl±Ab	Rt,TiOp, Gr,Tur,Spn,Ep		Syn-tectonic quartz veins
Porticciolo Member	phyllite	lepidoblastic	Ms±Chl±Qtz	Gr,TiOp		Contact metamorphism minerals: Amp, Cpx, And, Wo, Grt, Ep, Ilv, Bt, Crd
	metasandstone	granoblastic	Qtz+Ms	Tur, Zrn	Cal+Chl, Py+Hem, K-feld,Cal+Fe Ox	
	calcschist	granolepidoblastic	Cal±Qtz±Ms(±Ab)	Gr, FeOx		
	marble	xenoblastic to granoblastic	Cal±Qtz	Gr±TiOp		

Mineral symbols (after Kretz, 1983): Qtz- quartz, Ms- muscovite, Chl- chlorite, Ab- albite, Cal- calcite, Dol- dolomite, Kfs- K-feldspar, Tr- tremolite, Act- actinolite, Spn- sphene, Ep- epidote, Fe ox- Fe oxides and hydroxides, Py- pyrite, Gr- organic opaques, Ti op- Ti opaques, Zrn- zircon, Ap- apatite, Rt- rutile, Tur-t ourmaline, Hem- hematite, Amph- amphibole, Cpx- clinopyroxene, And- andalusite, Wo- wollastonite, Grt- garnet, Ilv- ilvaite, Bt- biotite, Crd- cordierite, Lws- lawsonite, Stp- stilpnomelane, Mag- magnetite.

Table 2 - Petrographic features of Gorgona Metasedimentary Unit. Mineral symbols as in Table 1

UNITS	LITHOLOGY	TEXTURE	MINERALOGIC ASSOCIATIONS			PARTICULAR REMARKS
			Main minerals	Accessories	Veins	
Punta Gorgona Calcschist	phyllite	lepidoblastic to granolepidoblastic	Ms+Chl±Qtz (±Ab±Cal)	Gr, Tur,Zrn, Ap?,Rt	Qtz, Fe Ox	Graphite-rich levels
	metasandstone and metasiltstone	granolepidoblastic to granoblastic	- Qtz+Ms+Chl+Ab±Cal - Qtz+ Mu+Chl (±Ab)	Gr,TiOp,Tur, Zrn,Spn, Ap, Py,Rt		Syn-tectonic quartz veins
	calcschist	granolepidoblastic to xenoblastic	Cal±Ms±Qtz±Chl±Ab	Gr,Py,Rt,Tur		Local Bt or Stp after Chl
	marble	xenoblastic to homeoblastic	Cal (±Qtz±Ms)	Gr		Infiltrations of Fe oxides/hydroxides along the schistosity plains
	prasinite	granoblastic to augen	Chl+Ab+Tr-Act± ±Cal±Qtz±Na-amph± ±Lws	Ep,Spn,TiOp, Py or FeOx		Scattered idiomorphic Mag
Cala di Pancia Metasandstone	phyllite	lepidoblastic	Ms±Chl±Qtz±Cal	Gr,Rt,TiOp	Cal+Qtz	
	metasandstone	granoblastic	Qtz+Ms+Chl+Ab±Cal	Spn,Ep,Tur,Py, TiOp,Gr,Ap, Zrn		

The petrographic data are summarized in Table 2.

The comparison of the petrographic data in Tables 1 and 2 reveals that the lithotypes of the two islands have a similar mineralogical composition. It is noteworthy the relatively high content of sodic plagioclase found in most of the sampled metasandstone beds of both successions (Fig. 6). Sodic plagioclase is represented either by inclusions-free, twinned (simple and polysinthetic twins) or un-twinned blasts of albite or by syntectonic albite porphyroblasts with inclusion trails (Fig. 7; see also Fig. 4 in Pandeli and Puxeddu, 1990). These albite-rich metasandstones may be referred to original graywacke beds, possibly fed also by mafic volcanics (Mazzoncini, 1965), as it is suggested by the abundance of chlorite and Ti-bearing minerals. The mineralogical analogy between the discussed metasandstones is strengthened also by the accessory mineral association. Remarkable is also the occurrence of organic matter in all the metasedimentary lithotypes and particularly in the phyllites (e.g., recurrent black phyllitic levels).

As regards the blastesis-deformation relationships, quartz+K-white mica+chlorite±albite grow either on S_1 or S_2 foliations (Fig. 8). S_1 foliation can be often transposed by D_2 deformations and it is recognizable only at the microscale as intrafoliar relics. The syntectonic albite porphyroblasts are post-S_1/pre-S_2 “eyes” (Fig. 7) which contain organic opaques±K-white mica±rutile inclusion trails (S_1). HP-LT minerals (Na-amphibole and lawsonite) were recognized at the border and within the prasinite lens of the Punta Gorgona calcschists, as well as (lawsonite) in the metabasalts and metagabbros of the overlying Ophiolitic Unit. The Na-amphibole is represented by crossite. These HP-LT minerals generally occur as stretched and partly retrogressed relics (syn- D_1?) within the S_2 greenschist facies foliation (e.g., chlorite+tremolite-actinolite±albite) (Fig. 9). Moreover, rare Fe-Mg carpholite, reworked by the D_2 event, was recently found in the Metasedimentary Unit by Jolivet et al. (1998). A later blastesis of albite porphyroblasts, which include trails of syn-D_2 opaques+Ti-minerals+chlorite+epidote±tremolite

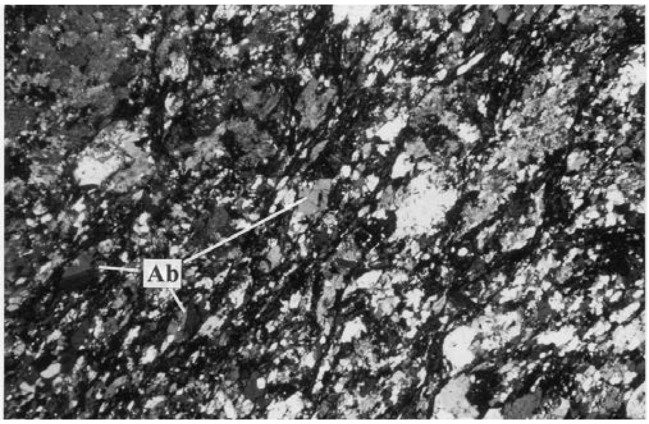

Fig. 6 - Photomicrograph of Ab-rich metasandstones within Acquadolce Unit (Acquadolce, south of Rio Marina). Crossed polars, 8,5x.

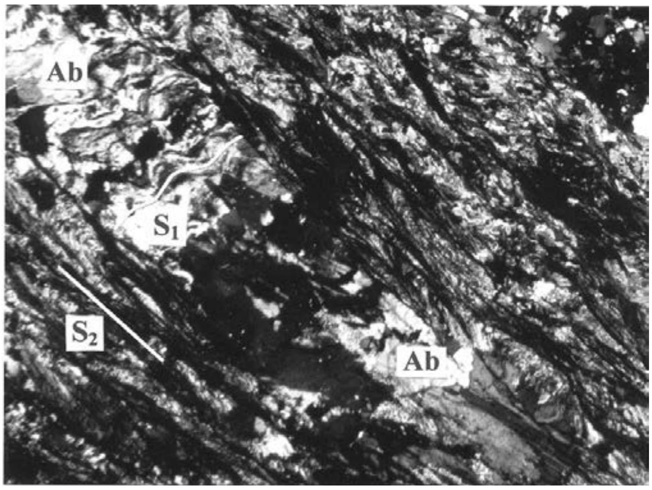

Fig. 7 - Pre-D_2 albite porphyroblasts within a quartzitic phyllite of the Metasedimentary Unit (Torre Vecchia, Gorgona I.). Crossed polars, 8,5x.

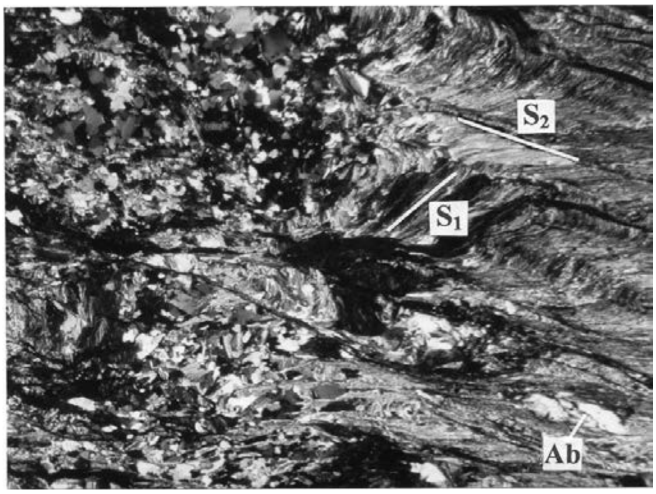

Fig. 8 - Photomicrograph of a quartzitic phyllite of the Acquadolce Unit (Ortano area, Elba I.). Crossed polars, 8,5x.

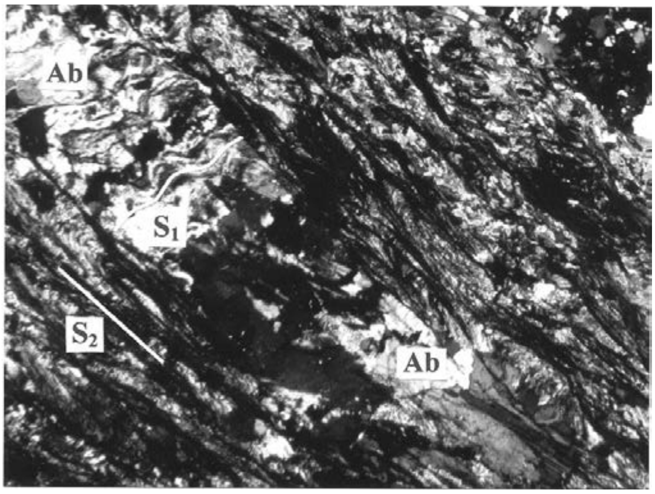

Fig. 9 - Photomicrograph of a prasinite within Metasedimentary Unit (Cala Martina, Gorgona I.). Syn-D_1 Na-amphibole is stretched and surrounded by syn-D_2 tremolite. Crossed polars, 8,5x.

inclusions trails and suffered D_3 deformations, is typical in the prasinite levels of the lower unit. Organic opaques±K-white mica locally occur along the C_3 foliations.

COMPOSITION OF THE K-WHITE MICA OF THE ACQUADOLCE UNIT

Nine samples of the Acquadolce Unit, showing no or little evidence of metasomatism, have been selected for the determination of the K-white mica composition. About 110 chemical analyses of the K-white mica found along both the S_1 and S_2 foliation have been performed using a Jeol JXA 8600 electron microprobe; operating conditions were: 15kV accelerating voltage, 10 nA excitation current and beam width <5 µm. The structural formula was calculated on the basis of 11 oxygens, all Fe was considered as Fe^{2+}.

The microprobe analyses and the calculated atoms per formula unit (a.p.f.u.) of the syn-D_1 K-white mica displaying the lowest and highest Si content are reported in Table 3. Fig. 10 shows the plot of the Si versus the $Mg+Fe^{2+}$ contents of the 72 analyses performed on the K-white micas parallel to S_1. These K-white micas are characterized by relatively variable compositions (Table 3). Despite these variations, no compositionally distinct populations of syn-D_1 K-white micas were found within each sample.

Microprobe analyses showed that the K-white micas, parallel to S_2 schistosity, are also characterized by wide compositional ranges, similar to those of the K-white micas found along S_1 schistosity. Therefore, it is likely that in the S_2 planes, some of the K-white micas formed during D_1 phase are mechanically re-arranged. As a consequence, the microprobe analyses of the K-white mica along S_2 might be not totally representative of the composition of K-white mica crystallized during the D_2 phase, hence these analyses are not reported here.

The relation between the Si and the $Mg+Fe^{2+}$ shown in Fig 10 by a large number of analyses of the syn-D_1 K-white micas can be related to the Tschermak substitution $[(Mg+Fe^{2+})^{VI}+Si^{IV}\leftrightarrow Al^{IV}+Al^{VI}]$. In fact, with the exception of the sample EL-6, most of the other analyses plot close to the ideal Tschermak substitution line, indicating that the wide variation of the Si content can be mostly imputed to this chemical substitution. The significant shift of the sample EL-6 above the ideal Tschermak substitution line can be ascribed to the presence of considerable amount of Fe^{3+}, in place of Fe^{2+}, as also suggested by the relatively high iron content and by the strong cation excess in the octahedral site found in these K-white micas (Table 3). Fig. 7, also, shows that numerous data points are slightly shifted above the ideal Tschermak substitution line. The latter observation could be related to the possible presence of modest amount of Fe^{3+} and/or to the addition of $Mg+Fe^{2+}$ from another substitution [i.e. $(Mg+Fe^{2+})^{VI}\leftrightarrow 2\ ^{XII}$, see below].

The K-white micas parallel to S_1 also exhibit either a deficiency in the interlayer site (the Σ^{XII} are mostly between 0.76 and 0.90 a.p.f.u.) and an octahedral cation excess (except for the sample EL-6, the Σ^{VI} are usually between 2.04 and 2.09 a.p.f.u.). The deficiency in the interlayer site is a common feature of metamorphic K-white micas (Guidotti, 1984; Wang and Banno, 1987). This deficiency was also noted in K-white micas of low-grade metamorphic metapsammites and metapelites of the Tuscan “Verrucano” Group (Baldelli et al., 1989; Giorgetti et al., 1998) and of metapelites of the Inner Ligurids (Leoni et al., 1998). The

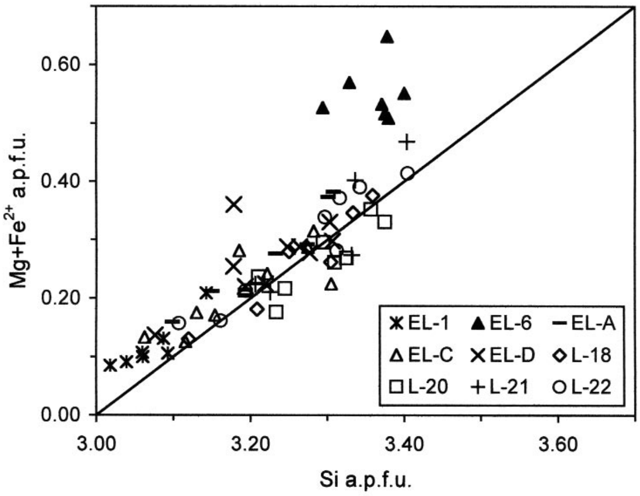

Fig. 10 - Plot of Si versus $Mg+Fe^{2+}$ content, expressed in atoms per formula unit (a.p.f.u.), of the syn-D_1 K-white micas found in nine samples of metapelites of Acquadolce Unit. The diagonal line represents the ideal Tschermak substitution.

Table 3 - Microprobe data and structural formula of syn-D_1 K-white micas showing the highest and lowest Si content found in nine samples of metapelites of Acquadolce Unit

	EL-D		EL-C		EL-A		L-18		EL-6		L-22		L-21		L-20		EL-1	
Oxides	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
SiO_2	51.28	47.00	51.09	47.31	50.38	47.08	52.15	48.34	52.39	48.84	52.45	47.68	52.77	49.62	51.75	49.18	47.96	45.33
TiO_2	0.11	0.17	0.16	0.28	0.11	0.13	0.20	0.23	0.08	0.27	0.09	0.70	0.09	0.27	0.11	0.19	0.91	0.17
Al_2O_3	32.04	36.82	32.81	37.39	30.70	35.89	30.64	36.88	28.26	28.81	29.34	36.01	28.98	34.47	30.57	33.82	34.33	37.70
Cr_2O_3	0.00	0.05	0.12	0.02	0.03	0.00	0.07	0.11	0.00	0.04	0.00	0.00	0.05	0.02	0.02	0.07	0.05	0.02
FeO	1.44	1.04	1.50	1.19	2.26	0.85	2.22	0.95	4.07	5.16	2.34	1.14	2.95	1.14	1.64	1.25	1.24	0.56
MnO	0.14	0.09	0.04	0.06	0.07	0.03	0.08	0.00	0.06	0.00	0.08	0.02	0.08	0.00	0.05	0.10	0.13	0.00
MgO	2.29	0.82	1.49	0.71	2.64	1.15	2.67	0.82	3.41	2.34	2.97	0.98	3.22	1.69	2.48	1.73	1.45	0.54
CaO	0.03	0.05	0.05	0.02	0.00	0.00	0.00	0.00	0.01	0.05	0.00	0.02	0.00	0.00	0.04	0.00	0.02	0.01
Na_2O	0.19	0.24	0.08	0.23	0.17	0.26	0.24	0.33	0.15	0.24	0.24	0.30	0.32	0.39	0.08	0.13	0.31	0.35
K_2O	9.80	9.69	9.11	9.99	9.80	10.38	9.05	8.97	9.27	9.28	9.16	9.33	9.27	9.03	8.90	9.62	9.69	9.36
Total	97.32	95.97	96.45	97.20	96.16	95.77	97.32	96.63	97.70	95.03	96.67	96.18	97.73	96.63	95.64	96.09	96.09	94.04
Si	3.31	3.08	3.31	3.06	3.31	3.10	3.36	3.12	3.40	3.29	3.40	3.11	3.40	3.21	3.38	3.21	3.14	3.02
Al^{IV}	0.69	0.92	0.69	0.94	0.69	0.90	0.64	0.88	0.60	0.71	0.60	0.89	0.60	0.79	0.62	0.79	0.86	0.98
Σ^{IV}	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Al^{VI}	1.74	1.92	1.81	1.92	1.68	1.88	1.69	1.93	1.56	1.58	1.65	1.87	1.61	1.83	1.73	1.81	1.79	1.98
Cr	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe2+	0.08	0.06	0.08	0.06	0.12	0.05	0.12	0.05	0.22	0.29	0.13	0.06	0.16	0.06	0.09	0.07	0.07	0.03
Mn	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Mg	0.22	0.08	0.14	0.07	0.26	0.11	0.26	0.08	0.33	0.24	0.29	0.10	0.31	0.16	0.24	0.17	0.14	0.05
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.03	0.00	0.01	0.01	0.01	0.04	0.01
Σ^{VI}	2.05	2.07	2.05	2.07	2.08	2.05	2.08	2.07	2.12	2.13	2.07	2.07	2.09	2.07	2.07	2.07	2.06	2.07
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.02	0.03	0.01	0.03	0.02	0.03	0.03	0.04	0.02	0.03	0.03	0.04	0.04	0.05	0.01	0.02	0.04	0.05
K	0.81	0.81	0.75	0.83	0.82	0.87	0.74	0.74	0.77	0.80	0.76	0.78	0.76	0.74	0.74	0.80	0.81	0.80
Σ^{XII}	0.83	0.84	0.77	0.86	0.84	0.90	0.77	0.78	0.79	0.83	0.79	0.82	0.80	0.79	0.75	0.82	0.85	0.84

The structural formula was calculated on the basis of 11 oxygens. All Fe was considered as Fe^{2+}. "EL" samples: Rio Marino-Porticciolo area, "L" samples: coast south of Norsi beach.

deficiency in the interlayer site can be controlled by a trioctahedral substitution: $(Mg+Fe^{2+})^{VI}\leftrightarrow 2\ {}^{XII}$ and/or by an illitic substitution: $K^{XII}+Al^{IV}\leftrightarrow\ {}^{XII}+Si^{IV}$ (Guidotti, 1984; Wang and Banno, 1987; Leoni et al., 1998). The systematic octahedral excess found in the syn-D_1 K-white micas of the Acquadolce Unit suggests that the interlayer cation deficiency could be related to the trioctahedral substitution. However, this substitution, which can compensate the absence of 0.08 to 0.18 K a.p.f.u., is not sufficient to explain all the interlayer cation deficiency. Consequently, the illitic substitution should have also contributed to this deficiency.

DISCUSSION AND CONCLUSION

The petrographic data shown in the previous paragraphs add new elements for the stratigraphic and paleogeographic understanding of the Acquadolce Unit and for the unravelling of the tectonic "puzzle" of the Elba Island. Original textures and mineralogical composition of these rocks are generally well recognizable in spite of the thermometamorphism generated by the Mio-Pliocene intrusions. Most of the Acquadolce Unit is made up of a metasiliciclastic sequence (phyllites, metasiltstones and minor metasandstones), locally including metric to decametric, at times coarse-grained metarenitic beds. This succession is comprised between basal marble-calcschists and a capping serpentinite slice. Locally, calcschist interbeddings occur within the siliciclastic succession, as well as minor decametric bodies of alternating calcschists, metacalcarenites, marbles and green to black phyllites (Porticciolo lithofacies, "*fc*" in Bortolotti et al., 2001a).

These lithological associations and their peculiar content in siliciclastics and organic matter rule out (see Pandeli and Puxeddu, 1990) the correlation of the upper part of the Acquadolce Unit with the Tuscan Dogger metasediments of the Apuan Alps, previously suggested (e.g. Barberi et al., 1969). Similar petrographic features are known also in some Paleozoic formations of the Tuscan Basement: for instance, a part of the Calamita Fm. of the Trevisan's Complex I, and the Lower phyllites of the Apuan Alps (cfr. Pandeli and Puxeddu, 1990 and Pandeli et al., 1994).

However, more lithological-compositional analogies are evident between the Acquadolce Unit and the Metasedimentary Unit of the Gorgona Island, even if the relative proportions of the lithotypes is partially different. In fact, the phyllite-metacarbonate alternation of the Porticciolo Member are common in the Gorgona Island (Punta Gorgona Calcschists), whereas the typical siliciclastic lithofacies of the Acquadolce Unit is less represented in the Gorgona Island. On the other hand, the metasandstone sequence of southwestern Gorgona (Cala di Pancia Metasandstones) may be easily correlated to the decametric metarenaceous body occurring in the Acquadolce Unit south of Rio Marina. Moreover, metamorphic ocean-type ophiolites overlie the metasedimentary succession in both islands (e.g., Ophiolitic Unit of the Gorgona Island: Capponi et al., 1990; top serpentinite of the Acquadolce Unit: Bortolotti et al., 1994).

The lithological analogies between the Acquadolce Unit and the Gorgona Metasedimentary Unit are emphasized by petrographic evidences, such as: i) the same mineralogical association occur in the metapelite and the metacarbonate lithotypes; ii) closely similar major and minor minerals in the metasandstones of both successions; iii) the occurrence of organic matter in the phyllites and metacarbonates. The relatively high content of sodic plagioclase and sheet silicates (e.g. chlorite) suggests a greywacke protolith for these rocks which are also rich in titaniferous minerals.

Moreover, the Acquadolce Unit and the Gorgona Metasedimentary Unit show a remarkably similar tectono-metamorphic evolution. Actually, both Units are strongly imprinted by D_2 isoclinal folding, whose axial plane schistosity frequently transposes the D_1 structures (e.g. the S_1 quartz+K-white mica+chlorite±albite intrafoliar relics). The pre-D_2 HP-LT minerals (Na-amphibole and lawsonite) found in the prasinitic lens of the Punta Gorgona Calcschist probably correspond to the S_1 relics and to the rare Fe-Mg carpholite (Jolivet et al., 1998) described in the surrounding metasediments.

The prasinite intercalations of the Gorgona Metasedimentary Unit are absent in the Acquadolce Unit. However, their present setting in the Metasedimentary Unit is not completely clear. Notwithstanding that Capponi et al. (1990) considered the two prasinite levels as many anticlinal culminations, these metabasite bodies could be referred to tectonic slices belonging to the overlying Ophiolitic Unit. This hypothesis can be supported by the nearness of the mylonitic contact between the two units and by the occurrence of a tectonic slice of calcschists in the basal part of the Ophiolitic Unit (Cala Maestra area: see Fig. 3).

Therefore, we think that the finding of typical HP-LT minerals in the Acquadolce Unit of the Elba Island is problematic because it implies either the lack of metabasalts and metagabbros (eventually including Na-amphibole and lawsonite relics) or the complete destruction of Fe-Mg carpholite, eventually present in the metasediments, occurred during the D_2 retrogression and the final thermometamorphic overprint.

Peak P-T conditions (13-16 kbar and 300-350°C) for the Gorgona Metasedimentary Unit have been recently proposed by Jolivet et al. (1998) on the basis of the Fe/Mg ratio in Fe-Mg carpholite, the Si content of the phengite associated with the Fe-Mg carpholite and the absence of chloritoid. The recent discovery of Fe-Mg carpholite evidenced an early Alpine high-pressure metamorphic event also in the Triassic metasediments of the Tuscan "Verrucano" Group at Monte Argentario (Theye et al., 1997; Jolivet et al., 1998), Giglio Island (Jolivet et al., 1998), and Monte Leoni-Montepescali areas (Giorgetti et al., 1998), and in the Paleozoic rocks underleying the "Verrucano" Group at Monte Leoni (Franceschelli et al., 1997). At Monte Argenatario and Giglio Island the metasediments are also spatially associated with metaophiolites with blue-schist mineral assemblages (Jolivet et al., 1998 and references therein).

The mineralogical assemblages of the Acquadolce Unit do not permit a precise constrain of the P-T conditions during metamorphism. Pressure indications can be obtained from the geobarometer of Massonne and Schreyer (1987), which is based on the variation of the pressure with the Si content (related to the Tschermak substitution) of the K-white mica, coexisting with K-feldspar+Mg/Fe-silicate+quartz. In our samples the K-feldspar is always lacking. In this view, the pressure calculated from the highest Si content of the K-white mica is only a minimum estimate (Massonne and Schreyer, 1987).

The highest Si content (3.40 a.p.f.u.) of the K-white mica found along S_1 of the Acquadolce Unit is displayed by the samples EL-6, L-21 and L22 (Table 3). Actually, because of the likely presence of Fe^{3+} in place of Fe^{2+}, which was not considered in the calculation of the structural formula, the Si content of K-white mica of the sample EL-6 is probably lower. The possible contribution of the illitic substitution (see paragraph 4) to the total Si content can also yield to an overestimation of the pressure computed with Massonne and Schreyer (1987) geobarometer. However, in the K-white mica showing the highest Si value of the sample L-21 the trioctahedral substitution, deduced from the octahedral excess (0.09 a.p.f.u.) can compensate most (0.18 a.p.f.u.) of the interlayer cation deficiency (0.20 a.p.f.u.), and the illitic substitution should contribute only for 0.02 a.p.f.u.. This Si excess produces a maximum pressure overestimation of about 0.5 kbar.

In Fig. 11 are reported the isopleth for a Si content of 3.40 a.p.f.u., and the reaction line jadeite + quartz = albite, calculated by the computer program *PeRpLeX* (Connolly, 1990) using the Holland and Powell (1998) thermodynamic database. This reaction constrains the upper pressure limit for the metamorphism of the Acquadolce Unit, as indicated by the common occurrence of albite either along S_1 or S_2, by the presence of detrital acidic plagioclase and by the lack of jadeite in the studied samples. Thus the pressure during the D_1 phase was relatively high (above 8 kbar assuming a hy-

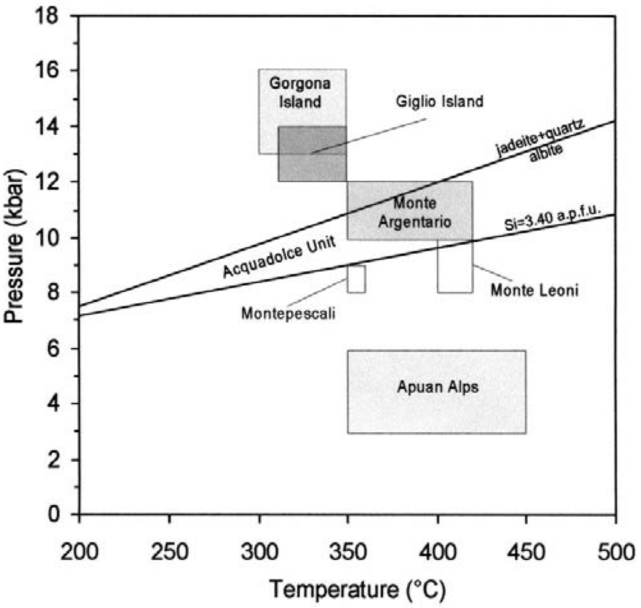

Fig. 11 - Pressure vs. temperature diagram showing pressure limits for Acquadolce Unit during D_1 and the pressure-temperature conditions of other Tuscan metamorphic complex. The maximum pressure in these albitic rocks is limited the reaction: albite = jadeite + quartz reactions, calculated using the PeRpLeX computer program (Connolly, 1990); the lower pressure is given by Si isopleth for the highest Si content of syn-D_1 K-white mica (Massonne and Schreyer, 1987). Pressure-temperature conditions of the Tuscan metamorphic complexes are from Jolivet et al. (1998) for Gorgona Island, Giglio Island and Monte Argentario, from Di Pisa et al. (1985), Franceschelli et al. (1986) and Franceschelli et al. (1997) for Apuane Alps, and from Giorgetti et al. (1998) for Monte Leoni-Montepescali. See text for details.

pothetical temperature of 300°C) and was comprised between the isopleth of 3.40 a.p.f.u. and the jadeite + quartz = albite line. Even if the pressure, and in particular the temperature conditions during the metamorphism of the Acquadolce Unit cannot be accurately evaluated, some indications may be obtained from the comparison between the pressure range, constrained by the isopleth of 3.40 a.p.f.u. and the jadeite + quartz = albite line, and the P-T peak conditions of different Tuscan metamorphic successions (Fig. 11). In particular, the peak pressures proposed for the Gorgona and Giglio Island Metasedimentary Units (Jolivet et al., 1998), and for the Apuane Alps metamorphic complexes (Di Pisa et al., 1985; Franceschelli et al., 1986; Franceschelli et al., 1997), are respectively significantly higher and lower than the pressure range of the Acquadolce Unit (Fig. 11). On the other hand, the pressure range of the Acquadolce Unit is compatible with the pressure estimated for "Verrucano" metasediments of Monte Argentario by Jolivet et al. (1998) and slightly higher then the pressure proposed by Giorgetti et al. (1998) for the "Verrucano Group" of Monte Leoni-Montepescali. The relatively high-pressure range proposed for the Gorgona Metasedimentary Unit by Jolivet et al. (1998) apparently contrast with the presence of albite (absence of jadeite) in the studied samples of this Unit. However, the same authors suggest that the pressure estimate derived from the Si content of K-white mica coexisting with Fe-Mg carpholite and sometimes with chloritoid (as in the case of the Monte Argentario successions) are uncertain and in particular they may be overestimated by about 3-5 kbar (Jolivet et al., 1998: pag. 12,135). A decrease of 5 kbar from the pressure proposed by Jolivet et al. (1998) would make the pressure range of the Gorgona Metasedimentary Unit to fall mostly within the stability field of albite. In this case the approximate pressure limits of the Acquadolce Unit do not significantly contrast with the pressure range of the Gorgona Metasedimentary Unit.

From a paleoenvironmental point of view, the sedimentary protoliths of both the Acquadolce and the Gorgona Metasedimentary Units, may be referred to a Upper Mesozoic-?Tertiary pelagic depositional area, as it is suggested by the Cretaceous pelagic fossils found in the Acquadolce Unit (Duranti et al., 1992). In particular, the lithological associations likely suggest a basin plain or trench area which was supplied by different imputs (i.e., carbonate-marly-shaly sediments and turbiditic siliciclastics). The siliciclastic rocks are more abundant in the Acquadolce Unit than in the Gorgona Metasedimentary Unit and in places they become prevalent (e.g., the Cala di Pancia Sandstone), suggesting the local development of arenaceous turbiditic deep-sea fan system. Such depositional paleoenvironment strictly recalls that of the Cretaceous-Lower Tertiary successions of the Ligurian and Ligurian-Piedmont Domains (cfr. Nardi, 1968; Abbate and Sagri, 1970; Durand Delga et al., 1978; Nardi et al., 1978; Durand Delga, 1984; Gardin et al., 1994; Marino et al., 1995 and references therein). These oceanic, probably trench successions include siliciclastic, often arcosic flysch fed by the Corsica-European active convergent margin (Abbate and Sagri, 1970; Abbate and Sagri, 1982; Sagri et al., 1982; Principi and Treves, 1984). In particular the Elba Acquadolce Unit and the Corsica Metasedimentary Unit may be equivalent to the following units:

i) Inner Ligurids (Vara Supergroup): the Upper Cretaceous-Paleocene Gottero sandstones which overlies Lower Cretaceous shales (Lavagna Shales) and shaly-carbonate alternation (Palombini Shales);

ii) Corsica Ligurids (Balagne and NE Corte): the Cretaceous Novella Sandstones of the Novella Unit, the Upper Cretaceous Alturaia arkose of the Navaccia unit or the slightly metamorphic Upper Cretaceous Tralonca flysch of the St. Lucia Unit;

iii) Corsica Ligurian-Piedmont Units (Inzecca): the low-grade metamorphic, Cretaceous-?Eocene Prunelli Flysch which rests onto shales and limestones (Erbajolo Fm.).

In the hypothesis that the Acquadolce Unit represents a Ligurian or Ligurian-Piedmont succession, its basal marble (Ortano Marble)-cherty calcschists may be correlated with the Lower Cretaceous Calpionella Limestones, and the phyllite-metacarbonate alternation of the Porticciolo Member could be considered a Lower Cretaceous, Palombini Shales-like unit.

Summing up, this study supports the attribution of the Acquadolce Unit to the oceanic Ligurian or Ligurian-Piedmont Domain and in particular the correlation with the HP-LT metasediments of the Gorgona Island. In addition, the barometric estimation, although approximate, indicate a relatively high-pressure metamorphic event (probably above 8 kbar) for the Acquadolce Unit.

Considering: i) the similar lithological-compositional features and the tectono-metamorphic imprint of both successions; ii) the 19.68±0.15 Ma ^{40}Ar/^{39}Ar age of the main schistosity (S_2) of the Acquadolce Unit, and iii) the finding of Cretaceous fossils in the Acquadolce Unit, the S_1 may be reliably attributed to the well known Upper Cretaceous-Eocene HP-LT events in the Corsica "Schistes Lustrés" and Western Alps.

The attribution of the Acquadolce Unit to a metamorphic Ligurian-Piedmontese succession allows a redefinition of the main tectonic boundaries in the Tuscan Archipelago. In this view, the frontal thrust of the "Schistes Lustrés" Nappe in the Tyrrhenian area should be located more to the east as previously supposed (e.g. Bartole et al., 1991; Perrin, 1975), i.e. in the Piombino Channel.

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