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NEW GEOLOGICAL DATA FROM GORGONA ISLAND (NORTHERN TYRRHENIAN SEA)

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ABSTRACT

The oceanic HP/LT metamorphic units cropping out in the Gorgona Island (Tuscan Archipelago) are an important element to define the Alps-Apennines geological boundary. In particular, they could represent a link between the Alpine *Schistes Lustrés* of the Corsica Island and the similar oceanic metamorphic units of the inner part of the Northern Apennines (e.g. Argentario Promontory, Giglio Island, Elba Island). The Gorgona Island tectonic stack includes two main units (the Metasedimentary Unit and the overlying Metaophiolitic Unit) separated by a north-eastward dipping cataclastic-mylonitic shear zone. These units are imprinted by a polyphased tectono-metamorphic evolution ranging from an Oligocene blue-schists event to the ?Miocene re-equilibration and exhumation in the green-schists facies. The new 1:2.000 mapping and the litostratigraphical, structural, petrographical studies presented here allow to improve the geological knowledge of the island. In the Punta Gorgona Calcschists (Metasedimentary Unit) three lithofacies were distinguished and mapped. Their areal distribution and the structural data (e.g. "s" and "z" - type asymmetries of the parassitic folds, the relationships between bedding and cleavages) evidenced several NW-vergent folds in the overturned limb of the D_2 mega-fold in the central-southern part of the island. Moreover, during the D_2 event, which exhumed and deformed the D_1 structures, shearing produced a mylonitic horizon between the two units. During the following extensional stages, an evident inversion of movement along the mylonitic horizon took place and produced a cataclastic texture. Later, weak folds, mainly E-W joints and possible high angle normal faults affected both units.

The reconstructed metamorphic-tectonic evolution is compared with that defined for "Alpine Corsica" and for the Northern Apennines chain. From a stratigraphic point of view the data suggest that the Cala di Pancia Sandstones may represent the stratigraphic top of the Metasedimentary Unit, and its probable lateral-vertical transition to part of the Punta Gorgona Calcschists are inferred. The Authors also discuss the possible correlations of the Gorgona Units with other Ligurian-Piedmontese Units cropping out in Corsica, in the Tuscan Archipelago and in the Northern Apennines.

INTRODUCTION

Located in the Northern Tyrrhenian Sea, about 33 kilometres from the Tuscan shoreline and about 65 kilometres from Capo Corso (Corsica Island), Gorgona is the northernmost island of the Tuscan Archipelago (Fig. 1).

Because of both its location and its geological features, the Gorgona Island plays a key role in the interpretation of the geological relationships between "Alpine Corsica", the Northern Apennine chain, the Ligurian-Provençal Basin and the Northern Tyrrhenian Sea (Bartole et al., 1991; Bartole, 1995; Jolivet et al., 1998). In particular, the litho-stratigraphic features of the poly-metamorphic Gorgona units represent important elements for correlating and reconstructing the paleogeographic relationships between the *Schistes Lustrés Nappes* of "Alpine Corsica" (Durand Delga, 1984; Jolivet et al., 1991 cum bibl.) and the similar non-metamorphic and metamorphic oceanic units cropping out in the Tuscan Archipelago and Southern Tuscany (e.g. Elba Island, Giglio Island, Argentario Promontory; respectively, Duranti et al., 1992; Bortolotti et al., 2001; Pandeli et al., 2001; Morelli, 2000; Pertusati et al., 1993; Capponi et al., 1997; Rossetti et al., 1999; Azzaro et al., 1977; Elter and Pandeli, this volume).

The Gorgona units are also pinning points for precising the geodynamic evolution of the Cretaceous-Eocene oceanic accretionary prism developed during the convergence of the Adria and Euroasia plates (Principi and Treves, 1984; Abbate et al., 1986; Bortolotti et al., 2001) and for localizing the Alps-Apennines geological boundary from the Sestri-Voltaggio (Cortesogno and Haccard, 1984) or the Villalvernia-Varzi-Levanto (Elter and Pertusati, 1973) to Tyrrhenian area (Elter and Sandrelli, 1994).

To improve the geological knowledge of this peculiar sector of the Tyhrrenian area, the Authors conducted a new 1:2.000 mapping and structural, petrographic analyses of the metamorphic succession of the Gorgona Island (see enclosed geological map) which reveal a more complicated lithostratigraphic framework than that previously available. The discussion of the obtained data allows to speculate on the possible stratigraphic setting of such unfossiliferous successions, on their possible correlations with the corresponding units in Corsica, in the Tuscan Archipelago and in the Northern Apennines. Moreover, the collected data improve the geodynamic knowledge of the Tyrrhenian Sea and of the double-vergent "Alpine Corsica" - Northern Apennines orogenic system.

GEODYNAMIC EVOLUTION OF THE CORSICA - NORTHERN APENNINES OROGENIC SYSTEM

Several Authors considered the "Alpine Corsica" - Northern Tyrrhenian Sea - Northern Apennines as a double- (e.g. Boccaletti et al., 1971; Boccaletti and Guazzone, 1974; Boccaletti et al., 1980) or a single- (Reutter et al., 1978; Reutter, 1981; Treves, 1984; Principi and Treves, 1984) fold and thrust orogenic system which is characterized by western (Corsica) and eastern (Northern Apennines) vergences. Two main stages occurred in the building up of the Northern Apennines (Principi and Treves, 1984; Bortolotti et al., 2001 cum bibl.): a) the Cretaceous-Eocene intra-oceanic subduction stage, with consumption of the Piedmont-Ligurian oceanic crust and the development of an accretionary

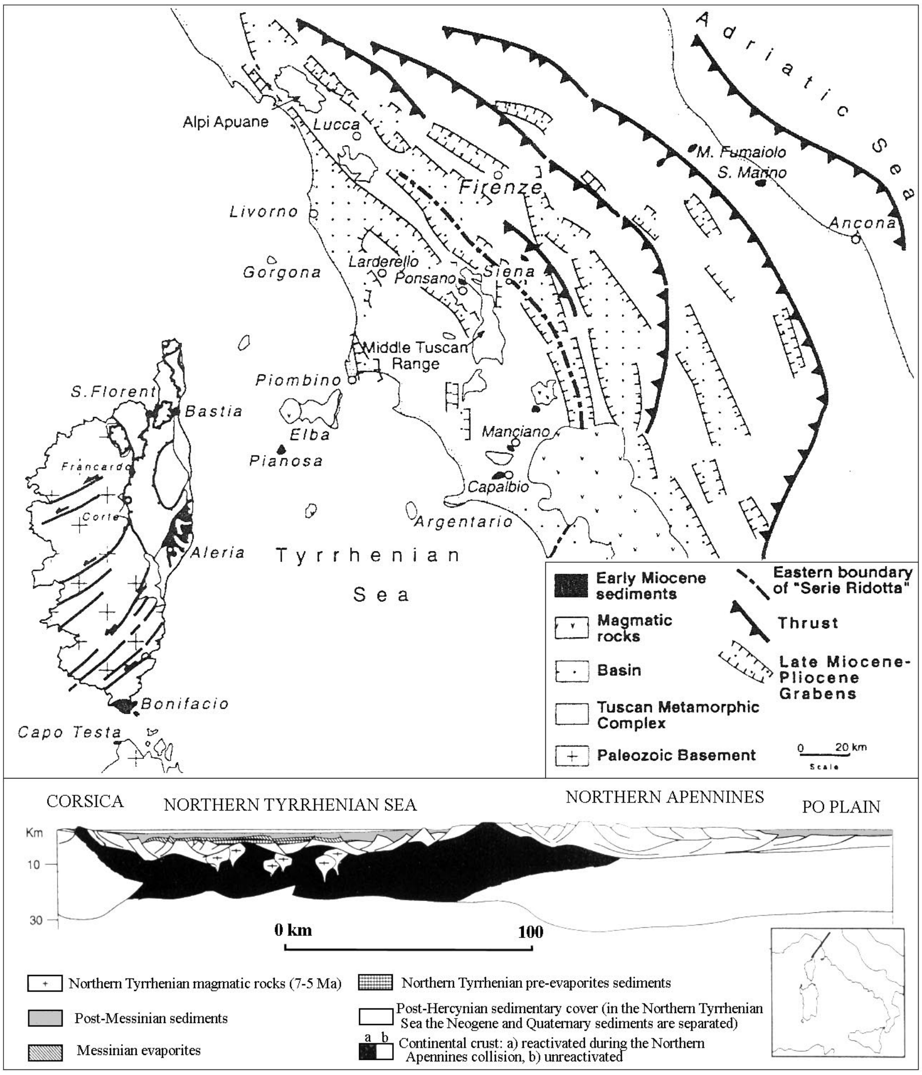


Fig. 1 - Geological sketch map of the Northern Tyrrhenian area (after Carmignani et al., 1995).

prism in which HP/LT metamorphism also occurs (e.g. *Schistes Lustrés Auctt.*); b) the Upper Eocene-Miocene syn-collisional stage of the Adria microplate against the European continental margin, which caused poly-phased shortening affecting both the Adriatic (e.g. Tuscan-Umbrian Units) and the European (e.g. "Alpine Corsica" Units) margins. In this stage we have the overthrusting of the oceanic accretionary prism onto the continental margins and the greenschists to HP/LT metamorphism of the Tuscan Units (Carmignani et Kligfield,1990; Elter and Pandeli, 1993; Jolivet et al., 1998; Giorgetti et al., 1998; Corsi et al., 2001); we have also the Oligocene - Lower Miocene opening of the Ligurian-Provençal basin, and finally the detachment from the Euroasiatic plate of the Corsica-Sardinia Massif and its counter-clockwise rotation.

It is still a matter of debate whether the exhumation of the deepest metamorphic units of the Alpine Corsica and Northern Apennines orogenic stacks was due to isostatic unroofing in a regional extensional context (e.g. Carmignani and Kligfield, 1990; Jolivet et al., 1991; Carmignani et al., 1995) or to syn-collisional exumation processes (Fazzuoli et al., 1994; Storti, 1995; Jolivet et al., 1998; Bortolotti et al., 2001).

During Miocene the compressional front shifted eastwards and extensional tectonics began in the inner part of the orogenic belt, thinning the crust through low- and high-angle normal faults (Carmignani et al., 1995; Bertini et al., 1991; Bartole 1995 cum bibl.). From Burdigalian to Quaternary these processes caused the opening, progressively from west to east, of the Tyrrhenian Sea, with the consequent development of the neoautocthonous basins and of the anatectic and sub-crustal magmatism (Bossio et al., 1993; Martini and Sagri, 1993; Serri et al., 1991 cum bibl.). At present the coexistence of both extensional and compressional tectonic processes is testified respectively in the inner (Tuscan and Umbria areas) and the outernmost zone (Marchean area and Adriatic foredeep) of the orogen (Boccaletti et al., 1985; Castellarin et al., 1985; Eva et al., 1990; Eva and Solarino, 1992).

HISTORICAL BACKGROUND

The geological studies of the Gorgona Island began during the 19th century. Pareto (1841), Lotti (1883), Franchi (1896), Ugolini (1902), described the main lithostratigraphical and mineralogical-petrographical features of the Island. Lotti (1883) first pointed out the similarities between the Gorgona successions and the ophiolitic successions cropping out in the Alps, Liguria, and Corsica.

The first complete geological and petrographical study was carried out by Mazzoncini (1965) who recognized the stacking of two tectonic units within the metamorphic succession (the lowermost one including albitic gneisses, calcschists, micaschists and minor prasinites, the uppermost one characterized by metaophiolites), superimposed by an eastward dipping cataclastic-mylonitic contact.

Capponi et al. (1990) refined Mazzoncini's stratigraphic-tectonic model of the Gorgona tectonic stack. They named the lower unit as "Metasedimentary Unit" (including the Cala di Pancia Metasandstone, the Punta Gorgona Calcschists and the Cala Martina Prasinites) and the upper unit as "Ophiolitic Unit" (constituted by the Cala Maestra Serpentinites and the Punta Maestra Metabasites). The Authors assign these units to different paleogeographic domains within the Piedmontese and Ligurian-Piedmontese realms, and also they defined a detailed structural evolution of their poly-deformed successions.

Recently, Rossetti et al., (2001) and Pandeli et al. (2001). Both papers outlined the metamorphic evolution of the succession from blue-schist metamorphism (25.5 Ma $^{40}Ar/^{39}Ar$ radiometric age in Rossetti et al., 2001; Brunet et al., 2000) to green-schist reequilibration. Finally Orti (2000), Pandeli et al. (2001) and Bortolotti et al. (2001) proposed a probable correlation of the Gorgona metasedimentary succession with the Acquadolce Unit outcropping in the Eastern Elba Island.

LITHOSTRATIGRAPHIC DATA

The Gorgona Island is mostly composed of metamorphic rocks showing a general NE-dipping foliation, except for the limited outcrops of Quaternary landslide debris (along the coast between Capo Zirri and Cala dell'Acqua, south of Belvedere and near Torre Garibaldi and Fanale) and the alluvial and colluvial covers (in the Gorgona Scalo valley and west of Piazza d'Armi: see geological map).

The areal distribution and geometrical relationships of the three lithofacies distinguished in the Punta Gorgona Calcschists (Orti, 2000) are mainly linked to the attitude of the D_2 folds (see below). In addition, the polyphased tectono-metamorphic evolution caused the obliteration of the sedimentary and magmatic structures, of the primary lateral and vertical relationships between such units, and of their original thickness. The three different lithofacies are described below, and the restoration of the pre-metamorphic stratigraphical assemblage is discussed next.

Metasedimentary Unit

Punta Gorgona Calcschists

This lithological unit constitutes the majority of the metasedimentary succession cropping out in the central and western part of the island, and its apparent thickness exceeds 1000 metres although it is likely increased by isoclinal folding. Three main lithofacies can be defined on the basis of the percentage of the phyllitic, carbonate, and siliciclastic component.

1) **Metalimestones with phyllitic intercalations (PGC1)**, consisting of lenticular, metric to decametric thick (max. 30 m) levels which are particularly well exposed in the area between Torre Vecchia, Punta Gorgona and Cala Scirocco (see geologicl map). PGC1 (Fig. 2a) is made up of alternating, generally decimetric (up to 35 cm) beds of light to dark grey calcschists and ± impure meta-calcarenites and meta-calcilutites with silver grey to black and minor greenish phyllitic intercalations. In some places (e.g. near Casa Bellavista), up to 5 metres thick, massive to stratified, locally saccaroidal marble bodies, whitish to dark grey in colour, are intercalated within the PGC1 and were quarried in the past. Locally, centimetric yellowish to light brown quartzitic levels also occur.
2) **Metasandstones, metalimestones and phyllites (PGC2)**. This lithofacies crops out in the central-western and southern part of the island, between Cala dell'Acqua and Cala Scirocco (Fig. 2b).
PGC2 consists of a centimetric to decimetric alternation of silver grey, greenish to black phyllites, grey to brown, or greenish, often feldspatic metasandstones and metalimestones fine to medium-grained in size and grey to dark grey metalimestones and calcschists. The content in metacarbonates is quite variable in different outcrops and, for example, it is low between Cimitero and Torre Vecchia, whereas it is relatively high in the Casa Bellavista area.
The apparent thickness of PCG2 varies from 40 to 80 m.
3) **Phyllites, metasandstones and metasiltstones (PGC3)**. PGC3 crops out extensively in the central part of the Gorgona Island, from Torre Vecchia to Cala Martina (fig. 2c). Silver grey, black, locally greenish phyllites generally prevail onto centimetric-decimetric (max. 35cm) intercalations of grey to greenish metasandstones and minor metasiltstones. Only in a few places (Cimitero, Punta Zirri, Casa Colonica and Torre Garibaldi), the metarenite/metapelite ratio is high (1,5 to 3). Rare thin-bedded (up to 5 cm) calcschists locally occur. The meta-arenite levels in the PGC2 and PGC3 are compositionally metagreywakes very similar to the Cala di Pancia Metarenites.

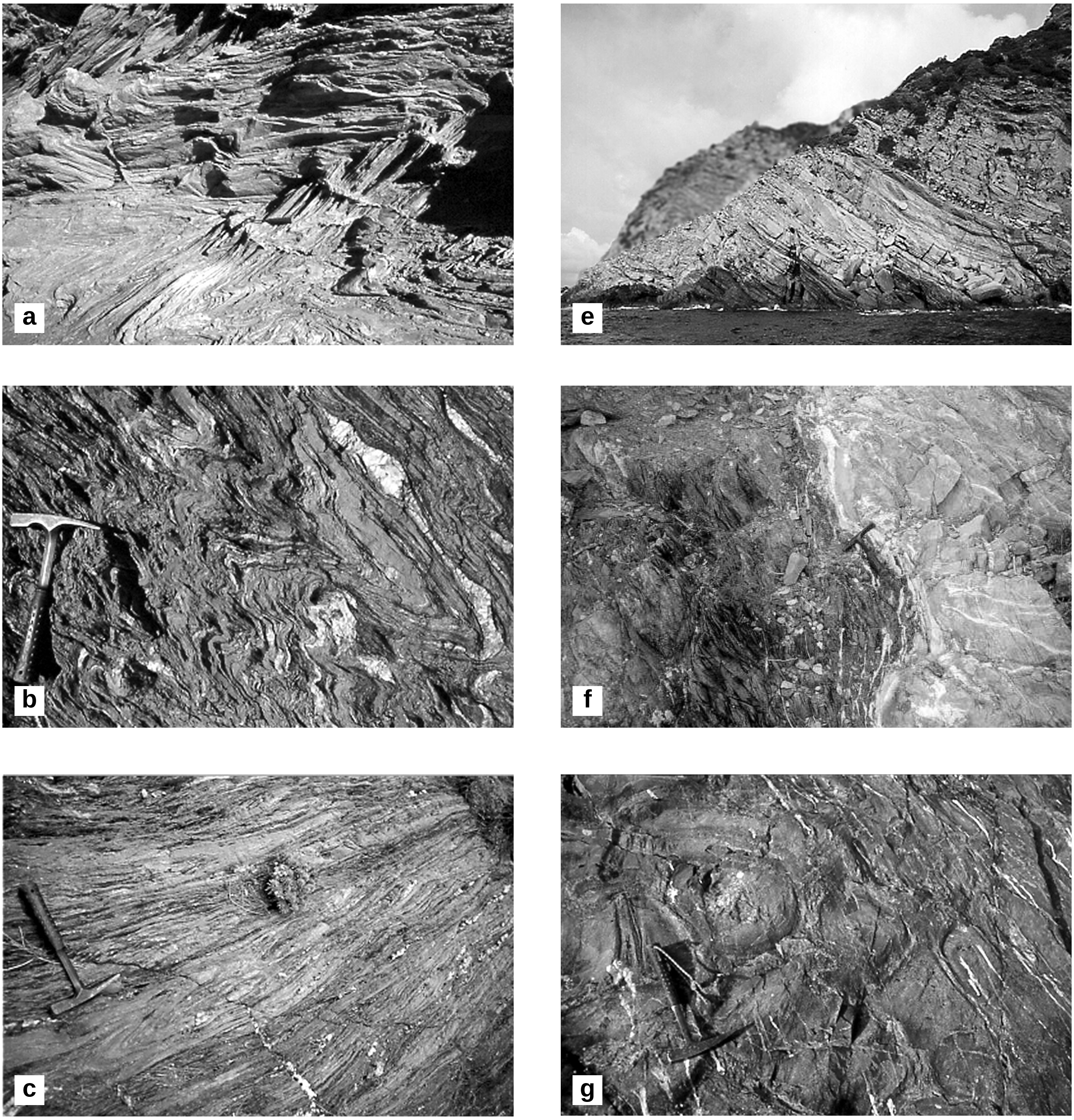
Cala Martina Prasinites

Cala Martina Prasinites (CMP) are present both in the Cala Martina and North of Torre dell'Orologio areas as lenticular intercalations within the geometrical uppermost part of the Metasedimentary Unit. In particular, at Cala Martina (Fig. 2d) they form two horizons, about ten-metres thick and pinching out to the northwest within the Punta Gorgona Calcschists (PGC2). The prasinites are light green, foliated metabasaltic rocks whose primary magmatic textures are completely obliterated by the tectono-metamorphic events. They are characterized by albite, chlorite, epidote, Al-free amphibole and sphene arranged in syn-tectonic assemblages. Relic blue amphibole can be locally present. The relative high content in sphene suggests a magmatic basic protolith. The contacts with the surrounding rocks are relatively sharp.

Pandeli et al. (2001) and Rossetti et al. (2001) consider the Cala Martina Prasinites as tectonic slices of the Metaophiolitic Unit within the upper part of the Metasedimentary Unit

Cala di Pancia Metarenites

The Cala di Pancia Metarenites (CPM) are exposed only along the SW coast of the Island, along the impressive cliffs of Costa dei Gabbiani-Cala di Pancia (see geological map), and they consist of arenaceous and arenaceous-pelitic lithofacies (Fig. 2e). CPM includes decimetric to metric (up to 5 m) no graded to very poorly graded metagreywackes which are medium to coarse grained in size and grey in colour. The metarenitic beds are separated by millimetric to centimetric (max 20 cm), grey to black phyllitic intercalations. In the geometric upper part of the succession, erosional bases and



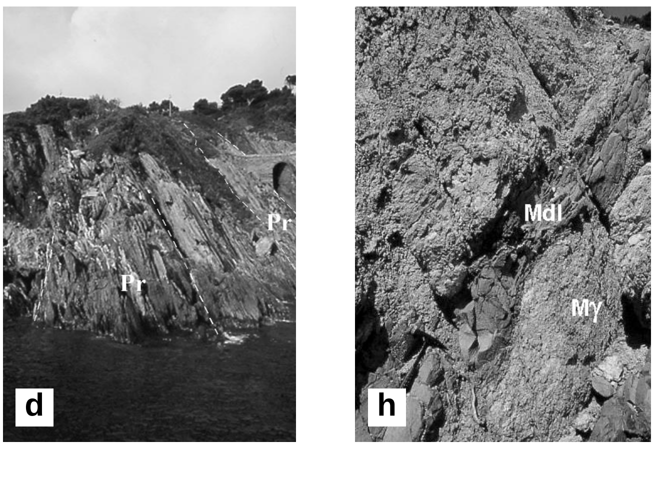


Fig. 2 - Lithological features of the Metamorphic Units of the Gorgona Island. a- PGC1 lithofacies of the Punta Gorgona Calcschists, deformed into D_2 tight folds, at Grotta del Soldato locality (nort-west of Casa Bellavista). b- PGC2 lithofacies of Punta Gorgona Calcschists, deformed into D_2 tight to isoclinal folds, along the path to Cala di Pancia. c- PGC3 lithofacies of Punta Gorgona Calcschists near Villa Margherita. d- Prasinite lenticular horizons (Pr) at Cala Martina. e- Cala di Pancia Metarenites at Cala di Pancia. f- Folded contact between foliated Cala Maestra Metaserpentinites (on the left) and the Punta Maestra Metabasite along the cliff south of Gorgona Scalo. g- Pillow lavas in the Punta Maestra Metabasites at Fanale di Cala Maestra. h- Metagabbros (Mγ) intruded by Metadolerites (Mdl) in the Punta Maestra Metabasites near Torre dell’Orologio.

welding are evident in the dominant coarse-grained and thick arenaceous beds which are frequently characterized by discontinous microconglomerate basal horizons and/or bands or crude laminations.

In the lower part of the Cala di Pancia cliff, a cyclic organization (metric, multiple-type, coarsening and thickening upward cycles) can be identified. The apparent thickness exceeds 230 m (the geometrical base is not exposed), but this value is likely overstimated because of local folding. The CPM geometrically underlies the Punta Gorgona Calcschists (PGC2 lithofacies), but the contact is generally poorly exposed and, according to Mazzoncini (1965), affected by post-metamorphic shearing. The presence of similar metarenites as intercalations within the Punta Gorgona Calcshists (e.g. PGC2 and PGC3 lithofacies) suggests a probable gradational relationships between the two units.

Metaophiolitic unit

This unit, which constitutes the north-eastern part of the Island, tectonically overlies the Metasedimentary Unit and shows a minimum apparent thickness of 300m (lacking of the geometrical top). It consists of (from the geometrical base to the top):

Cala Maestra Metaserpentinites (CMS)

This unit of maximum 40 m thick is discontinuosly exposed along a northwest/southeast trending belt from Scalo di Gorgona to Cala Maestra (Figs. 2f). In the Torre dell'Orologio area CMS is missing and the Punta Maestra Metabasites directly overlie the Metasedimentary Unit. Minor metaserpentinites pods locally occur in the lower part of the Punta Maestra Metabasites. CMS is composed of green to dark green-black antigorite-chrysotile serpentinite schists which are generally foliated and polydeformed and with local veins and coatings of steatite. The original texture (olivine and pyroxene assemblage) is rarely preserved. The basal part of CMS is sheared (see the cataclastic-mylonitic horizon described below) and some discontinous shear zones also occur within the highly deformed metaserpentinites.

Punta Maestra Metabasites (PMM)

They form most of the Metaophiolitic Unit and includes several lithologies: a) foliated fine-to medium-grained massive metabasalts, dark to light green to light grey-brown in colour. Porphyritic textures can be rarely recognized and, at places (e.g. Fanale di Cala Maestra and between Torre Nuova and Torre dell'Orologio), pillow lavas also occur (Fig. 2g). b) More or less amphibolized, at times coarse-grained, metagabbros that are commonly intruded by doleritic dikes (Fig. 2h). This lithologic assemblage crops out discontinuously above the Metaserpentinites along a belt between Scalo di Gorgona and the area north of Torre dell'Orologio, but also along the coast below Torre Nuova. The gabbros are locally transformed into nematoblastic tremolite-actinolite amphibolites in correspondence to the basal cataclastic-mylonitic shear zone (e.g. area north of Torre dell'Orologio). c) Green to greenish, often porphyritic metadolerites locally belonging to a complex network of intersecting dikes, centimetric to decimetric in thickness. In spite of the pervasive tectono-metamorphic deformation, in some outcrops (e.g. at the crossroad to Fanale, few metres east of Torre Nuova) the dikes show an evident decrease of the crystal size from core to rim that can be referred to primary cooling structures ("chilled margins").

STRUCTURAL AND METAMORPHIC DATA

The meso- and micro-structural analysis points to a complex tectono-metamorphic evolution of the oceanic units of the Gorgona Island (see Figs. 3a, b). Three main deformation events were recognized: the first two syn-metamorphic in the blue-schist and green-schist facies, respectively, showing different imprint in the two units. Therefore the structural framework will be separately described for the Metasedimentary Unit and the Metaophiolitic Unit, that are tectonically superimposed by a cataclastic-mylonitic horizon. All over the Island, the main foliation, which is generally a composite schistosity, constantly deeps to the northeast (Fig. 3a, b). Details of the blastesis and deformation

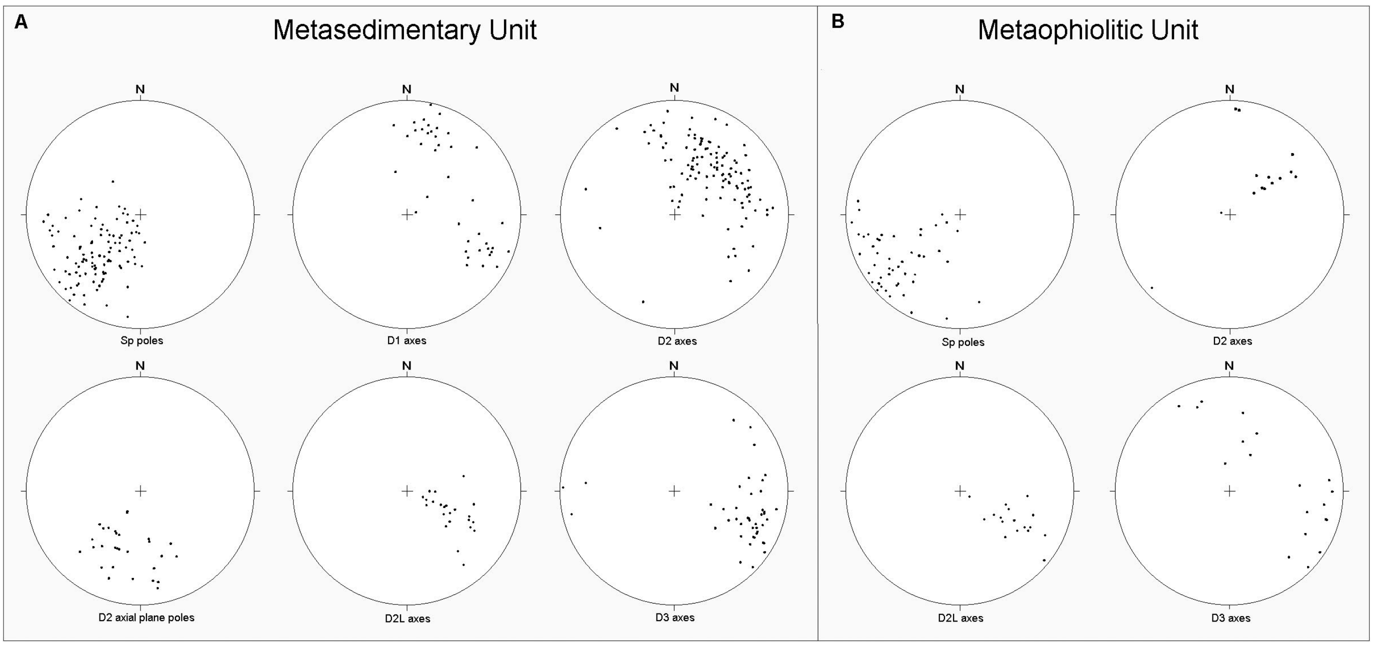


Fig. 3 - Stereonets of the structural elements of the metamorphic units: A) Metasedimentary Unit; B) Metaophiolitic Unit. Lower hemisphere Schmidt projection.

events are shown in Table 1 and Table 2 (mineral symbols after Kretz, 1983).

The Metasedimentary Unit

D_1 event. The main continuous penetrative schistosity (Sp) which is recognizable at the mesoscopic and microscopic scale is related to the axial plane foliation of the D_1 folds. The D_1 folds (Fig. 4a), whose field evidence is scarce because of the strong transposition caused by the D_2 structures (Fig. 4b), are tight to isoclinal, often unrooted and decimetric to metric in size. The plunge of their axes is toward north/northeast or east/southeast (Fig. 4a).

Sp is made up of quartz + muscovite + calcite + chlorite ± albite (Fig. 4c), but pre-D_2 relics of typical blue-schists minerals (Na-amphibole, lawsonite) were recognized in the Cala Martina Prasinites (Fig. 4d) and sorrounding rocks. Moreover phengite + Fe-carpholite ± chlorite was identified by Rossetti et al. (2001) in syn-tectonic (pre-D_2) quartz veins. This chloritoid-free mineralogic association and the Si content of phengite, allowed Jolivet at al. (1998) and Rossetti et al. (2001) to suggest thermo-barometric peak conditions of ~ 1.5 GPa for T = 300-350°C. On the other hand, Pandeli et al. (2001) proposed a P-T range of P = 0.8 - 1.4 GPa for T = 300-450°C because of the composition of the white micas, the abundance of Ab, and the lack of jadeite. A 25.5 ± 0.3 Ma Ar^{40}/Ar^{39} age for the HP - LT phengites was defined by Rossetti et al. (2001) and Brunet et al. (2000). Sp is the main planar structure in most of the outcrops of the Metasedimentary Unit, but close to the contact with the cataclastic-mylonitic horizon, this foliation is recognizable only as intrafoliar relic within S_2 schistosity. The occurrence of a pre-D_2 inter-kinematic static blastesis (M_{S1} event) of albite and quartz porphyroblasts, which contain helicitic inclusions and trails of graphite and/or rutile, was also observed (Fig. 4e).

D_2 event. The D_2 meso-folds (Fig. 4f) are the most evident structures within the Metasedimentary Unit. They are millimetric to decametric, close/tight to isoclinal folds which frequently show an asymmetric shape (mostly "z-type", looking to the north: see also the map of Capponi et al., 1990) and curved to sharp hinges. The plunge of A_2 is towards the north-east quarter and the dip progressively increases going towards the cataclastic-mylonitic horizon (e.g. from Cala di Pancia to Cala Martina: see Fig. 4b and geological map); the axial surfaces generally dip towards north-east (Fig. 4a). The dispersal of the F_2 axes onto their axial surface is generally not more than 35°. The interference pattern between F_2 and F_1 is type-3 of the Ramsay classification (see also fig. 7-4 in Capponi et al., 1990) and suggests a sub-axial folding.

The spaced S_2 foliation generally consists of a millimetric to centimetric discrete crenulation cleavage (Fig. 4g and 4h), evolving towards northeast into a continuous, thinly-spaced schistosity made up of greenschists-facies minerals (quartz + muscovite + chlorite ± albite, ± tremolite - actinolite and ± epidote in the Cala Martina Prasinites: Fig. 4i). In the limbs of the tight to isoclinal F_2, S_2 locally overprints S_1 and gives origin to a composite schistosity. In the latter case, S_1 is completely transposed and it is only locally recognizable within intrafoliar mica fishes. The attitude of S_2 is either parallel to the F_2 axial surfaces or forms convergent fans. At

Table 1 - Blastesis and deformation events in the Metasedimentary Unit.

Formation	Texture	D_1 (M_1)	M_{S1}	D_2 (M_2)	M_{S2}	D_{2L}	D_3	M_{S3}	D_4	NOTE
Punta Gorgona Calcschists	granoblastic to granolepidoblastic// lepidoblastic	Cal+Ms+Chl+ +Qtz+Ab+ Gr mica fish (±Ms±Chl±Qtz) Fe-Mg Cp in Qtz syn- -tectonic veins	Ab Qtz	Cal+Ms+Qtz+Gr± ±Chl±Ab ↓ Ms±Gr±Qtz±Chl		crenulations Ox, Gr	fracture cleavage, zonal crenulations and kinks	Bt after Chl	jointing and faulting	syn-tectonic veins of polycristallineQtz±Ms± ±Chl±Cal and of Cal± ±Qtz±FeOx post-tectonic veins of Cal+Qtz±FeOx
Cala di Pancia Metasandstones	blastopsammitic to granoblastic	Qtz+Ab+Ms+Chl+Ca l	Ab	Ms+Chl+Qtz+Cal±Ab			Idem		Idem	Fe ox/hydrox infiltrations
Cala Martina Prasinites	porphyroblastic/ /granolepidoblastic to nematoblastic	Na-Am (Gln, Cro)+ +Ms+Lws±Chl mica fish (Ms+Chl)	Ab	Chl+Ab+Ep±Cal±Tr- -Act±Ms±Qtz±Spn± ±TiOx	Ab	Idem	Idem		Idem	relics of magmatic Cpx and Pl post-tectonic veins of Cal+Qtz and Ab±Qtz± ±Cal±Chl±Py

Table 2 - Blastesis and deformation events in the Metaophiolitic Unit.

Formation	Texture	D_1 (M_1)	D_2 (M_2)	D_{2L}	D_3	M_{S3}	D_4	NOTE
Cala Maestra Metaperidotites	cellular to lepido/nematoblastic	Ant ± ox	Crs + Chl ±ox	Crs + Chl	fracture cleavage, zonal crenulations and kinks		jointing and faulting	relics of magmatic Cpx Fe ox/hydrox, Cal, Crs and/or talc veins
Punta Maestra Metabasites	porphyroblastic/ /granolepidoblastic to nematoblastic	Lws ± Ab ± ± Na-Am (Cro) mica fish (Chl±Ms)	Chl+Ab±Tr- -Act±±Qtz± ±Ms±Ep± ±Spn±Tiox	Chl	Idem	Bt ±Chl Mag	Idem	relics of magmatic Cpx post-tectonic veins of Ep, of Qtz+Tr- -Act+Ab, of Ab+ +Cal+Ep and of Ab±Cal±Qtz

places (e.g. Cala di Pancia) the interference relationships between S_2 and $S_0//S_1$ (Fig. 4h) and the extimated closure of the folds by "s" and "z"-type asymmetries suggest a western vergence of the D_2 folds. On the basis of parageneses and mineral compositions Rossetti et al. (2001) estimated P < 0.55 GPa for T = 190°C or P = 0.6-0.7 GPa for T = 300-350°C for the D_2 event. In the Cala Martina area, late D_2 crystallization (M_{S2} event) of albite, which includes syn-S_2 epidote and actinolite-tremolite, can be also recognized (Fig. 4i)

In the surroundings of the cataclastic-mylonitic horizon, a late-D_2/pre-D_3 deformation event (D_{2L}) is suggested by close to tight decimetric folds with a steep east-south east axial plunge (Fig. 4a), locally with "z-type" (looking to the west) asymmetries, and spaced zonal crenulation to fracture cleavage, which deform the D_2 structures. The D_{2L} lineations are generally at right angle with respect to the D_2 ones, which are also folded by the D_{2L} event. According to Jolivet et al. (1998), the D_{2L} structures are due to the rotation of the D_2 axes parallel to the strike of the main schistosity during the formation of the mylonite.

D_3 event. It is characterized by gentle to open, symmetric folds with sub-vertical axial surfaces and metric to decametric size. A spaced fracture cleavage is associated to F_3 and the axes plunge east/southeast (Fig. 4a). A later static blastesis of biotite after chlorite (M_{S3} event) was also locally recognized.

Later, a mainly E-W-trending jointing and normal faulting also took place (D_4 event) and mineralizations locally filled this fracture pattern (see Table 1).

Metaophiolitic Unit

The relative uniform lithologic features of the metabasites did not favour the development of the secondary meso-structures except than in the serpentiniteschists. In any case, the meso- and micro-structural analyses point to three deformation events also in the Metaophiolitic Unit (Fig. 4a and Table 2):

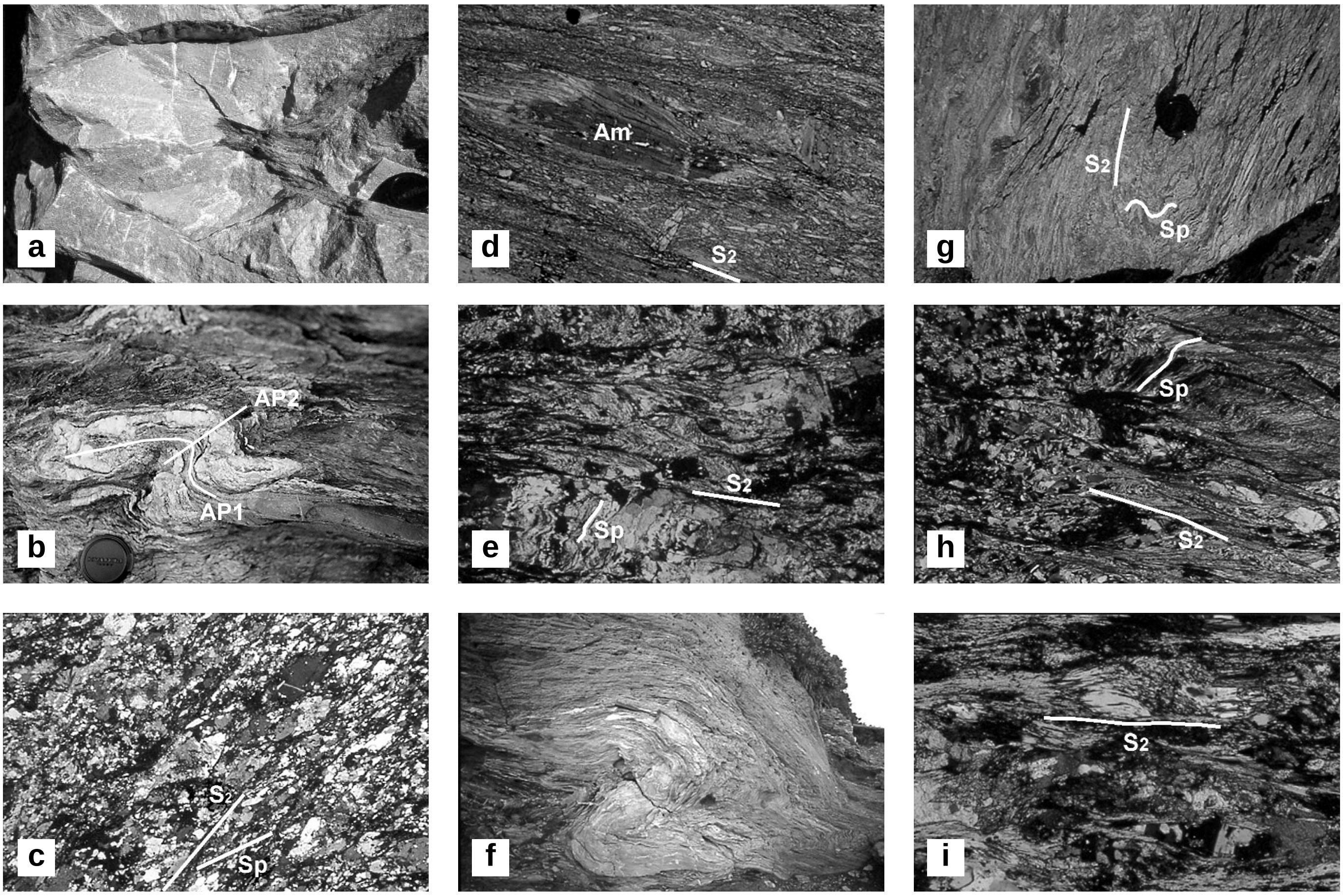


Fig. 4 - Meso- and Micro-structural features of the metamorphic unit of Gorgona. a- Isoclinal D_1 fold in a metacalcareous level in the PGC1, north of Cala di Pancia. b- D_2 refolding a decimetric syn-D_1 isoclinal fold, near Torre Vecchia. AP1- axial plane of the D_1 fold; AP2- axial plane of the D_2 fold. c- Photomicrograph of the Cala di Pancia Metarenites pervaded by Sp and S_2 foliations. 25X, two polars. d- Stretched Syn-D_1 Na-Amphibole (Am) surrounded by syn-D_2 tremolite-actinolite. 25X, one polars. e- Inter-kinematic (post-D_1/pre-D_2) Albite-porphyroblast. 25X, two polars. f- D_2 fold in the PGC2 lithofacies cropping out along the path from Cala Scirocco to Cala Martina. g- Interference pattern between the continuous Sp foliation and the spaced D_2 foliation associated with tight-isoclinal folds. h- Photomicrograph of the interferences pattern into the D_2 folds of the previous figure. Note the interference relationships between S_2 and $S_0//S_1$, 25X, two polars. i- Photomicrograph of the Cala Martina Prasinites (mineral assemblage of S_2 = Albite ± Tremolite-Actinolite ± Epidote ± Qtz ± Cal). It is worth to note the late D_2 blastesis of Ab porphyroblasts. 25X, two polars. j- Mylonitic-cataclastic horizon. Brittle and semibrittle (e.g. book-shelf-like structures, asymmetric boudinage-like structures) structures overprinting ductile fabric (e.g mylonite texture, asymmetric folds), along the cliff south of Gorgona Scalo, looking to west.

D_1 event. It is recognizable at a microscopic scale by HP/LT minerals (lawsonite, crossite) occirring as intrafoliar relics within S_2 of the metabasites. Antigorite in the metaserpentinites is probably connected to the HP/LT event too.

D_2 event. In the Punta Maestra Metabasites, tight to isoclinal folds with NE plunging axes and very pervasive axial plane schistosity marked by greenschist-facies minerals (S_2 = tremolite-actinolite + chlorite + albite + quartz + epidote + sphene) were frequently observed. Porphyroblasts of Ep and Ab, which are pseudomorphs of plagioclase phenocrysts, also occur. The same folds, with an associated more or less penetrative, thin to medium spaced foliation, consisting of chlorite + chrysotile fibres, are locally present in the serpentiniteschists of the Cala Maestra Metaserpentinites.

South of Gorgona Scalo, also the contact between metaserpentinites and metabasites is clearly folded by the D_2 event (Fig. 2f). In the same area, a decimetric later folding similar to the D_{2L} one (see previous paragraph) is recognizable close to the basal contact with the cataclastic-mylonitic horizon.

D_3 event. This event produced weak to open folds which are characterized by curved hinges and subvertical axial plane. The axes mainly plunge toward south-east (Fig. 3a). The centimetric spaced axial plane foliation is generally a fracture cleavage, but locally gentle crenulation and kinks occur.

A post tectonic blastesis (M_F event) of biotite±chlorite and magnetite is also evident as well as an east/north-east west/south-west to east-west trending faulting and jointing event (D_F).

The cataclastic-mylonitic shear zone

The Metasedimentary Unit and overlying Metaophiolitic Unit are separated by a cataclastic-mylonitic horizon (Fig. 4j) which dips 60-70° toward north-east and shows a variable thickness (from some decimetres to some metres). Along the coast south of Gorgona Scalo, this horizon is a light green to brownish, about 1 meter thick body which include heterometric clasts of phyllites and metasandstones (abundant in the lower part of the body) and metapeserpentinites in a foliated matrix composed of chlorite, serpentine, tremolite-actinolite, talc, ± muscovite, ± quartz. This horizon has an attitude sub-parallel to S_2 of the under- and overlying unit which are locally deformed by z-type D_{2L} decimetric folds. This mylonitic assemblage is overprinted by S-C and semi-brittle structures (e.g. boudinage, book shelf) showing a top to east/south-east sense of shear and by a later weak folding corresponding to the D_3 event (see previous paragraph).

Capponi et al. (1990) interpreted this tectonic horizon as a syn-metamorphic thrust surface, whereas Rossetti et al. (2001) associated it to extensional tectonics occurred during the D_2 stage.

In the Torre dell'Orologio area, where the metaserpentinites are absent, this shear zone particularly affects the basal part of the metagabbros which are trasformed into a tremolite-actinolite foliated body. It is also notable the occurrence of several tectonic slices of the Metasedimentary Unit and of metaserpentinites in the lower part of the Metaophiolitic Unit (between Torre dell'Orologio and Cala Maestra) which are likely connected to the activity of the cataclastic-mylonitic shear zone.

According to some Authors (Pandeli et al., 2001; Rossetti et al., 2001) also the Cala Martina Prasinites can be interpreted as tectonic intercalations at the top of the Metasedimentary Unit produced during the same shearing event.

At places (e.g. Cala Maestra), the occurrence of east to west trending, sub-horizontal striae, suggest also later brittle trascurrent tectonics.

DISCUSSION

The collected data contribute to the knowledge of the structural and stratigraphic framework of the Gorgona Island and allow to refine the survey performed by previous Authors (Capponi et al., 1990; Pandeli et al., 2001; Rossetti et al., 2001) and to better unravel the tectonic evolution of the "Alpine Corsica" - Northern Apennines orogenic system (see the correlations of the deformation events in Table 3).

Both the Metasedimentary and the Metaophiolitic Unit were affected by three main deformation events (D_1, D_2, and D_3).

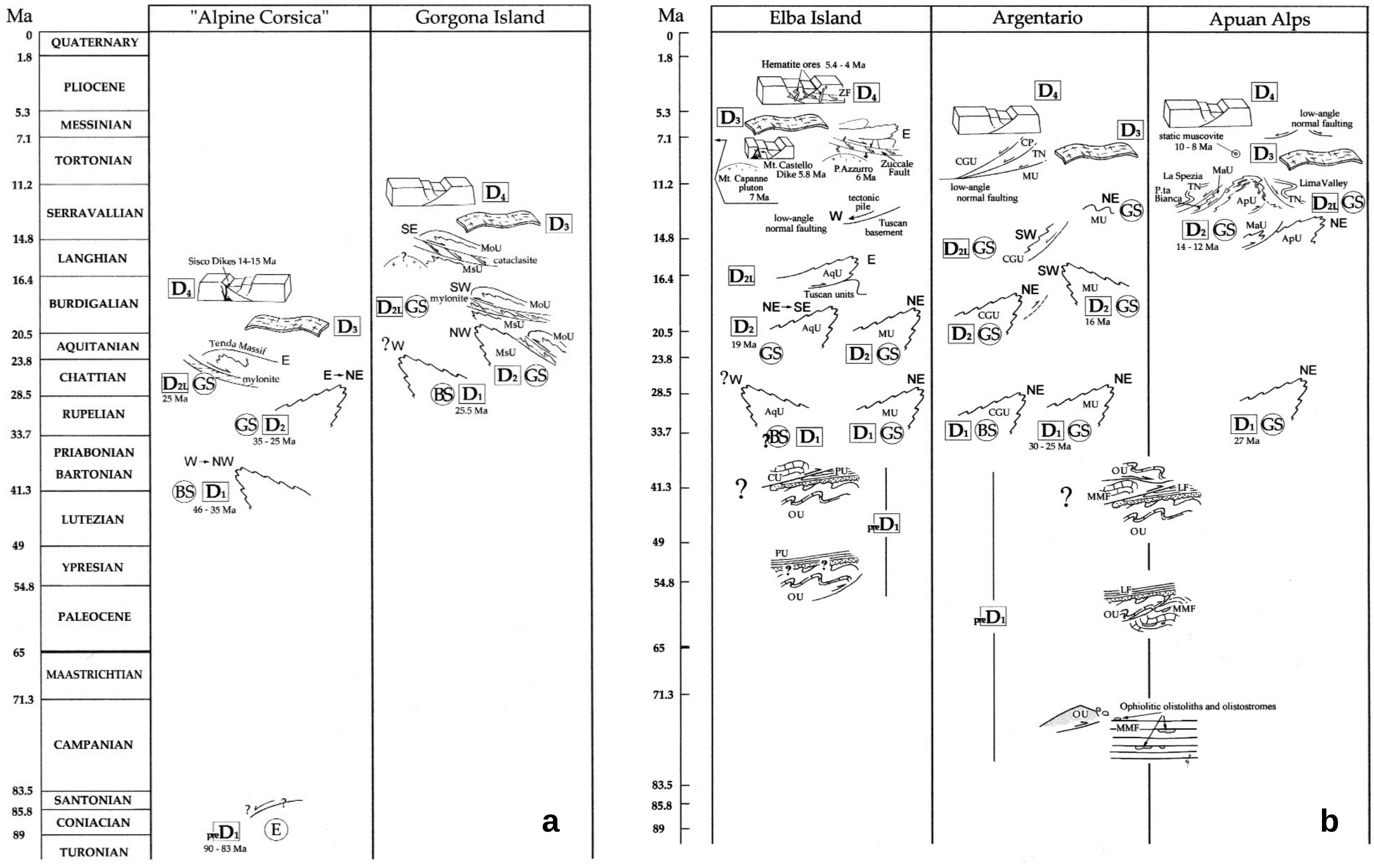
The isoclinal D_1 folding, whose vergence is not definable because of its strong transposition by D_2. It occurred in a blue-schist tectono-metamorphic conditions, as testified by presence of lawsonite and glaucophane-crossite in the metabasitic rocks and Fe-carpholite in the metasediments. The blue-schist facies event of the *Schistes Lustrés* in "Alpine Corsica" (Duran Delga, 1984; Jolivet et alii, 1991; Bortolotti et al., 2001, cum bibl.) can be related to Late Eocene subduction of the Ligurian-Piedmontese lithosfere, which occurred immediately before or at the beginning of the Adria-Europe collision (Table 3). The Oligocene radiometric age of 25.5 Ma obtained by Rossetti et al. (2001) for the D_1 event of the Gorgona succession suggests a correlation with the main shortening tectono-metamorphic event of the Apenninic tectogenesis dated 27 Ma in the Tuscan Metamorphic Units of the Apuan Alps (Kligfield et al., 1986). It is worth to note that also the Tuscan Metamorphic units reached during this event (25-30 Ma 39Ar/40Ar radiometric age; Brunet et al., 2000) HP/LT thermo-barometric conditions up to 0.9 GPa for T = 300 - 350°C (Mg-Fe carpholite in the Triassic Verrucano metasediments of the Argentario Promontory and of Mt. Leoni: Theye et al., 1997; Giorgetti et al. 1998).

The D_2 folding event occurred in greenschist facies conditions, and it was probably linked to near isothermal exumation processes of the HP/LT metamorphosed units. This event produced the most evident structures at the meso- and micro-scale in the Gorgona Island. In particular, mapping the lithofacies of the Punta Gorgona Calcschists has given evidence, in the central-south part of the island, of several parassitic D_2 decametric/hectometric folds whose geometries and interference pattern with S_0/S_1 suggest a northwestern vergence and which likely belong to the overturned limb of a D_2 megafold (see also Capponi et al., 1990).

However, the northwestern vergence of the D_2 folds in the Metasedimentary Unit of the Gorgona Island is peculiar. In fact, the D_2 folding in green schist facies of the *Schistes Lustrés* in Corsica (Oligocene- Lower Miocene event: Jolivet et al., 1991; Brunet et al., 2000), eastern Elba Island (19 Ma: Deino et al., 1992) Giglio Island (Rossetti et al., 1999) and Argentario Promontory (Elter and Pandeli, this volume) are all characterized by an eastern vergence.

In the Tuscan Metamorphic Units, instead, the D_2 event (14-12 Ma: Kligfield et al., 1986) shows an overall regional double-vergence (Table 3) from Punta Bianca - Apuan Alps to the Argentario Promontory (Carmignani and Kligfield,

Table 3 a, b - Synoptic sketch of the deformation events in “Alpine Corsica”, Northern Tyrrhenian Sea (Gorgona Island and Elba Island) and Northern Apennines. E- eclogitic event; BS- blue schist event; GS- green schist event. Gorgona Island: MsU- Metasedimentary Unit, MoU- Metaophiolitic Unit; Elba Island: OU- Ophiolitic Unit, PU- Paleogene Flysch Unit, CU- Cretaceous Flysch Unit; W-Tuscany: MMF- Monteverdi M.mo Fm. + Montaione Flysch, OU- Ophiolitic Unit, LF- Lanciaia Fm., CGU- Cala Grande Unit, MU- Monticiano-Roccastrada Unit, MaU- Massa Unit, ApU- Apuan Unit, PBU- Punta Bianca Unit, TN- Tuscan Nappe.



1990; Carosi et al., 1995; 1996; Storti, 1995; Elter and Sandrelli, 1994; Corsi et al., 2001 cum bibl.) even if local variations are recognizable (e.g. Pisani Mts., Elba Island;. Uccellina Mts.). This pattern is related to regional extensional synmetamorphic detachments on the flanks of rising mega-antiforms (Carmignani and Kligfield, 1990) or to syn-orogenic extension on the back of crustal thrusts (Jolivet et al., 1998).

We think that the second hypothesis fits better the regional structural data. An emblematic case (cfr. Fazzuoli et al., 1994) is the thrusting of the high greenschist facies Massa Unit (which bears static post-D_1/pre-D_2 kyanite) onto the low greenschist facies Apuan Unit and the D_2 Tyrrhenian-vergent detachments and folding (e.g Punta Bianca fold: Storti, 1995) on the western side of the Apuan Alps. All these structures can be framed in a complex D_2 event linked to the development of east-vergent “out-of-sequence” crustal thrusts (see Table 3) and to the consequent discharge at the back and at the front of these structures.

Therefore also the west-vergent D_2 folding and the HP-LT units exhumation in the Gorgona Island could be connected to similar compressional exumation phenomena widespread in the whole Northern Tyrrhenian area.

During the D_2 event, shearing between the Metasedimentary Unit and the Metaophiolitic Unit is testified by the D_2 greenschist mineralogic association which defines the foliation of the cataclastic-mylonitic horizon and by the increasing of transposition of the D_1 structures by D_2 going towards the shear zone.

The tectonic intercalation of several slices at the base of the Metaophiolitic Unit (e.g. the calcschists slices of Cala Maestra) and possibly of the Cala Martina Prasinites in the upper part of the Metasedimentary Unit also took place during $D_{2.}$

At the end of this stage a “top to the southwest” ductile shearing also occurred along the mylonitic horizon (D_{2L} event).

Finally, an extensional event probably referable to the inception of the regional extension which exumed the Gorgona Units, began. The kinematic indicators recognized along the catyaclastic-mylonitic horizon and pointing to a “top to the east/southeast” sense of shear are related to this evident semi-ductile/brittle inversion of the movement along such surface.

The general increase of the axial dip of the D_2 folds in the Metasedimentary Unit towards the cataclastic-mylonitic horizon can be referred to the bending of the A_2 due to the deformations produced by east/southeast shearing (Fig. 5).

The following weak D_3 folding of the structural pile and the D_4 high-angle brittle tectonics (e.g. east-west jointing) are referable to those described for the Northern Apennines chain and in particular for the central-eastern Elba Island, even if the high angle faulting is poorly developed in the

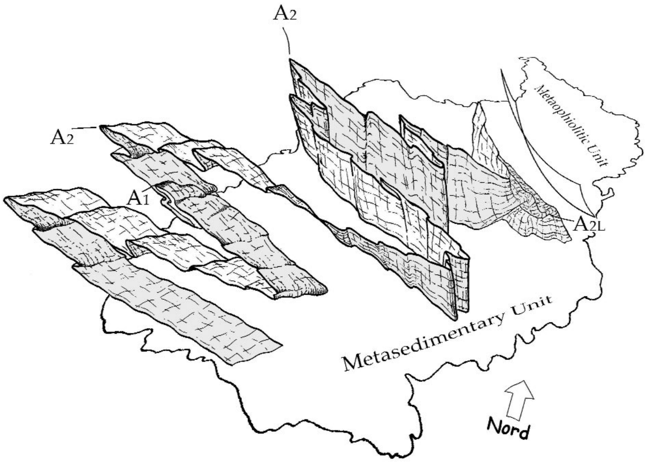


Fig. 5 - Sketch of the structural setting of the Gorgona Island.

Gorgona Island. However these latter structures are identified in the sea in the surrounding of the Island (cfr. Capponi et al., 1990). In the Elba Island it is particularly evident that the final weak folding affected semi-ductile/brittle detachment horizons (e.g. the Zuccale Fault) connected to the uplift of the Messinian granitoids which, together with the late high angle faults dissected the tectonic pile (Bortolotti et al., 2001 cum bibl.).

It is worth to underline the finding of static biotite in the Metasedimentary Unit of the Gorgona Island which could be related to late Miocene-Pliocene thermo-metamorphism.

The mapping of the lithofacies of the Punta Gorgona Calcschists and the structural study also added new elements for the stratigraphic reconstruction of the metamorphic successions of the Gorgona Island. In particular, the geometries of the folds whitin the Metasedimentary Unit suggest that the PGC3 lithofacies (Phyllites, metasandstones and metasiltites) is at the core of the antiforms, while the PGC1 (Metalimestones with phyllitic intercalations) is at the core of the synforms. Taking into account the overall overturned attitude of the successions cropping out in the central-southern Gorgona Island, PGC3 could represent the geometric lowermost unit of the metasedimentary succession. In this view, the Cala di Pancia Metasandstones, which geometrically underlie the PGC2 lithofacies (Metasandstones metalimestones, and phyllites) of the Punta Gorgona Calcschists, could pass laterally to the PGC3 lithofacies. This hypothesis is supported by the structural data (Cala di Pancia Metasandstones and PGC3 are at the limbs of a synform with PGC2 and PGC1 at the core) and by the abundance of metasandstone intercalations in the PGC3 particularly in the Belvedere area.

However, the penetrative D_1 isoclinal folding prevents to restore the original stratigraphy and to define whether the Cala di Pancia Metasandstones were at the top of the sedimentary succession or not.

The structural relationships between the Cala Martina Prasinites and the sorrounding rocks suggest that they suffered together the D_2 tectono-metamorphic event. Therefore, in the hypothesis that the Cala Martina Prasinites are slices of the Metaophiolitic Unit at the top of the Metasedimentary Unit (cfr. Pandeli et al., 2001; Rossetti et al., 2001), their tectonic intercalation occurred during the D_2 event (see other tectonic slices within the cataclastic-mylonitic shear zone) or perhaps in pre-D_2 times, during the HP/LT D_1 event. On the other hand, the data are not in contrast with the possibility that these prasinites could represent original intruding magmatic bodies (e.g. basaltic dikes) or olistolithes within the PGC2 metasediments.

The lithostratigraphic and petrographic features of the Gorgona succession can be compared with those of other Ligurian-Piedmontese Units of Tuscany. Concerning the Argentario Promontory and the Giglio Island, the metasediments of the Cala Grande Unit (associated with metaophiolitic bodies), differ from the Gorgona ones, because the former consist of varicoloured phyllites and metalimestones with local intercalations of metacherts and metaradiolarites (cfr. Elter and Pandeli, this volume). Close analogies are instead outlined with the Acquadolce Unit of the Eastern Elba Island (see also Pandeli et al., 2001 and Bortolotti et al., 2001) which, apart from basal marble and calcschists, largely consists of metasiliciclastics (metagreywackes, metasiltstones and phyllites with intercalations of metalimestones and calcschists). In addition, a decametric body of stratified, often coarse-grained metagreywackes is present south of Rio Marina and strictly resembles the Cala di Pancia Metasandstones. The correlation is also stressed by the presence of a metaserpentinite slice at the top of the Acquadolce Unit (Santa Filomena sub-unit: Bortolotti et al., 2001). In this hypotesis the Punta Gorgona Calcschists are of Cretaceous age, as obtained by microfossils in the metacarbonate intercalations of the Acquadolce Unit (Duranti et al., 1992).

Within the metamorphic Ligurian-Piedmontese units of "Alpine" Corsica, some analogies can be pointed out with the Inzecca "Arenaceous-Pelitic Flysch" (Durand Delga, 1984; Padoa 1997) correlated with the metasandstones of the Cretaceous-?Eocene Prunelli Flysch which stratigraphically overlies the shales and limestones of the Erbajolo Fm.

Siliciclastic inputs are also well-known in the Cretaceous-Early Tertiary, non-metamorphic successions of Corsica (e.g. Macinaggio Unit: Nardi et al., 1978; Durand Delga, 1984; Gardin et al., 1994; Marino et al., 1995 cum bibl.), and of the Northern Apennines (e.g. Gottero Sandstones in the Vara Supergroup; Ghiaieto Sandstones of the Cretaceous Elba Flysch: Abbate and Sagri, 1970; 1982; Sagri et al., 1982; Principi and Treves, 1984; Gardin et al., 1994; Marino et al., 1995, cum bibl.).

FINAL REMARKS

The study of the metamorphic units of the Gorgona Island allows the following conclusion:

1) The recognition and mapping of three lithostratigraphical units in the Metasedimentary Unit show the complex polyphased geological structure of the Island and, in particular, the meso- and macro-structures obtained by interference between the D_1 and D_2 folds.
2) The reconstruction of the attitude of the D_2 folds, characterized by peculiar northwest vergence, allows to hypothesize that the original stratigraphic succession of the Metasedimentary Unit consisted of basal carbonates and pelites which vertically graded into siliciclastic deposits. These latter were locally represented by coarse-grained turbiditic facies (Cala di Pancia Metarenites). The close lithostratigraphical analogies of the Metasedimentary Unit with the Acquadolce Unit of the central-eastern Elba Island, which include Cretaceous microfossils, allow to correlate their sedimentary evolution to that of the Ligurian and Ligurian-Piedmontese successions. The Cala di

Pancia Metarenites of the Gorgona Island are one of the few examples of a metamorphic siliciclastic flysch, Cretaceous-?Tertiary in age, in the "Alpine Corsica" and Northern Apennines tectonic stacks.

3) The blastesis-deformation evolution of the Gorgona Island tectonic units is similar to that reconstructed for "Alpine Corsica" and the western part of the Northern Apennines. However, the radiometric ages of the correspondent tectono-metamorphic events suggest to correlate the metamorphic-structural evolution of the Gorgona Island to the Oligocene-Middle Miocene events of the Northern Apennines which locally are characterized by HP-LT metamorphism (e.g. Argentario Promontory, Mt. Leoni).

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