Journal of Structural Geology 27 (2005) 1355–1378

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Structure of the Monte Reventino greenschist folds: a contribution to untangling the tectonic-transport history of Calabria, a key element in Italian tectonics

Walter Alvarez*

Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA

Received 17 November 2004

Abstract

Calabria, an anomalous pile of largely crystalline nappes resting on top of the mostly sedimentary fold–thrust belts of the Apennines and the Sicilian Maghebides, has moved several hundred kilometers southeastward, opening the Tyrrhenian Sea in its wake. This study treats the Monte Reventino area in the northern third of crystalline Calabria, where pre-Mesozoic schist appears to rest on deep-water Mesozoic sedimentary rocks along a thrust surface marked by discontinuous bodies of serpentinite and banded greenschist with a complex internal structure. Detailed mapping led to a structural analysis of an unusual pattern of folds in the banded greenschist, resulting from twisting of opposite major fold limbs in opposite directions. A useful aspect of this fold distortion is that the sense of rotation of minor fold axes enables one to determine the sense of tectonic transport; in this case, it was generally westward. For many years, the structure of Calabria has been thought of as a pile of nappes emplaced through entirely compressional thrusting. Recently some geologists have begun to reinterpret the structure as resulting from large-scale, low-angle extensional faulting that has stretched and torn apart the nappe edifice. Monte Reventino appears to be a key location for evaluating this possibility.

Keywords: Calabria; Italy; Ophiolite; Folds; Extension; Thrusting

1. Introduction

This paper presents a detailed geologic map, cross-sections, and a structural analysis of a folded, banded greenschist that is part of a metamorphosed ophiolitic body lying along a low-angle fault in Calabria, the toe of the Italian boot. Calabria in the geologic sense, comprising a number of largely crystalline allochthons emplaced over the dominantly sedimentary rocks of the fold–thrust belts of the Apennines and Sicily, is a critical block for understanding the complex microplate tectonics of the central Mediterranean. In particular, it is important to untangle the complicated history of tectonic transport directions in different phases of the evolution of Calabria. This structural analysis of greenschist folds at Monte Reventino, in Central Calabria, also offers a novel method for determining tectonic transport direction.

The study is based on fieldwork at Monte Reventino and its surroundings done between 1971 and 1976. A short paper was published (Alvarez, 1978) and a full manuscript prepared, but publication was long delayed because of the distraction from other research projects. Monte Reventino had previously been mapped in a schematic way in the 1960s during preparation of the 1:25,000 maps covering all of Calabria (see sheet ‘Martirano Lombardo’). That schematic mapping has been incorporated in tectonic syntheses up to the present time (Bonardi et al., 1976; Rossetti et al., 2001). The detailed map presented here will allow the Monte Reventino area to be more accurately represented in future syntheses. I have not been able to find any indication that other geologists have worked on the Monte Reventino greenschist folds since then, so the results continue to be the latest available study of these structures.

In updating the manuscript, I have changed the study of

---

* Tel.: +1 510 642 2602.
E-mail address: platetec@berkeley.edu.

0191-8141/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2005.05.012

Monte Reventino itself very little, mostly by updating some references and correcting a few mistakes; it thus reflects geological thought at the time the study was done. On the other hand, I have rewritten the introduction and discussion to reflect advances in understanding Calabrian geology in the intervening years, so that the detailed results will be more useful in current thinking about Calabria.

It is now widely accepted that Calabria has moved southeastward to its present position, opening the triangular Tyrrhenian Sea in its wake (Haccard et al., 1972; Alvarez et al., 1974; Kastens et al., 1988; Sartori, 2001). In early phases of Italian geological research, Calabria was recognized as a largely crystalline element within the dominantly sedimentary Apennine and Sicilian orogenic belt, and was thought to represent the basement on which those sediments were deposited (Cortese, 1895). Limanowski (1913) first argued that the Calabrian crystalline rocks were not uplifted basement, but rather a nappe of allochthonous origin emplaced on top of the Apennine and Sicilian sedimentary rocks, and this view has been abundantly confirmed. Many useful tectonic studies of Calabria have been published since then (Quitzow, 1935; Caire et al., 1960; Grandjacquet et al., 1961; Dubois, 1970; Haccard et al., 1972; Ogniben, 1973; Amodio-Morelli et al., 1976; Bonardi et al., 1976, 2001; Dietrich, 1976, 1988; Schenk, 1984, 1988; Vai, 1992). Geologic mapping at 1:25,000 of the entire Region of Calabria between 1958 and 1963, sponsored by the Cassa per il Mezzogiorno, was summarized by Burton (1970).

Through the 1980s, the structural geology of Calabria was generally interpreted in terms of thrust tectonics only. After the recognition elsewhere that extension plays a critical role in compressional orogens (Platt, 1986), some authors have begun to investigate the role of extension in the tectonic evolution of Calabria (Platt and Compagnoni, 1990; Wallis et al., 1993; Knott, 1994; Thomson, 1994, 1998). Most recently, Rossetti et al. (2001) have offered a major reinterpretation of the sequence of tectonic units in Central Calabria, citing extension as a key determinant in producing the observed geology. The detailed study of Monte Reventino bears on the question of the role of extension in Calabria tectonics, as discussed at the end of this paper.

Geological Calabria (Fig. 1, inset) is divided into the three segments of Central Calabria (the Sila block), Southern Calabria (the Serre-Aspromonte block), and northeastern Sicily (the Peloritani block). These segments are separated by the two transverse depressions of the Catanzaro Lowland and the Strait of Messina. In Central, but not Southern, Calabria, below the Hercynian crystalline terranes, there are exposures of Mesozoic rocks, comprising an ophiolitic suite (primarily metabasalts and serpentinites), low-grade metamorphosed phyllites and quartzites, and unmetamorphosed platform carbonates. The exposure of these lower units makes Central Calabria appealing for those interested in the Alpine history of the Mediterranean, which was the motivation for the present study.

1.1. Central Calabrian nappe structure

In Central Calabria, the Catena Costiera, or Coastal Chain (Sorriso-Valvo and Sylvester, 1993), forms a southward geographical (but not geological) continuation of the Southern Apennines (Fig. 1). To the east, the Catena Costiera is separated by the Crati River Valley (apparently a young graben) from the mountainous Sila region. South of Cosenza the Crati Valley disappears and the Catena Costiera is linked with the Sila by the east–west range of the Sila Piccola, or Lesser Sila, that looks down on the Catanzaro Lowland to the south. Monte Reventino (1417 m), north of Lamezia Terme, is the highest summit in the western Sila Piccola.

The simplified tectonic map of Fig. 1 combines the many nappe units that have been distinguished into a few major units, in order to clarify the gross structure, which is not as evident on maps with a more detailed subdivision. More detailed tectonic maps of Central Calabria have been published by Ogniben (1973), Dubois (1976), Bonardi et al. (1976), and Scandone (1991). The nappe edifice of Central Calabria dips gently to the east or northeast, so that the deeper units are exposed mainly in the Catena Costiera and the Sila Piccola. The upper nappes dominate the Sila, but occur only as klippen in the western areas. The primary distinction in Fig. 1 is between (1) the Calabride nappes that represent pre-Mesozoic continental basement and its Alpine-cycle sedimentary cover, (2) units that represent the Tethyan oceanic realm that opened and closed during the Alpine cycle, and (3) the dominantly carbonate units that represent a Mesozoic continental margin that flanked the Tethyan Ocean. The following description reflects the classic paper of Amodio-Morelli et al. (1976). Later discussion treats the alternative interpretation of Rossetti et al. (2001).

(1) Four major units are generally recognized in the Calabride nappe complex, each of them subdivided on detailed maps. The highest is (a) the Stilo unit, which is widely developed in southern Calabria but thought to be present only locally in Central Calabria. The largest area in Central Calabria is occupied by (b) the Sila unit, tilted northeastward so that lower continental crust is exposed along the southwest margin of the Sila (Schenk, 1981; Caggianelli et al., 2000; Graessner and Schenk, 2001) while the Mesozoic sedimentary cover of this crustal fragment is still preserved in the northeast, around Rossano and Longobucco (Teale, 1988; Tavarnelli et al., 2004). Beneath the Sila unit is (c) the Castagna unit, mainly represented by augen gneiss and mica schist. The lowest member of the Calabride nappe complex is (d) the Bagni unit, which is composed largely of phyllite. The Sila, Castagna, and Bagni units

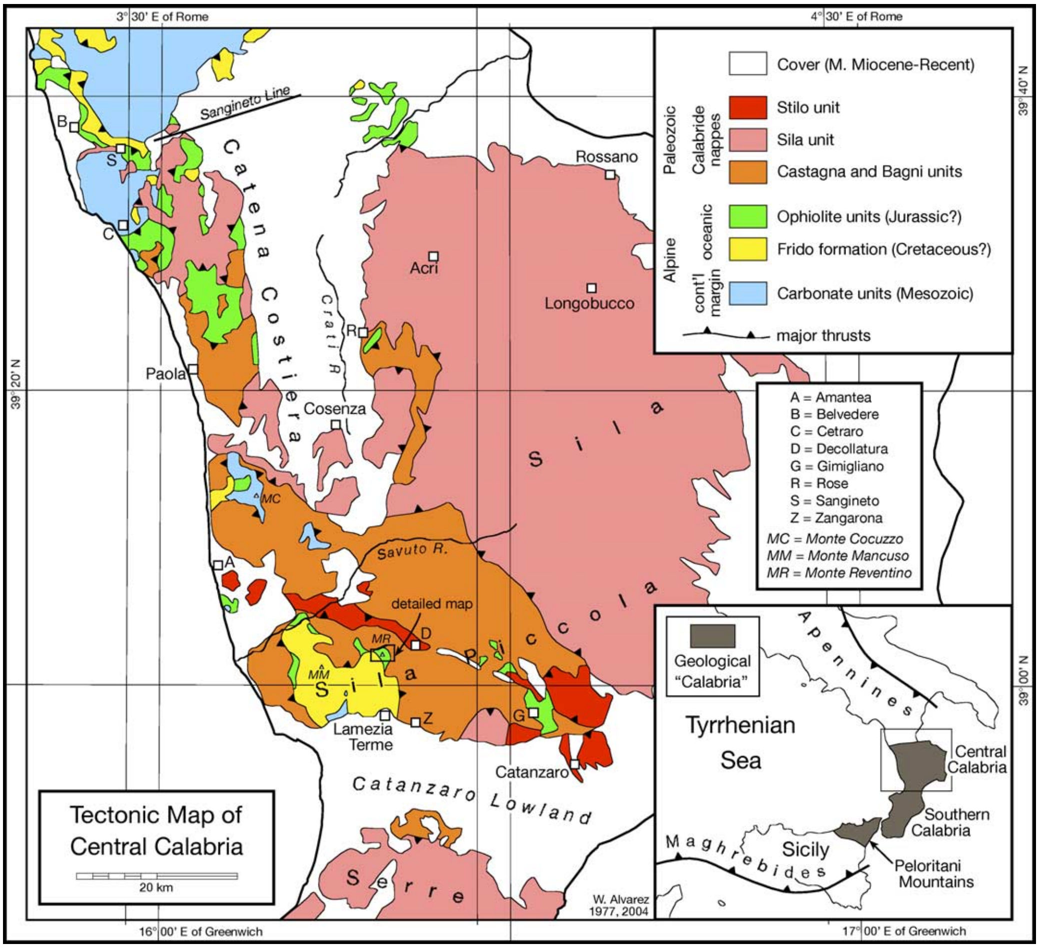


Fig. 1. Tectonic map of Central Calabria, largely based on the map of Bonardi et al. (1976), revised for the western Sila Piccola, and simplified by (1) omitting all subdivisions within the major tectonic units and (2) combining the Bagni and Castagna units, which are not well distinguished in the western Sila Piccola, around Monte Reventino, which is the focus of this study. The concept of Bonardi et al. (1976), based on stacking of nappes in two different compressional regimes (a Cretaceous–Paleogene event with vergence toward Europe, followed by a Neogene event with vergence toward Africa), has been the basis for most subsequent interpretations of Calabrian geology. Recently, Rossetti et al. (2001) have reinterpreted the geology of the Sila Piccola in terms of extensional tectonics. The main difference in their view, as it would show up on a map like this one, is that the meta-ophiolitic rocks around Monte Reventino and Gimigliano are placed in their ‘Lower Ophiolitic Unit’. All the rest of the nappe edifice, with the sequence shown here, is placed in their ‘Upper Tectonic Complex’, and the contact along which the Upper Tectonic Complex overlies the Lower Ophiolitic Unit is interpreted as a major extensional detachment surface. Observations relevant to choosing between the two interpretations are discussed at the end of this paper.

that dominate the Calabride nappes in Central Calabria are stacked in reverse order of metamorphic grade. In Fig. 1, the Castagna and Bagni units are lumped together, because the mapping necessary to distinguish them in the western Sila Piccola has not been done. For the rest of Central Calabria, these units are distinguished on the map of Bonardi et al. (1976). Above the thrust that runs northward from Lamezia Terme into the detailed map area at Monte Reventino, the Castagna unit is present in the form of a mica schist that is here called the Zangarona schist, as a simplification of the name ‘micascisti di Zangarona-Ievoli-Monte Dondolo,’ used informally by Colonna and Piccarreta (1975a).

(2) The second major group of tectonic units represents the Tethyan oceanic realm. Although complete ophiolite sequences are absent in Calabria, there are abundant exposures of serpentinite, metabasite, and their metamorphosed sedimentary cover that probably originated by the dismemberment and metamorphism of ophiolites and deep-water sediments. In addition, quartzites and phyllites derived from deep-water sandstones and shales of the Cretaceous Frido formation are found from the Southern Apennines to Lamezia Terme, and have been interpreted as remnants of the sedimentary fill of the Tethyan Ocean. Ophiolitic rocks and the metasediments of the Frido formation outcrop at Monte Reventino and are described in detail below.

(3) The structurally lowest group of tectonic units is formed by Mesozoic–Tertiary continental-margin carbonates. They are largely covered by higher nappes in Central Calabria, but show through as tectonic windows near the west coast as far south as the Catanzaro Lowland. These rocks have long been correlated to the shallow-water limestones and dolomites that dominate the geology of the

Apennines and Sicily (Ogniben, 1973; Bonardi et al., 1976; Dietrich, 1976). The implication is that the crystalline nappes of Central Calabria were thrust over the sedimentary Apennine rocks. However, Ietto et al. (1995) have presented evidence that the Central Calabrian carbonates are unrelated to those of the Apennines.

1.2. Motivation for the structural study of Monte Reventino

The general tectonic structure of Central Calabria, with unmetamorphosed platform carbonates tectonically overlain by oceanic sediments and ophiolitic rocks that have at least in part been through an episode of blueschist metamorphism, surmounted in turn by thrust sheets of continental crust, is reminiscent of the structures of the Alps and of Alpine Corsica. This led to the proposal, in the 1970s, that Calabria had formerly been part of the Europe–vergent Alpine collisional belt, and subsequently moved southeastward to its present position, with the Tyrrhenian Sea opening in its wake (Haccard et al., 1972; Alvarez et al., 1974). To test this hypothesis it was important to compare the geology of Alpine Corsica and Central Calabria, and also the eastern part of Sardinia, which would have been the foreland of the Calabrian Alpine belt. As part of an effort to carry out that test (Alvarez and Cocozza, 1974; Alvarez, 1991), I undertook a detailed structural study in Central Calabria aimed at determining the direction of tectonic transport during nappe emplacement, to test whether the vergence was toward the west, as would be expected if Calabria had been part of the Alpine orogenic belt.

The vergence of the Calabrian nappes has been the subject of debate over many years, as reviewed by Ogniben (1973) and Dietrich (1976). The map pattern of tectonic units (Fig. 1) does not afford any evidence for the direction of nappe transport. The outcrop patterns of the various tectonic units are determined in large measure by the late folding and subsequent erosion. In such a situation, one can turn to smaller-scale structural features, particularly minor folds, as evidence for the transport direction. This approach encounters difficulties in Calabria since the more massive rock types—including the carbonates, granites, and high-grade metamorphic rocks—seem to have behaved rigidly during nappe emplacement and show few minor folds that can be attributed with confidence to this tectonic event. The widespread phyllites and schists are extensively folded, but these rocks have in many places been moved by landsliding due to the rapid uplift of Calabria and the consequent downcutting by streams (Cotecchia and Melidoro, 1974; Carrara and Merenda, 1976), and structural measurements are therefore of dubious value. To avoid difficulties of both kinds, the summit area of Monte Reventino was chosen for detailed study. Piccarreta and Zirpoli (1969a,b) had previously noted the abundant development of minor folds in greenschists at Monte Reventino, and the greenschists are sufficiently massive to have resisted landsliding. These minor folds (Fig. 2) proved rich in structural information.

The western end of the Sila Piccola forms the southernmost of the late-stage, northwest-trending antiforms (Fig. 1). Structurally, this range is a compound tectonic window. A small nucleus of carbonates west of Lamezia Terme is surrounded by an outcrop area of the Frido formation in the first thrust sheet. The Frido is in turn overlain and surrounded by the Bagni and/or Castagna units, which are surmounted in the Amantea–Decollatura synform by granitic rocks of the Stilo unit and locally their Mesozoic carbonate cover. The thrust contact between the Bagni or Castagna unit and the underlying Frido formation is marked by discontinuous bodies of serpentinite and greenschist, and one of these resistant bodies holds up the highest summit of the Range—Monte Reventino (1417 m). At Monte Reventino the Castagna unit is present above the serpentinite–greenschist body, and is represented by the Zangarona schist.

2. Monte Reventino: structural geometry

The geology of Monte Reventino is marked by a large lens of meta-ophiolitic rocks apparently lying along a thrust contact that places the Zangarona schist over the epimetamorphic phyllites and quartzites of the Frido formation. The massive banded greenschist and serpentinite of the ophiolitic lens hold up the summit of Monte Reventino.

A careful examination shows that the ophiolite is quite irregular in shape and has a complicated internal structure. The essence of this structure is that the banded greenschist has been deformed into a pattern of tight folds. The serpentinite occupies the cores of the major greenschist folds and partially or completely surrounds isolated bodies of greenschist.

Figs. 3 and 4 present the detailed structural geometry of Monte Reventino. The geological map (Fig. 3) is based on field mapping at 1:5000 carried out from 1972 to 1977. In areas of complicated outcrop pattern, individual outcrops have been mapped and the nature of rock fragments in the soil cover is shown. In areas where the rock type seen in outcrop and in the float is unchanging, individual outcrops are not delineated. The profiles of Fig. 4 were obtained by projecting outcrop features onto a plane normal to the major fold axes. This requires the assumption that the structures are cylindrical, which probably does not produce large errors over the few hundred meters projection distance. The profiles are located on the map (Fig. 3) by showing the position of a horizontal reference line in the dipping profile plane, as well as the trace of the profile plane on the topographic surface. The locations of features on the map of Fig. 3 are given by reference to the letters and numbers in the margins (C-1, B-2, etc.).

Because of the position of the Monte Reventino summit area on the flank of the late stage Monte Reventino antiform,

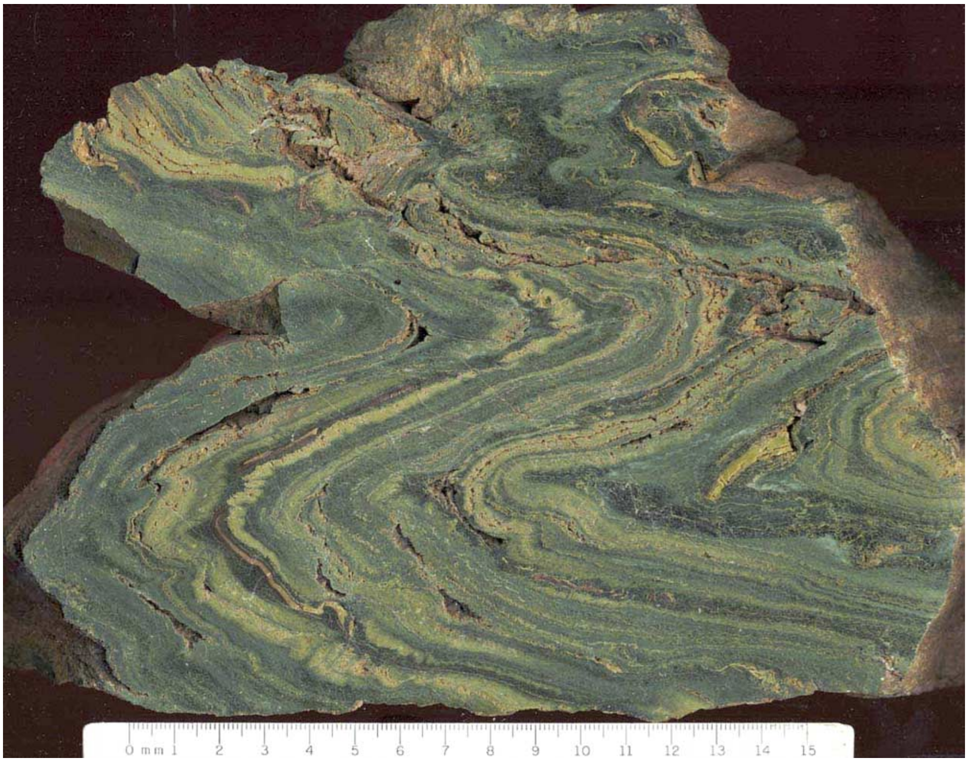


Fig. 2. F_2 folds deforming the S_1 foliation in the Monte Reventino banded greenschist (loc. C, in grid square B-2 on Fig. 3). Smallest intervals on scale bars are millimeters.

the general dip of the nappe pile is toward the east or northeast (Fig. 5). As a result, the three major units form bands trending northwest and apparently separated by thrust contacts. The structurally lowest unit, the Frido formation, occupies the southwest corner of the map, while the highest unit, the Zangarona schist, dominates the northeastern part of the map. Immediately south of the map area, the Zangarona schist rests in thrust contact on the Frido formation, but in the map area they are separated by the ophiolite lens of Monte Reventino, which forms the central outcrop band and reappears from beneath the Zangarona schist in the tectonic window of Colacino (C-1).

The internal structure of the ophiolite lens is complicated but not chaotic. The structure is outlined by the greenschist masses, where the main foliation (S_1) has been deformed into tight, inclined folds (F_2) whose axes plunge moderately toward the east. Major F_2 folds in the greenschist have amplitudes and wavelengths of a few tens to a few hundreds of meters, and minor F_2 folds on a 10-cm scale are abundantly developed both on the limbs and in the hinges of the major folds. These minor folds provide the structural information that has made it possible to work out the geometry of the major folds.

The second member of the ophiolite sequence is serpentinite, which forms the matrix in which the greenschist bodies are embedded. Serpentinite almost completely encloses the greenschist, and tongues of serpentinite occupy the cores of major F_2 folds. Serpentinite outcrops are everywhere cut by multitudes of shear surfaces, and in some places shearing plus metasomatism have converted the serpentinite into a layered ophicalcite. Shearing of serpentinite has probably occurred more than once, and shearing during F_2 folding has enabled the serpentinite to shape itself to the contours of the greenschist folds.

Profile A–A′ (Fig. 4a) shows the internal structure of the ophiolite body in the central part of the map. In this area the major fold axes plunge about 25° toward the east, as shown by minor fold axes in the hinge regions, and the plane of the projected profile thus strikes north–south and dips 65°W. This profile shows the Zangarona schist at the top of the nappe pile and the Frido formation at the bottom, with the ophiolite lens lying between them. Two minor thrusts lie beneath the main upper thrust surface, and greenschist immediately below the upper thrust is strongly retrograded. This provides important information for determining the time relationships between deformation and metamorphism; it is clear that the nappes were emplaced after greenschist-facies metamorphism of the ophiolitic rocks.

The central part of profile A–A′ shows the largest greenschist body, with its shape dominated by major F_2 folds. The geometry of these major folds is specified by labeling the domains used in structural analysis later in the paper (hinge domains in ovals—6 N/S, etc.; limb domains in circles—5 S, etc.). As will be shown, greenschist facies metamorphism was contemporaneous with F_2 folding.

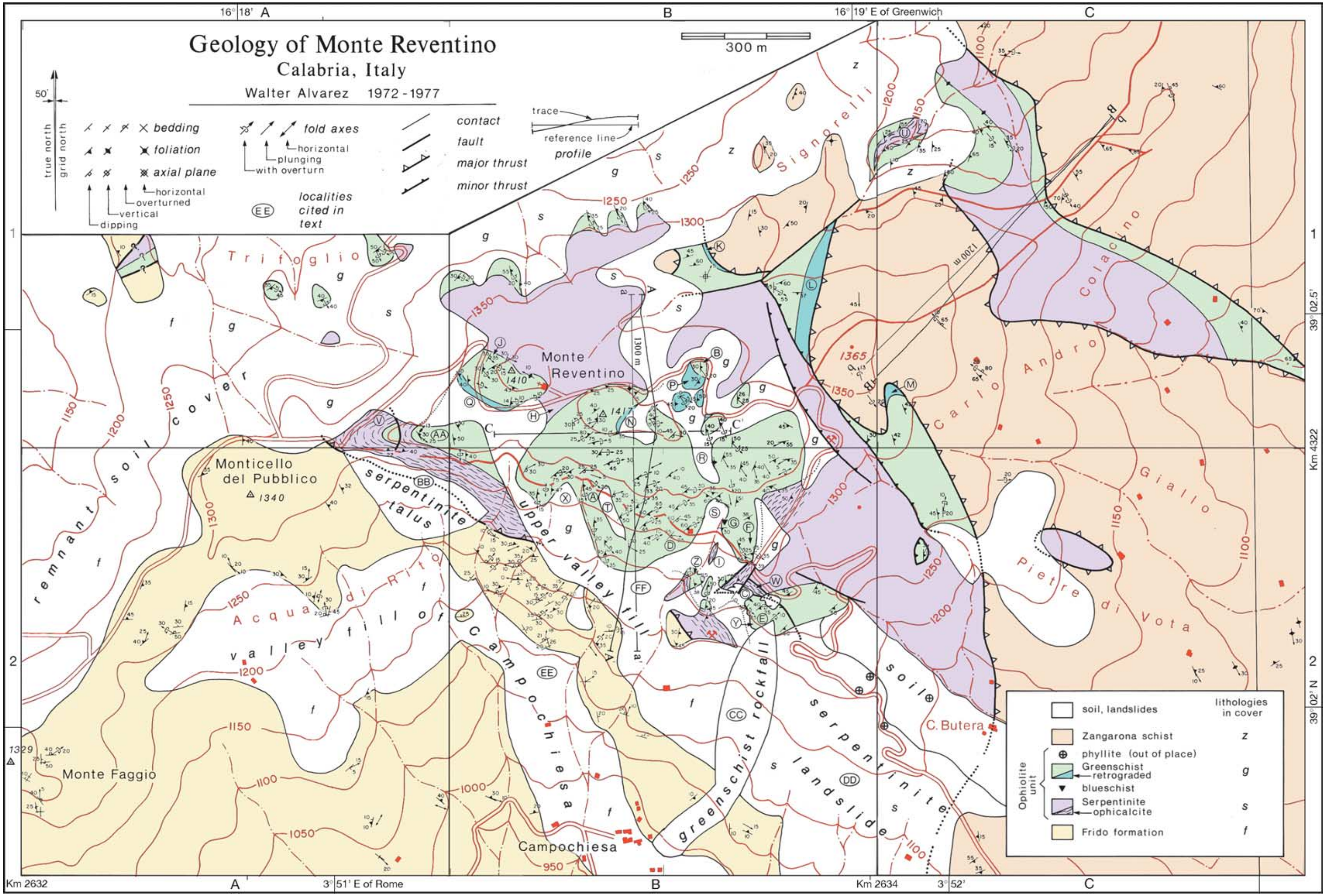


Fig. 3. Geologic map of the summit area of Monte Reventino. Original mapping at 1:5000.

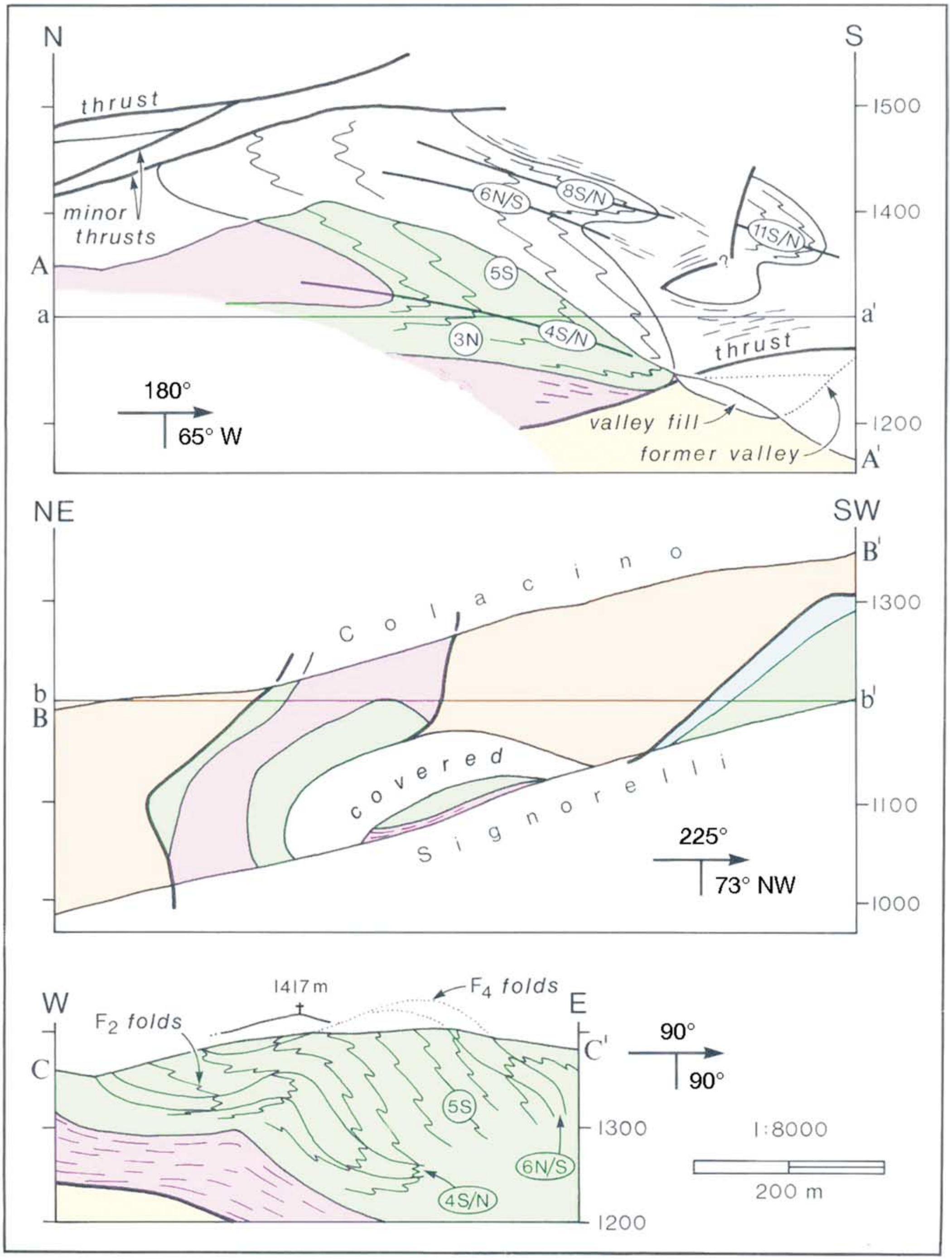


Fig. 4. Projected profiles. These sections show contacts and other features projected onto planes perpendicular to the axes of major folds in the greenschist (F_2 for profiles A and B, F_4 for profile C). A–A′, B–B′, and C–C′ are the traces of the topographic surface on the plane of the profile; a–a′ and b–b′ are reference lines formed by the intersection of the non-vertical profile planes and a datum level, and are plotted on Fig. 3. Large strike-and-dip symbols show the attitude of the profile plane. F_2 fabric domains and schematic foliation traces are shown in profiles A and C.

During subsequent tectonic displacements, the greenschist bodies behaved as brittle masses, which were partially sliced up and sheared off. It is this episode that accounts for the decapitation of the greenschist fold mass along the lower of the two minor thrusts, and for the isolation of the smaller mass of greenschist in the upper right hand part of the profile.

Profile B–B′ shows the structure of the Colacino window. In this area fold axes in the greenschist plunge about 17° to the southeast, so the profile plane was constructed with a northeast–southwest strike and a dip of 73°NW. The most important observation from this profile is that the Colacino window is not simply a topographically controlled cut through a planar thrust surface. The thrust contact of

Fig. 5. View looking northeast from Monte Faggio to the double summit of Monte Reventino; the lower summit at the far left is Monticello del Pubblico (Fig. 3). The summit of Monte Reventino is due to the presence of a large lens of folded greenschist (G) and serpentinite (S) that lies along the thrust separating the Frido formation (F) from the Zangarona schist (Z). In the distance is the low-lying belt along the Amantea–Decollatura synform.

Zangarona schist over the ophiolite units is tightly folded or imbricated and shows at least 200 m of relief. A vertical wall of serpentinite, with a sheath of greenschist, rises from the streambed of the Signorelli Valley and flattens over toward the southwest. This structure has the geometry of a tight greenschist antiform, with a core of serpentinite, overturned toward the southwest. The antiform has a considerable extent along strike; it is mapped for 1 km to the southeast of Signorelli (Fig. 3) and discontinuous exposures track the vertical serpentinite wall for 1 km toward the northwest, outside the map area. The covered area in the center of profile B–B′ obscures the geometry somewhat, but the Zangarona schist appears to have been folded into the synform beneath the ophiolite antiform. This indicates that the antiform developed during or after nappe emplacement.

Profile C–C′ is a vertical section, perpendicular to the axes of a synform–antiform pair (F_4) that deforms the F_2 folds in the main greenschist body.

3. History of deformation and metamorphism at Monte Reventino

Table 1 places the geologic events that can be inferred from the Monte Reventino rocks into a historical sequence. Prior to nappe emplacement, the Frido formation, the ophiolite complex, and the Zangarona schist are kept separate since they clearly represent separate paleogeographic domains with separate histories. Because of the lack of chronological information, the historical events are rather imprecisely defined. Basically, one can separate (1) Paleozoic orogeny from (2) Alpine cycle (Mesozoic–Cenozoic) deposition and (3) Alpine cycle orogeny (Cretaceous–Tertiary). The Alpine orogeny in the Mediterranean region is thought to have included three major phases—Cretaceous, Paleogene, and Neogene—one or more of which affected Calabria, but at Monte Reventino it is possible only to distinguish events that occurred before, during, and after nappe emplacement. The numbers in parentheses following events listed in Table 1 refer to the sections that follow.

3.1. Paleozoic orogeny

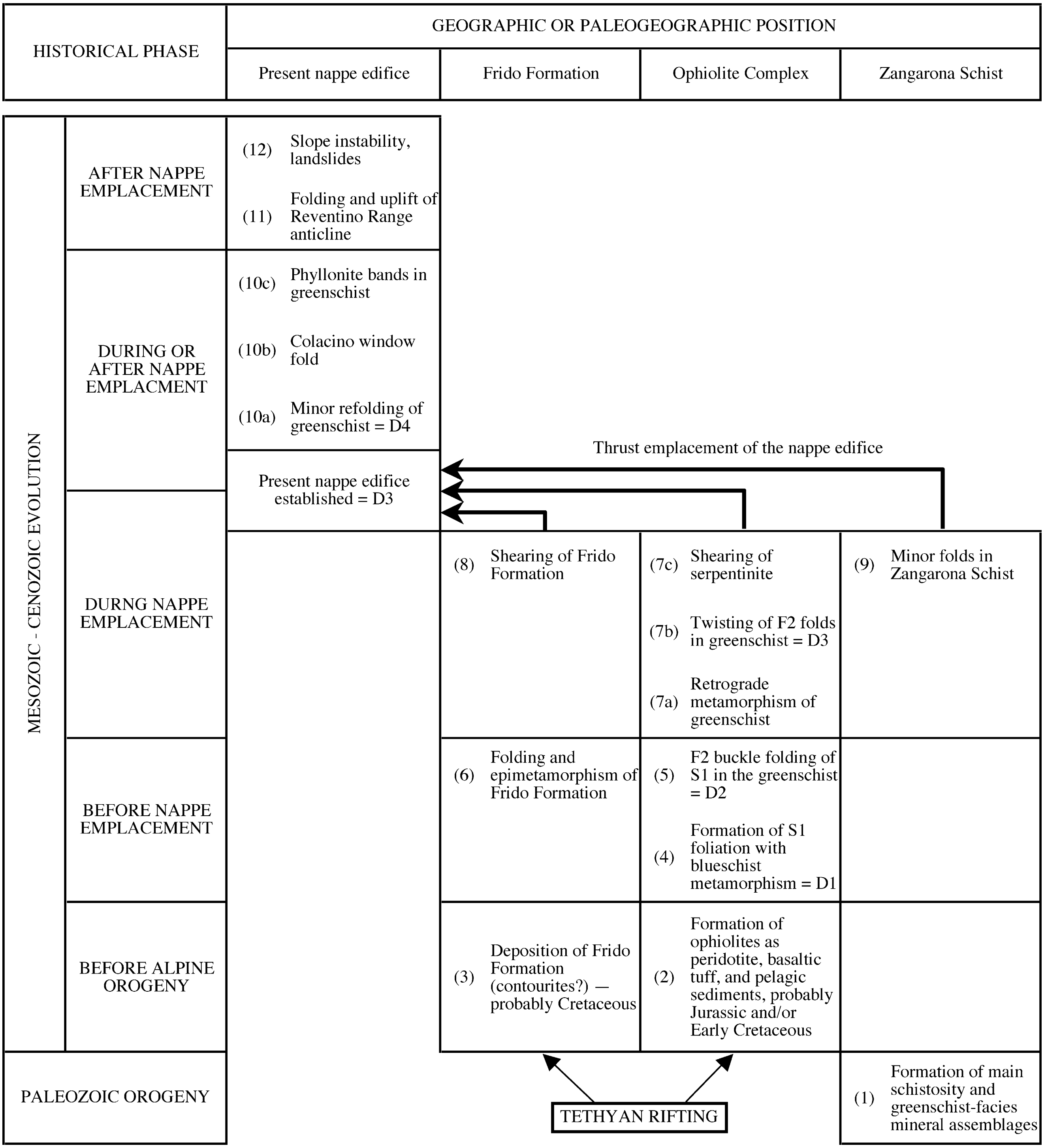
3.1.1. (1) The Zangarona schist

The Zangarona schist is apparently the only unit in the Monte Reventino summit area that carries a record of Paleozoic deformation and metamorphism. In their sketch map of the Monte Reventino area, Colonna and Piccarreta (1975b, fig. 2) show two units—the Zangarona-Ievoli-M. Dondolo micaschist and the Pomo River phyllite—in the area here mapped as Zangarona schist. The contact they show between their two units was not recognized in the present study, and since these rocks are almost entirely schists, rather than phyllites, the term Zangarona schist is used here as a simplification of the first of their two names.

The Zangarona schist shows a metamorphic foliation and/or schistosity, commonly marked by laminae of quartz and white mica. Opaques are generally present, and chlorite and garnet are seen in some sections, but biotite was not identified during this study. Detailed descriptions are given by Piccarreta and Zirpoli (1969b) and by Colonna and Piccarreta (1975a,b).

Studies a number of years ago on the mineralogy and petrology of the western Sila Piccola and nearby areas (Piccarreta, 1972; Di Pierro et al., 1973; Piccarreta and Zirpoli, 1974; Colonna et al., 1975; Colonna and Piccarreta, 1975a,b; Lorenzoni and Zanettin-Lorenzoni, 1975, 1976; Piccarreta and Zirpoli, 1975; Dietrich et al., 1976) laid out the basic metamorphic history of these rocks. Of the rocks here mapped as Zangarona schist, the Pomo River phyllites

Table 1
Sequence of geological events inferred from evidence at Monte Reventino



HISTORICAL PHASE		GEOGRAPHIC OR PALEOGEOGRAPHIC POSITION			
		Present nappe edifice	Frido Formation	Ophiolite Complex	Zangarona Schist
MESOZOIC - CENOZOIC EVOLUTION	AFTER NAPPE EMPLACEMENT	(12) Slope instability, landslides (11) Folding and uplift of Reventino Range anticline			
	DURING OR AFTER NAPPE EMPLACMENT	(10c) Phyllonite bands in greenschist (10b) Colacino window fold (10a) Minor refolding of greenschist = D4			
	DURNG NAPPE EMPLACEMENT	Present nappe edifice established = D3	(8) Shearing of Frido Formation	(7c) Shearing of serpentinite (7b) Twisting of F2 folds in greenschist = D3 (7a) Retrograde metamorphism of greenschist	(9) Minor folds in Zangarona Schist
	BEFORE NAPPE EMPLACEMENT		(6) Folding and epimetamorphism of Frido Formation	(5) F2 buckle folding of S1 in the greenschist = D2 (4) Formation of S1 foliation with blueschist metamorphism = D1	
	BEFORE ALPINE OROGENY		(3) Deposition of Frido Formation (contourites?) — probably Cretaceous	(2) Formation of ophiolites as peridotite, basaltic tuff, and pelagic sediments, probably Jurassic and/or Early Cretaceous	
PALEOZOIC OROGENY					(1) Formation of main schistosity and greenschist-facies mineral assemblages

have potassic white micas that crystallized under low *P*/*T* conditions probably during the Hercynian event, and were partially re-equilibrated under high *P*/*T* conditions during the Alpine event (Colonna et al., 1975), and the Zangarona-Ievoli-M. Dondolo mica schist also shows a pre-Alpine—presumably Hercynian—metamorphism of low *P*/*T* character overprinted by high *P*/*T* Alpine event (Colonna and Piccarreta, 1975a, p. 20) witnessed by the presence of lawsonite and soda-amphibole. More recent studies of the metamorphism and geochronology of the Castagna unit, which includes the Zangarona schist, given by Rossetti et al. (2001), confirm the Alpine high *P*/*T* metamorphic overprint on an earlier greenschist to amphibolite metamorphism, but yielded mixed ages that could not fully separate these two events.

3.2. Evolution of the Mesozoic ocean

3.2.1. (2) The ophiolite sequence

It is now widely accepted that a rifted ocean formed in the Alpine–Mediterranean region in the Jurassic (Dewey et al., 1973; Dercourt et al., 1986), and most of the ophiolites found in the Alpine belt and the Apennines are thought to have formed during spreading of this ocean (Bortolotti et al., 2001; Dilek and Robinson, 2003). The Monte Reventino ophiolites and related metasedimentary rocks were thus attributed to the Jurassic–Lower Cretaceous by Amodio-Morelli et al. (1976), although direct age information is lacking.

The Monte Reventino greenstone–serpentinite complex is a partial, or possibly dismembered, as well as metamorphosed and intensely deformed, ophiolite. Gabbro and sheeted dikes are absent or at least unrecognizable; the dominant rock types are serpentinite and banded greenschist. The serpentinite was developed from an original lherzolitic peridotite. Ductile folding of the kind seen in some Alpine peridotites (Nicolas and Boudier, 1975) is not present. The greenschist is strikingly banded, but this banding is a foliation (S_1) in which occasional appressed fold hinges demonstrate that this is not original bedding. Piccarreta and Zirpoli (1969a) have described the petrography of this unit in detail. They concluded, on the basis of the banded texture, the mineralogy (presence of relict pyroxene crystals), and chemical analyses, that the greenschist was formed by metamorphism of a basic igneous tuff with some admixture of non-volcanic sediment. This interpretation may be correct, but an alternative is that the protolith was a pillow basalt that had undergone severe stretching. The production of banded metabasic rocks by extreme deformation of pillow lavas has been documented by Kusky and Huddleston (1999, fig. 10).

At Gimigliano, 20 km ESE of Monte Reventino, the same complex of serpentinite and banded greenschist reappears, and associated with it are foliated marbles, phyllites, and lightly metamorphosed sandstones and microconglomerates (Dubois, 1970, 1976; Colonna and Piccarreta, 1975b, 1977; Rossetti et al., 2001), which have been interpreted as the original sedimentary cover of the ophiolite sequence. These rocks are not clearly displayed at Monte Reventino, but possibly equivalent phyllite is locally present in the soil cover (Fig. 3, B-2, C-2). In addition, small slices of marble like that at Gimigliano are present in the Zangarona schist bounding the Colacino window, close to the contact with the greenschist (Fig. 3, C-1, and north of the map area), which suggests that the ophiolite–Zangarona thrust contact may actually be a zone of minor imbricate thrusting.

3.2.2. (3) The Frido formation

The Frido formation seems to represent Mesozoic deep-water sedimentation. This unit is composed dominantly of tan, epimetamorphic phyllites and massive to laminated quartzites. The phyllites are more important volumetrically, but the quartzites are more impressive because of their rugged outcrops. The pelitic varieties contain very fine-grained phyllosilicate minerals that impart a phyllitic sheen to the rock, but mica flakes can never be distinguished. Bedding is generally recognizable, but neither graded bedding nor other top indicators can be identified. Small lenses of fine-grained, bluish, crystalline limestone are an extremely minor constituent of this unit. Neither fossils nor fossil fragments have ever been found, despite careful search by the author and by other geologists. Yet the grade of metamorphism is too low to account for the absence of fossil material, so it seems probable that the formation was deposited in an oceanic environment, below the CCD; this agrees with the paucity of limestone.

Piccarreta (1973) first noted the lithologic similarity between the rocks now referred to the Frido formation in the western Sila Piccola and the type Frido formation in the southern Apennines (Vezzani, 1969). In subsequent papers (Colonna and Piccarreta, 1975b; Amodio-Morelli et al., 1976) this similarity was considered strong enough to support a correlation, and the name Frido was applied to the rocks in the western Sila Piccola. Microfossils found in the Frido in areas to the north indicate a Cretaceous age—Lower Cretaceous in the type area (Vezzani, 1969) and in the Catena Costiera (Lanzafame and Zuffa, 1975, 1976), and Upper Cretaceous in the Cilento area (Amodio-Morelli et al., 1976).

3.3. Alpine-cycle deformation—before nappe emplacement

3.3.1. (4) D_1 in the greenschist: the S_1 foliation

The most striking feature of the greenschist is a layering marked by alternating light- and dark-green compositional bands on a millimeter- to centimeter-scale (Fig. 2). This layering is present in almost all outcrops, and ranges from quite subtle to extremely conspicuous. If the greenschist banding is a transposed foliation S_1, and not simply relict bedding S_0, one might expect to find metamorphic minerals oriented along this foliation. Unfortunately the blocky epidote and albite that dominate the greenschist are not suitable for petrofabric studies, but some information is available from a single outcrop of blueschist (glaucophane–epidote–chlorite–sphene) that was found at Monte Reventino (Fig. 3, B-2, locality G). This 1×2 m outcrop is entirely surrounded by soil cover, and its relation to the surrounding greenschist is therefore uncertain, but it occurs in the core of a major F_2 greenschist fold. The blueschist is folded, and its fold style is indistinguishable from that of many of the greenschist folds, so it is likely that foliation and folds in the blueschist are equivalent to foliation and folds in the greenschist. Foliation in the blueschist is marked by the

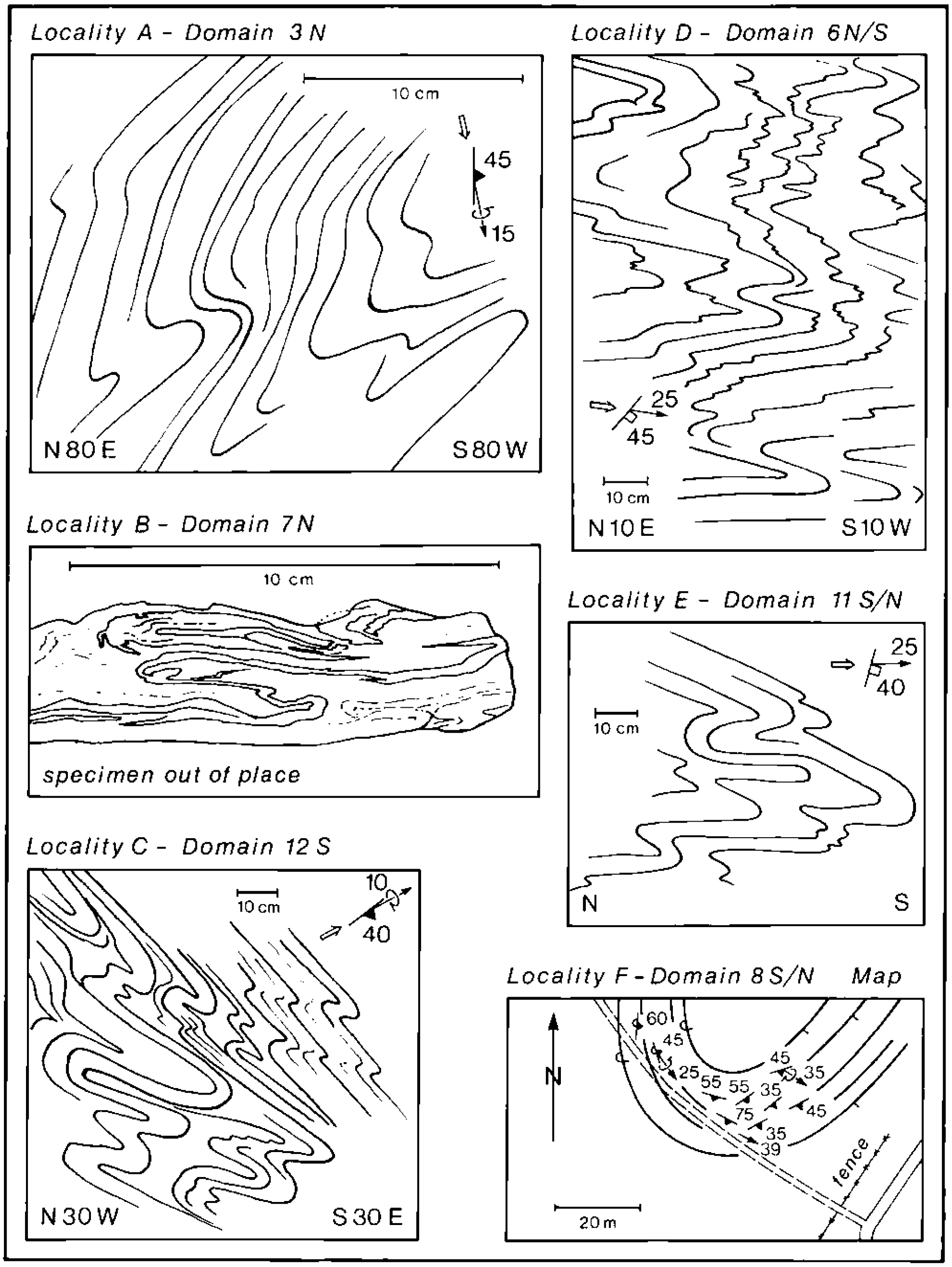


Fig. 6. Profiles of folds in the greenschist. Insets give the viewing direction (open arrow) and the attitude of the fold axis and of the main foliation or the axial plane (symbols as in Fig. 3). In A–E the profile is projected onto a plane perpendicular to the fold axis. F shows a mapped closure of a major fold. Overturn symbols in F are relative to the eastern fold limb; these are on foliation S_1 and no orientation of original bedding is implied.

alignment of felted glaucophane needles that are straight in the unfolded parts of the foliation and kinked where the foliation is tightly folded. Although it is possible that the glaucophane simply grew parallel to an unfolded bedding, it seems more likely that this direction was an active secondary foliation parallel to isoclinally folded bedding. On this basis the banding of the Monte Reventino greenschist is identified as S_1.

3.3.2. (5) D_2 in the greenschist: the F_2 folds

As striking as the compositional banding is the presence of very common folds on a centimeter- to meter-scale, which deform the banding in more than half of the greenschist outcrops. These folds deform S_1 and never show refolding relationships, so they are all attributed to a single phase of deformation, D_2. As mentioned in the previous section, if the correlation by style between the greenschist folds and the folds in the single isolated outcrop of blueschist is correct, the F_2 folds deform glaucophane needles that grew during development of the S_1 banding. The timing of F_2 folds relative to growth of the greenschist mineral assemblages is harder to determine because the

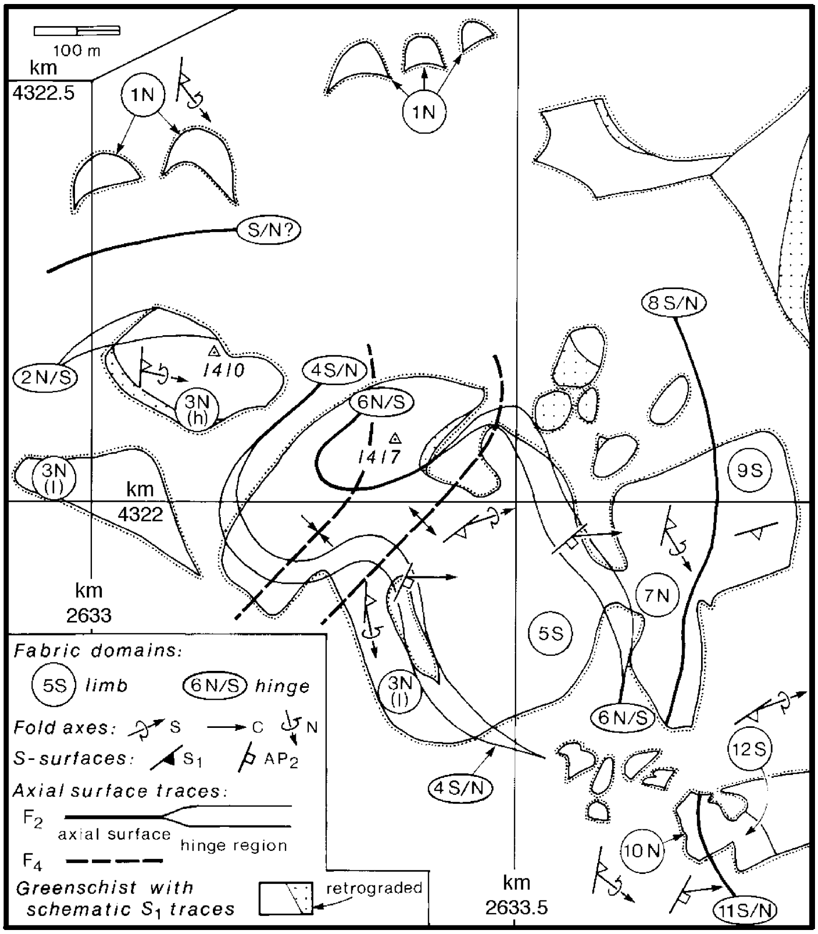


Fig. 7. Structural domains in the Monte Reventino greenschist. Each domain is characterized by point maxima of planar and linear fabric elements. Domains are numbered sequentially upward from 1 to 12, and letters are appended to show their position in the pile of major F_2 folds. 'N-limbs' and 'S-limbs' are characterized by minor folds with northward and southward overturns, respectively (e.g. 7N, 5S); hinge domains are noted as N/S or S/N to show the limb types above and below the axial surface. The attitudes of planar and linear fabric elements are calculated mean directions for the various domains (see Figs. 8 and 9 and Appendix B).

blocky habit of the dominant epidote and albite makes them almost useless as indicators of deformation and timing relationships. Chlorite is more useful; in a given fold, chlorite flakes may be bent around the hinge, lie unbent in the axial plane, or both. Since there is no evidence of more than one episode of folding, these relationships suggest that F_2 folding took place during an extended interval in which the greenschist mineral assemblage was crystallizing.

From the pattern of minor F_2 folds it is possible to understand the geometry of the major F_2 folds. However, the pattern of minor folds is unusual; it has been distorted by subsequent movements related to emplacement of the overlying Zangarona schist. This type of distortion (Alvarez, 1978) gives information on the direction of tectonic transport. Structural analysis of the greenschist folds will thus be divided into two parts. Observations leading to recognition of the major F_2 folds are given here, while the subsequent distortion during nappe emplacement is discussed in Section 3.4.1.

Profiles of typical F_2 folds are shown in Fig. 6. They range from fairly open to rather strongly flattened, but only rarely become isoclinal. Axial plane cleavage is generally absent, probably because of the blocky habit of the dominant minerals, and measured axial surfaces are based on limb geometry, not on the presence of a fabric element with this orientation.

Both symmetric and asymmetric folds are common. Because of the rather gentle plunges of the fold axes (A_2), it is more useful to designate asymmetry by direction of overturn than by use of the 'S' and 'Z' convention. Thus asymmetric folds overturned toward the north and toward the south are referred to as 'N-folds' (Fig. 6A and B) and 'S-folds' (Fig. 6C), respectively, while symmetric folds, because of their gently dipping axial surfaces, are referred to as 'cascade-folds' or 'C-folds' (Fig. 6D and E).

Representative structural attitudes are plotted on Fig. 3. The trends and overturn directions of minor F_2 folds allow them to be grouped into three types, and homogeneous domains of the three types reappear several times, as shown in Fig. 7. The attitudes of S_1 foliations, and the axes (A_2) and

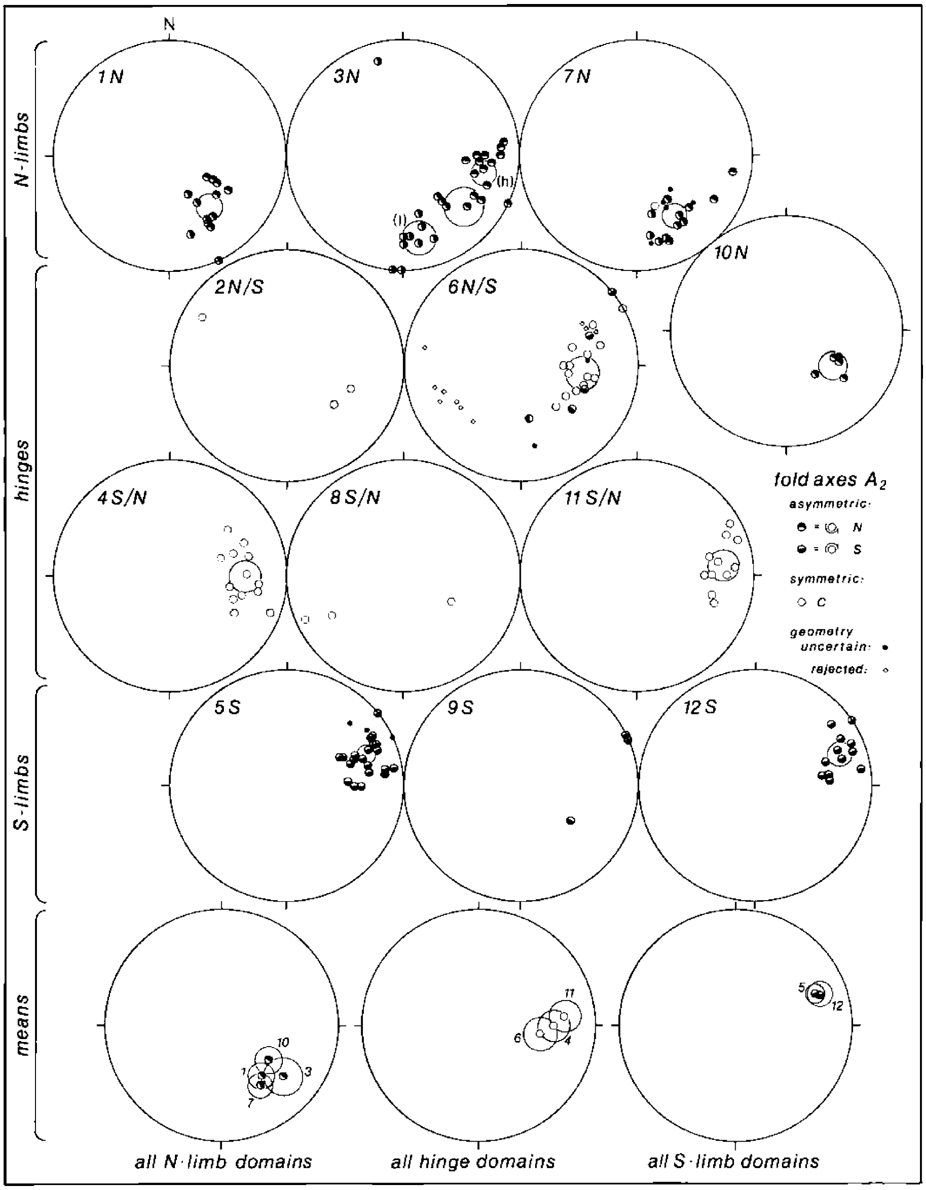


Fig. 8. Linear structural elements in the greenschist. Large circles are limits of 95% confidence around the calculated mean directions; the means only are plotted in the lower row of diagrams. Extra confidence circles in domain 3N refer to axes close to hinge domain 2N/S (h) and to axes well out on the major fold limb (l). Rejected axes in domain 6N/S are in an area rotated by F_4 folding. Lower hemisphere, equal-angle projections.

axial surfaces (AP_2) of F_2 folds shown on Fig. 7 are the calculated mean directions for each domain. The data used in these calculations are shown in Fig. 8 (linear elements) and Fig. 9 (planar elements). In almost all domains, these data points show strong clustering. Rather than contouring the points on equal-area projections, I have chosen to plot the data on equal-angle projections and calculate vector means and circles of 95% confidence (Watson and Irving, 1957; Irving, 1964), which allows the data from different domains to be compared rigorously. (The raw data and calculations of means are available as an on-line appendix.)

The plots of minor fold axes in Fig. 8 show that within domains of a given type the axial directions are indistinguishable or nearly so (overlapping confidence circles, with or without mutually enclosed mean directions), but that A_2 means in the three domain types do not coincide. This unusual feature is explained in Section 3.4.1 as the result of later distortion of the major F_2 folds. Ignoring for a moment this dispersion of minor fold axes, the pattern of domain types in Fig. 7 shows a cyclical sequence of domains characterized by folds with one sense of asymmetry, symmetrical ‘cascade’ folds, folds with the opposite asymmetry, and back. This pattern is characteristic of the arrangement of minor, parasitic buckle folds developed on the limbs and in the hinge regions of larger buckle folds. That this was in fact the origin of the minor folds is confirmed by examination of Figs. 3, 4a and 7, where it can be seen that the folded outline of the major greenschist body

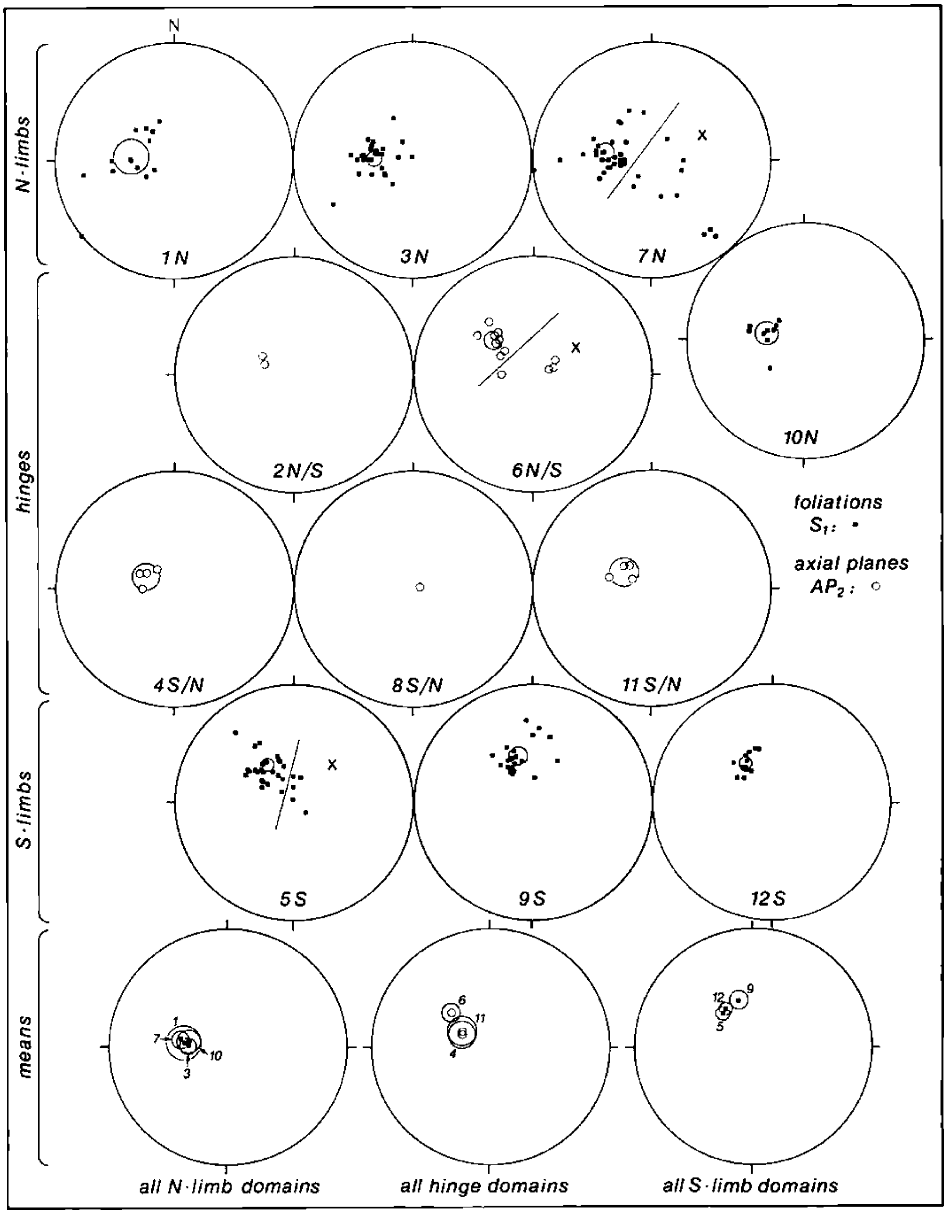


Fig. 9. Planar structural elements in the greenschist. Conventions as in Fig. 8. Data in the zones marked ‘x’ in domains 5S, 6N/S, and 7N are in areas rotated by F_4 folding and have been omitted from calculations of the means.

has the form predicted by assuming the minor folds to be of parasitic origin. It is clear from these figures that tongues of serpentinite are found in the cores of major F_2 folds (Fig. 3, B-1, loc. H; B-2, loc. I). Because of the discontinuous outcrop, it is generally difficult to follow the S_1 foliation around major F_2 fold closures, but this can be done in two places—at locality J (B-1) and locality F (B-2, illustrated in Fig. 6).

Three lines of evidence—the distribution of minor fold shapes, major folds in S_1, and the folded shape of the greenschist–serpentinite contact—thus converge to indicate that D_2 deformation produced a set of major folds in the greenschist.

3.3.3. (6) Folding and epimetamorphism of the Frido formation

The first recognizable tectonic event that affected the Frido formation was a phase of ductile deformation under epimetamorphic conditions that produced buckle folds in the quartzite beds, with axial-planar phyllitic slaty cleavage in the pelitic layers. There seems to have been only one phase of folding in this unit; the dispersal of fold axes (Fig. 10) results from the abundance of strongly non-cylindrical, curvilinear folds, which are quite common in Frido outcrops. (Field observations with Enrico Tavarnelli in 2004 confirmed the abundance of curvilinear folds in the Frido formation.)

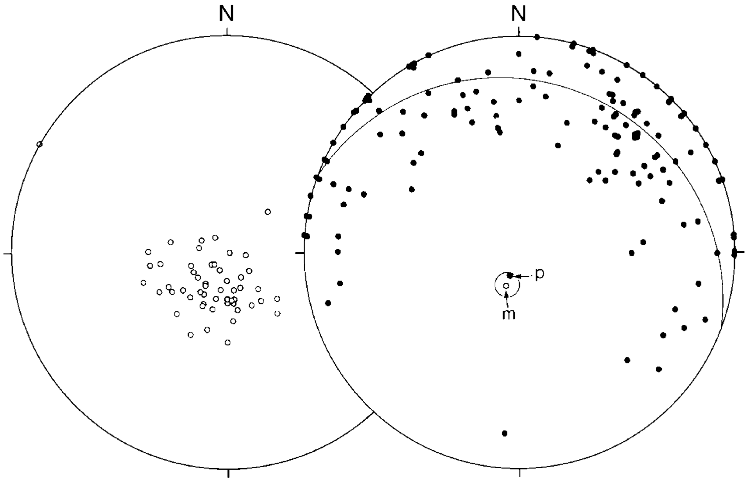


Fig. 10. Structural elements in the Frido formation. Open circles at left are poles to axial-plane phyllitic slaty cleavage: their calculated mean direction (D: 200°, I: 71°S) and circle of 95% confidence (6°) are given by *m*. Filled circles in the right-hand plot are minor fold axes related to the cleavage. The best-fit great circle to these axes is shown, and the pole to this circle (D: 200°, I: 77°S) is given by *p*. Lower-hemisphere, equal angle projections.

Fold axes in the Frido fall in a girdle pattern that dips gently north with a maximum trending northeast; the girdle coincides with the plane of the axial foliation (Fig. 10). It is not clear whether folding of the Frido was contemporaneous with D_2 in the greenschist; if it was, the two units must have been some distance apart because of the difference in metamorphic grades.

3.4. Alpine-cycle deformation—during nappe emplacement

3.4.1. (7) Effects in the ophiolite complex

Movements during nappe emplacement appear to be responsible for three features of the ophiolite complex: (a) retrograde metamorphism of the greenschist, (b) distortion of the F_2 folds, and (c) shearing of the serpentinite.

(a) In several places the greenschist, which is normally a massive, resistant rock, has been converted to a crumbly, greenish-gray, chlorite-rich lithology. Despite this change, it is still possible, in most cases, to recognize the original S_1 banding and F_2 folding. This retrograding occurs in two situations—immediately under the Zangarona schist nappe, where a band of retrograded greenschist follows the thrust contact for part of its length (B-1, loc. K, L; C-1, loc. M), and within the greenschist mass, either along the axial surfaces of major F_2 folds (B-1, loc. N, P) or where there is a break in the mass (B-1, loc. Q). It is clear that the saddle immediately east of the 1417 m summit (loc. N) is topographically low and lacks outcrop because of the presence of the soft, retrograded form of the greenschist. Since the resistant greenschist generally outcrops strongly, this leads to the inference that other soil-covered areas along the F_2 axial surfaces (B-2, loc. R, S, T) are also underlain by retrograded greenschist.

Because of the way in which a band of retrograded greenschist closely follows the thrust contact, it seems reasonable to conclude that they formed at the same time. The retrograde metamorphism would have been facilitated by circulation of water through fractures generated by thrusting. Although there could possibly have been more than one episode of retrograde metamorphism, it seems highly likely that the retrograded rocks along the F_2 axial surfaces also formed during nappe emplacement.

(b) At this point it is necessary to return to the pattern of dispersed minor A_2 axes in the greenschist, and to expand the brief treatment of Alvarez (1978). Fig. 11 is a summary plot of the structural data of Figs. 8 and 9. Note that there is a clear statistical difference between mean poles to S_1 foliation in the two types of major fold limbs. The difference is actually much greater than it appears, for the recognition of tight major fold hinges shows that the N-limb foliations are inverted with respect to the S-limb foliations. The mean pole to axial planes of minor folds in the hinge regions of major folds closely bisects the angle between the two foliation attitudes, as expected. The planar features thus fall into a standard pattern.

However, the pattern of minor fold axes in Fig. 11 is quite unusual. One expects minor fold axes to remain roughly parallel throughout a sequence of major folds, but here the maxima in the three domain types do not coincide. Mean A_2 directions on the two limbs are separated by about 65°; mean axes in the hinge regions fall in between, but somewhat closer to A_2 in the S-limbs.

Five possible explanations for this pattern have been considered and rejected:

(1) Curvilinear fold hinges. This is rejected because the fold axes are straight in any given outcrop (unlike the Frido Formation, where curvilinear hinges on outcrop scale are abundant), and the axes are statistically parallel within any single major fold limb (except for Domain 3N, which seems to have been broken apart, with the two fragments differently rotated, as discussed below).

(2) A single phase of folding, with minor fold axes systematically different on different limbs. This is rejected, for it is commonly observed that minor fold axes are generally parallel to the axes of major folds (Ramberg, 1963, 1964).
(3) Two phases of folding. This possibility is rejected because the A_2 axes are not refolded in any of the outcrops examined, and because the direction of the minor fold axes is dependent on their position in the pattern of major folds.
(4) Buckling followed by non-homogeneous flattening. Divi and Fyson (1973) showed that on a scale of kilometers minor buckle-fold axes can be dispersed during subsequent flattening, but this is rejected for the Monte Reventino case because it requires too unlikely a coincidence between original buckle geometry and fold rotation during flattening, and at Monte Reventino fold rotation switches back and forth abruptly on a 100-m scale.
(5) Folding where the axis separation angle includes the slip line (Hansen, 1971, Chapter 3). The pattern of dispersed fold axes in the Monte Reventino greenschist superficially resembles the patterns observed by Hansen (1971) in that the axes are dispersed in a plane and show a separation angle between opposite overturn senses. However, the separation-angle technique for determination of the slip line is definitely not applicable in this case, for two reasons. First, Hansen (1971) stresses (p. 51) that in order for the method to be applicable, the asymmetric folds that are used must be 'located between two adjacent axial surfaces of the next lower-order folds of the same generation'. This is definitely not the case at Monte Reventino; a separation angle is not observed unless minor folds from both limbs of the next lower-order (larger) folds are plotted together. Second, the axis pattern from the greenschist differs significantly from the patterns observed by Hansen (1971, figs. 17, 69 and 72) and Scott and Hansen (1969, figs. 97 and 98). In the greenschist there is a major concentration of neutral cascade fold axes lying in the separation angle between the two orientations of asymmetric folds; this pattern was not observed by Hansen (1971).

I have only been able to construct one hypothesis that satisfactorily accounts for the observed pattern; this hypothesis envisions twisting of the limbs of recumbent folds during simple shear, and is illustrated in Fig. 12. The scenario begins with the tight, major F_2 folds lying in a recumbent position, with subhorizontal axial planes and

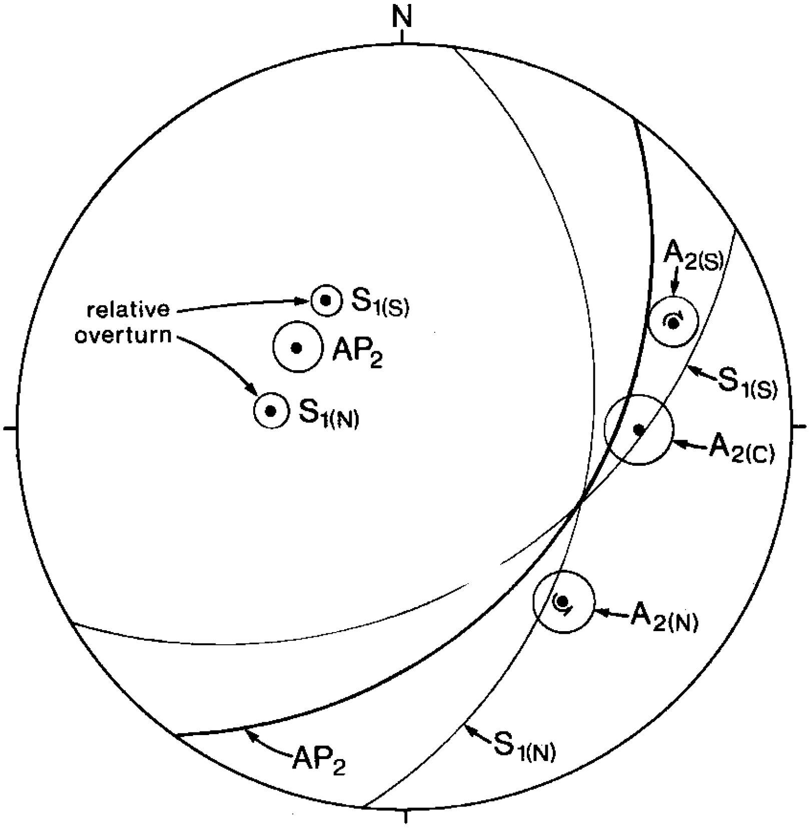


Fig. 11. Summary of greenschist structural data. Shown here are the means of all acceptable measurements in domains of a given type, excluding domains with fewer than four measurements. This figure thus combines the data shown in the bottom row of plots in Figs. 8 and 9. The means (given as declinations/inclination/a_{95}) are as follows: *N-limb domains*: Axes = $A_{2(N)}$: (137.7/26.7/6.5); foliation on dominant limb of minor folds = $S_{1(N)}$: (277.5/51.7/4.4); hinge domains: Axes = $A_{2(C)}$: (91.1/27.4/7.3); axial planes = AP_2: (306.6/51.8/6.6); *S-limb domains*: Axes = $A_{2(S)}$: (68.3/16.6/4.5); foliation on dominant limb of minor fold = $S_{1(S)}$: (329.1/47.7/4.0). Lower hemisphere, equal-angle projections.

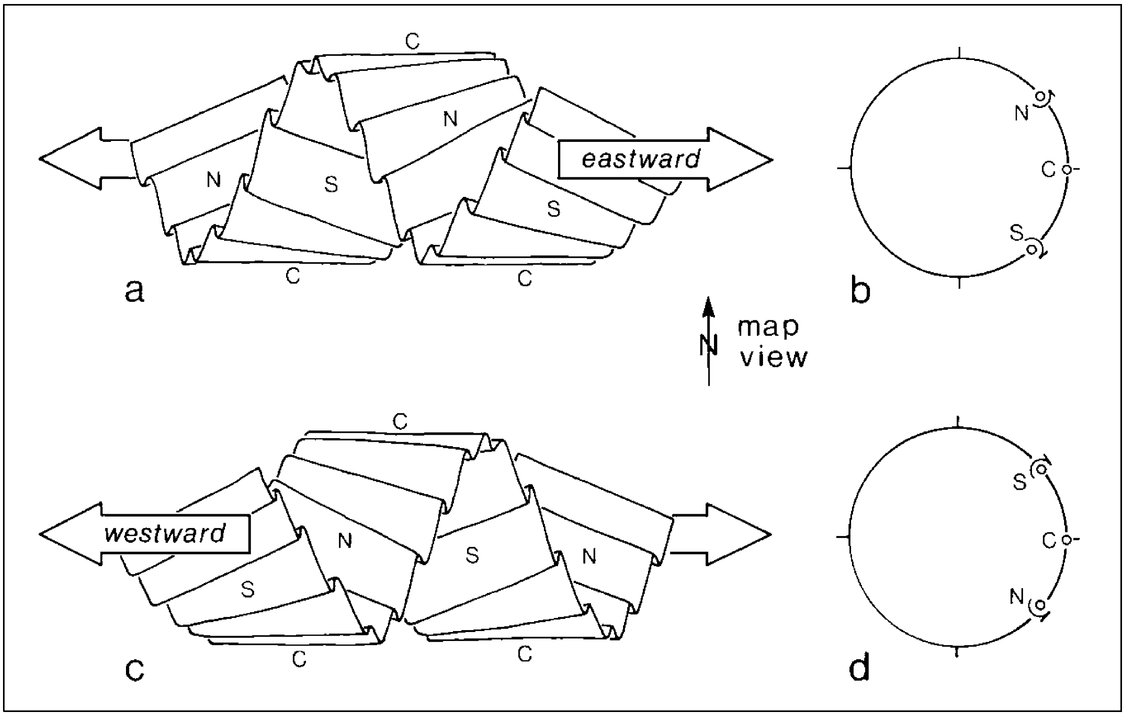


Fig. 12. Twisting of F_2 folds in the greenschist. This mechanism is proposed to account for the observed pattern of minor fold axes. Prior to the thrusting, an undistorted pile of folds is in a recumbent position with east–west axes. The resulting fold distortion and orientation of minor fold axes are shown in (a) and (b) for eastward thrusting, and in (c) and (d) for westward thrusting. The observed pattern of minor fold axes (Fig. 11) corresponds to (d), leading to the conclusion that tectonic transport was directed generally westward.

axes that trend roughly east–west. This is a common orientation for folds of this generation throughout Central Calabria (Dubois, 1970; Carrara and Zuffa, 1976). If simple shear deformation then occurred, with the plane of shear roughly horizontal (parallel to the axial planes of the F_2 folds), and the shear, or transport, direction roughly parallel to the fold axes (directed either toward the east or toward the west), it is clear that the limbs of the folds would be subjected to torques. The key point is that the minor fold axes in the greenschist lie in strong major fold limbs that are encased in weak serpentinite. Each major limb slants up through the plane of later shearing, and will thus experience a torque that will twist the major limb and its included minor fold axes. Successive major limbs slant through the shear plane orientation in opposite directions, and therefore will be twisted in opposite directions. This distortion of the F_2 folds has been designated as deformation phase D_3 (Table 1); since it is not a phase of folding, there are no F_3 folds.

A particularly interesting feature of this type of deformation is that the minor folds, which serve as markers on the rotated major fold limbs, are dispersed in opposite senses depending on the direction of tectonic transport (Fig. 12). The pattern of minor folds in the Monte Reventino greenschist clearly corresponds to the pattern predicted by westward thrusting (compare Fig. 11 with Fig. 12d), and I suggest that this provides evidence for simple shear toward the west at some time after the formation of the F_2 folds.

During this type of fold distortion, movement will be concentrated in the hinge regions of the major folds, where the limbs shear past each other as they rotate in opposite directions. This would account well for the occurrences of retrograde metamorphism of the greenschist in the hinge regions (loc. N, P, R, S, T), and suggests that fold rotation occurred at the same time as retrograding and the emplacement of the Zangarona schist nappe. Retrograded greenschist also occurs at locality Q (B-1). The soil-covered and topographically recessed area immediately southwest of this locality indicates that retrograding is extensive here, or even that the greenschist body is interrupted. The latter interpretation can explain the partial-girdle distribution of minor fold axes in Domain 3N (Fig. 8). Axes directed toward the east, in the typical hinge-domain direction, occur to the north of the gap of locality Q, close to the hinge domain 2 N/S, while the more typical, southeast-trending axes occur on the other side of the gap. These directions are shown in Fig. 7, and this reasoning leads to the interpretation that the gap at locality Q is a place where the major fold limb of Domain 3N broke during twisting of the F_2 folds, with the parts on either side of the gap rotating relative to one another. The occurrence of retrograded greenschist at the edge of this gap again indicates that fold twisting and retrograding were contemporaneous and occurred during emplacement of the Zangarona schist nappe.

In summary, then, structural analysis of the fold pattern in the Monte Reventino greenschist provides evidence that the F_2 folds were distorted during emplacement of the Zangarona schist nappe, that movement during nappe emplacement was toward the west, and that this movement led to retrograde metamorphism of the greenschist in places where deformation was most intense.

(c) The third recognizable effect of nappe movement is intense shearing in the serpentinite. Polished and striated shear surfaces are ubiquitous in the serpentinite, usually with spacings on the order of 10 cm. The presence of these closely spaced shear surfaces has evidently enabled the serpentinite to show ductile behavior on a large scale and thus conform to the shape of the greenschist folds.

In some areas, however, the shearing has been much more intense and was accompanied by crystallization of carbonates to form ophicalcites. The petrography of these rocks has been described by Piccarreta and Zirpoli (1969a). The distribution of ophicalcites is shown in Figs. 3 and 4; they are most abundant along the south face of the mountain between the Frido formation and the bottom of the greenschist fold pile, but also occur in the Signorelli Valley (C-1, loc. U). Where the ophicalcites take the form of breccias, they strongly resemble the sedimentary serpentinites described by Lockwood (1971), and range from what appear to be sandstones to rocks resembling coarse conglomerates or boulder beds. In a few places (particularly loc. V, A-1), it is possible to see clear transitions from massive serpentinite through sheared serpentinite to a pseudo-conglomerate of unquestionable tectonic origin. I have therefore interpreted all of these rocks as tectonic breccias. In some cases a sedimentary origin cannot be excluded on the basis of field evidence, but invoking a depositional episode at this stage would require a considerably more complex tectonic history.

In a few places (e.g. loc. W, B-2) the ophicalcites have been further deformed. This is seen as a flattening and stretching of serpentinite fragments into lenses surrounded by interlacing calcite–talc bands. Where this flattening has been carried to extreme lengths, a foliation develops, marked by serpentinite and calcite–talc layers. This foliation may in turn be deformed with the development of kink folds.

3.4.2. (8) Effects in the Frido formation

The Frido has been affected by extensive brittle shearing, which makes it difficult or impossible to carry out a standard structural analysis of this unit. Although the shearing was not pervasive on the centimeter or meter scale, the continuity of the unit is frequently interrupted, lithologies and structures change abruptly between one outcrop and the next, and massive, boldly outcropping marker beds of quartzite are fragmented or offset, and may disappear abruptly. Exotic lithologies are not found, however, and the Frido should thus be considered a broken formation (Hsü, 1968). This episode of shearing has not been securely dated.

3.4.3. (9) Effects in the Zangarona schist

The effect of nappe emplacement on the Zangarona schist is not entirely clear, but there is one set of post-foliation structures that may be attributable to this event. These are asymmetric 1–10 cm scale folds that deform the foliation, and which were observed in a number of outcrops close to the thrust contact with the greenschist. Good outcrops are rare enough to make it impossible to say how common these folds are. Measured axes are plotted in Fig. 13, which shows that overturns are consistently toward the southwest.

3.5. Alpine-cycle deformation—during or after nappe emplacement

3.5.1. (10) Structural effects in the ophiolite complex

Three features of the ophiolite complex are due to movements either late in the history of nappe movement or subsequent to it: (a) minor refolding of the greenschist fold pile, (b) folding of the ophiolite–Zangarona schist contact in the Colacino window area, and (c) development of local phyllonitic shear bands in the greenschist.

(a) A minor synform–antiform pair, designated as F_4, refolds the pile of major F_2 folds in the main greenschist body. The axial surfaces of these F_4 folds strike north–south and dip west. The profile of the folds is shown in Fig. 4c, and the effect of F_4 folding on the outcrop pattern can be seen at locality X (Fig. 3, B-2).

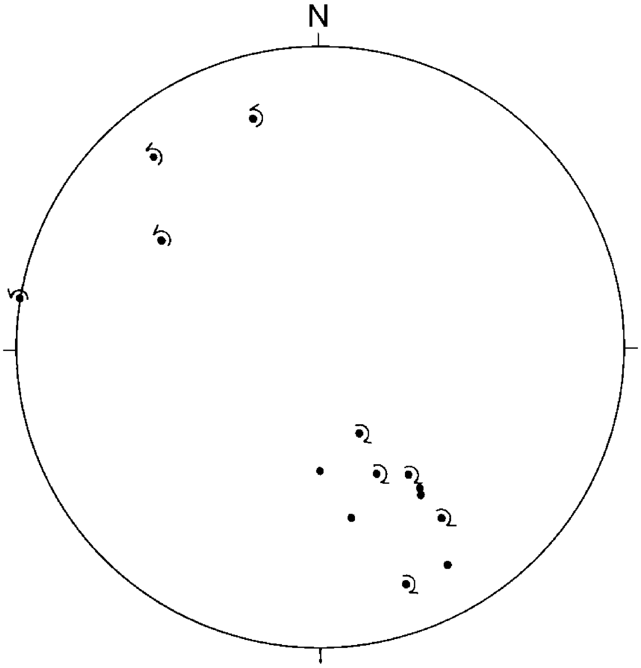


Fig. 13. Minor folds in the Zangarona schist. These folds all deform the main foliation in the schist, and their overturn, where recognizable, is consistently directed toward the southwest. Lower hemisphere, equal-angle projection.

This folding has spread out the patterns of minor fold axes in domain 6 N/S (Fig. 8) and of poles to foliation and axial planes in domains 5 S, 6 N/S, and 7 N (Fig. 9). Data from minor folds in the rotated limb between the F_4 antiform and synform have been omitted from calculations of mean directions in Figs. 8 and 9.

(b) The folded ophiolite–Zangarona schist contact in the Colacino window is displayed in the profile of Fig. 4b. Soil cover obscures its exact form, but it is clear that the general shape is an antiform overturned toward the southwest. Although this can only be seen in the valley of Signorelli, the extent of the Colacino window indicates that the overturned antiform is probably continuous for at least 2 km along strike.

(c) In several places along the lowermost part of the main pile of F_2 folds (Fig. 3: B-2, loc. Y, Z; B-1, loc. AA), the greenschist is cut by thin shear bands, which arbitrarily cross the previous structures, and which are marked by very finely recrystallized chlorite. These phyllonite bands are not penetrative; where present they are spaced some tens of centimeters apart. They are generally marked by two lineations lying in the plane of the shear band—a crenulation, and a mineral or extension lineation. The two lineations are at approximately right angles (Fig. 14) and would seem to indicate that the shearing movements were directed either toward the southwest or the northeast.

It is difficult to be sure about the interpretation of the three kinds of late- or post-nappe emplacement structures, but the overturning of the Colacino window antiform suggests movement directed toward the southwest, which is a direction consistent with lineations on the phyllonite bands, and with the late-stage minor folds in the Zangarona schist mentioned in Section 3.4.3. Similarly, the F_4 antiform–synform pair could be viewed as a very large asymmetric fold indicating westward movement.

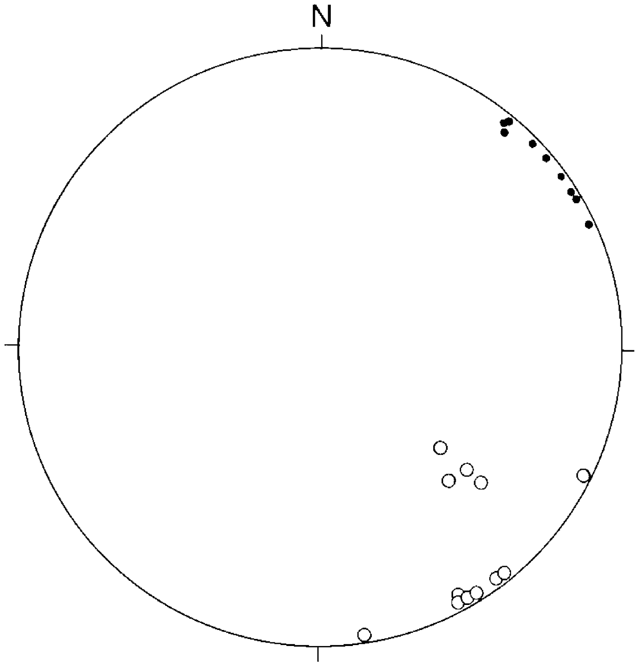


Fig. 14. Lineations in phyllonitic bands cutting the greenschist. Dots are mineral lineations. Open circles are crenulation axes. Lower hemisphere, equal-angle projection.

3.6. Alpine-cycle deformation—after nappe emplacement

3.6.1. (11) Folding and uplift of the antiform of the western Sila Piccola

An antiformal uplift extends east-southeastward from Monte Mancuso and Monte Reventino to Gimigliano (Fig. 1), bounded by the synformal axis of Decollatura to the north. This uplift apparently occurred at least partly during the Quaternary since four marine terraces are visible at the west end of the Sila Piccola between sea level and 1000 m (Gueremy, 1972). Normally, in the Mediterranean, the highest of these terraces is not found above 300 m (Butzer, 1964, Chapter 2). The Monte Reventino antiform is a fold with an axial saddle passing between the culminations marked by Monte Mancuso and Monte Reventino (Fig. 1). This saddle is due to a cross-synform, or axial depression, with a north–south trend. This depression continues north to join the Crati Valley, which is thus a longitudinal depression extending through all of Central Calabria. In the western Sila Piccola this cross-synform shows up in the contours of uplifted and gently folded soil profiles and in the outcrop pattern of the thrust that bounds the window where the Frido formation is exposed (Fig. 1).

3.6.2. (12) Recent slope instability and topographic evolution

Because of the mechanically weak lithologies of the dominant rock types of Central Calabria (phyllite, schist, retrograded granitic rocks) and because of the rapid Quaternary uplift and consequent downcutting by streams, slope instability is very common in this region (Cotecchia and Melidoro, 1974; Carrara and Merenda, 1976). Rotation of landslide masses makes structural studies in many areas difficult or impossible and was a prime reason for choosing the massive, stable greenschist of Monte Reventino for this study. Three major landslide areas occur on the south side of the mountain (Fig. 3: A-2, loc. BB; B-2, loc. CC, DD), but the outcrops used for structural analysis are in zones free of slope instability. Two other major covered areas on the south side of the mountain are labeled ‘valley fill’ (Fig. 3: B-2, loc. EE, FF). These are outcrop-free ramps of loose rock and soil that descend gradually toward the southeast; they can be traced 2–3 km south of the map area, and seem to be remnants of debris-choked valleys whose south sides have been removed by subsequent erosion. The upper valley fill is shown in profile in Fig. 4a. The covered area in the northwest corner of the map is part of a large area of remnant soil cover that has been warped by the folding and uplift of the Monte Reventino antiform, and has not yet been removed by erosion.

4. Discussion

Three phases can be recognized in the interpretation of the tectonic architecture of Calabria: In the first phase, the Calabrian crystalline rocks were seen as autochthonous basement emerging from beneath the Mesozoic–Cenozoic sedimentary section of the Southern Apennines and Sicily (Cortese, 1895). In the second phase, the crystalline rocks were seen as one or more nappes emplaced on top of the Apennine and Sicilian sedimentary rocks by thrusting in an exclusively compressional environment (Limanowski, 1913; Quitzow, 1935; Dubois, 1970; Ogniben, 1973; Amodio-Morelli et al., 1976; Bonardi et al., 1976; Scandone, 1982; Del Moro et al., 1986; Dietrich, 1988). A third phase is emerging as geologists consider the extent to which some of the rock units may have reached their present position by transport along extensional faults (Platt and Compagnoni, 1990; Wallis et al., 1993; Knott, 1994; Thomson, 1994, 1998; Argentieri et al., 1998; Mattei et al., 1999, 2002; Rossetti et al., 2001, 2002). The present study of Monte Reventino was carried out during the second phase, but published during the third phase. The approach in this discussion will be first to see how the study at Monte Reventino fits into the thrust-only interpretation of the second phase, and then to consider how the results of the study might have to be revised in the light of the extensional concepts of the third phase.

4.1. Interpretation of Monte Reventino in terms of thrusting alone

When the original study was done in the 1970s, I was trying to test whether Central Calabria had formerly been a continuation of the Alpine Chain of northeastern Corsica. The dominant vergence in Alpine Corsica is toward the west, and I concluded that the westward transport direction inferred from the twisted folds at Monte Reventino provided some support for Central Calabria having been an Alpine continuation, but certainly was not a definitive proof.

Perhaps it is no longer necessary to find evidence in the geology of Calabria to test the contention that Calabria formerly lay adjacent to Sardinia, along the continuation of the Corsican Alpine belt. That interpretation was strongly and independently supported by evidence from Ocean Drilling Project Leg 107, showing that the Tyrrhenian Sea has grown in the wake of Calabria as it moved southeastward (Kastens et al., 1988; Mascle et al., 1988; Kastens, 1990). Instead, one can accept that Calabria is an Alpine fragment and use the geologic evidence to investigate its history.

Using this approach, a possible interpretation of the greenschist at Monte Reventino in the thrust-only model would be the following. (1) The S_1 foliation formed during extreme stretching and blueschist metamorphism of pillow lavas subducted during Alpine subduction. (2) F_2 folding occurred together with greenschist metamorphism during compressional thrusting that thickened the greenschist body and emplaced it as one of a set of thrust-nappe bodies, between the Frido and the Bagni-Castagna nappes. (3) Continued motion along the thrust contacts broke the ophiolite up into isolated lenses and twisted the folds.

4.2. Interpretation of Monte Reventino in terms of thrusting followed by extension

Invoking large-scale extension solves some of the puzzles that were present during the compression-only second phase. In addition to problems discussed already by the extensional authors, I have long been impressed by the evidence for thinning of the stack of nappes, especially in the northern Catena Costiera. Dietrich (1976), studying an area around Cetraro (Fig. 1), pointed out the extreme thinning of the tectonic units: “The zone is extremely complex from the tectonic point of view, with all the Alpine units strongly thinned; it is not rare in a few tens of meters to pass across four or even five overthrust nappes” [p. 64, transl.]. She noted that there is a progressive thinning of the overthrust edifice along the Catena Costiera from south to north, describing it as a gigantic thinning wedge (‘questo gigantesco becco di flauto,’ p. 68). This geometry is in accord with the concept of a nappe pile emplaced through compressional thrusting and subsequently thinned by large-scale, low-angle extensional faulting.

The possibility that the Monte Reventino meta-ophiolite lens lies along an extensional fault would change the significance of the greenschist structures. The twisted folds would argue for westward transport of the overlying extensional allochthon, and would say nothing about the vergence during the earlier thrust emplacement. It is interesting to note that Rossetti et al. (2001, 2002) found evidence for westward tectonic transport of the extensional allochthon; my results thus support their conclusion.

There is, however, one apparent disagreement between the conclusions of Rossetti et al. (2001, 2002) and the present study. In their work, the Monte Reventino ophiolite is considered to be part of a Lower Ophiolitic Unit, separated by a major extensional fault from an Upper Tectonic Complex (from base upward: (1) unmetamorphosed limestones and dolostones, (2) Upper Ophiolitic Unit, including the Frido formation, and (3) Calabrian Nappe Complex, comprising the Bagni, Castagna, and Stilo units). Reflecting this interpretation, their structural map of the western Sila Piccola (Rossetti et al., 2001, fig. 3) shows a northwest–southeast-striking normal fault at Monte Reventino, dipping moderately to the southwest, on which the Frido formation has dropped down adjacent to the greenstone–serpentinite body.

That interpretation disagrees with the detailed geologic map and section of Figs. 3 and 4a and c in the present paper, which show the Frido passing beneath the ophiolitic rocks, separated by a low-angle fault. However, the map of the present paper was made at a time when only thrusts were anticipated, so it is relevant to consider which interpretation is correct.

The serpentinite–Frido contact runs along the southwest flank of Monte Reventino (loc. BB to southeast of FF). This fairly straight contact could be either a gently northeast-dipping thrust, as interpreted in Fig. 3, or a moderately southwest-dipping normal fault, as in Rossetti et al. (2001, fig. 3). The actual contact was never observed in place (although in one spot it was narrowed to a 5 m wide covered zone), so there is no direct evidence for its dip. Favoring the thrust interpretation is the observation that layering in the ophicalcitic serpentinite dips moderately into the mountain (see two north-dipping attitudes between localities V and BB), as would be expected if this layering is due to shear on a subhorizontal thrust just beneath these outcrops. Favoring the normal-fault interpretation is the observation that the southern face of Monte Reventino, from about 1250 to 1400 m elevation, is a roughly planar geomorphic slope that strikes about N 65° W (295°) and dips about 25° toward the south-southwest. The presence of this smooth surface, cutting through strong greenschist masses whose internal structure is entirely different, is compatible with the presence of a normal fault dropping Frido down into contact with the ophiolitic unit, and it impresses me as an attractive explanation for this otherwise puzzling planar geomorphic slope.

On the other hand, the contact of the ophiolite body with the Zangarona schist northeast of Monte Reventino is harder to explain by extensional unroofing of the ophiolite, as proposed by Rossetti et al. (2001). The ophiolite–Zangarona contact (B-1, C-1, C-2 in Fig. 3) is complicated, and Fig. 4b shows that there is at least 200 m of relief on this contact, with a pattern more compatible with compressional folding than with extensional faulting. Although fig. 3 of Rossetti et al. (2001) does not mark this contact as an extensional fault, it should be one, in their interpretation, as the greenschist–serpentinite body comprises their Lower Ophiolite Unit and the Zangarona schist would be part of their Upper Tectonic Complex.

Existing geologic and tectonic maps (Piccarreta and Zirpoli, 1969b, fig. 2; Ogniben, 1973; Bonardi et al., 1976; Lorenzoni and Lorenzoni, 1983; Scandone, 1991; Rossetti et al., 2001, fig. 3) show the geology of the Monte Reventino ophiolitic rocks in a schematic way only, mostly based on the 1:25,000 geologic map of Calabria (Martirano Lombardo sheet), which was evidently done by aerial photograph interpretation with some field checking. The present map and sections (Figs. 3 and 4) result from the first exhaustive field study of this area, and will allow a more accurate representation of this part of Calabria on future compilation maps. However, further field work will still be necessary to resolve the question whether the greenschist–serpentinite body occurs as an isolated lens lying on a thrust that placed the Zangarona schist over the Frido formation, or whether it is part of a deeper unit that is emerging from beneath the Zangarona and the Frido by tectonic unroofing.

Acknowledgements

Acknowledgments for the 1970s: I am particularly indebted to Tommaso Cocozza for advice in the field at the beginning of the study, to Alberto Carrara for several instructive field excursions and for his continued interest and advice, and to Milly Alvarez, Aldo Bonadio of Platania, and the Giuseppe Conte family of Nicastro for their many contributions to a very long field project. I have benefited from the comments and suggestions of Alberto Carrara, Tommaso Cocozza, Ian Dalziel, Bruno D'Argenio, Terry Engelder, Peter Geiser, Gianni Lanzafame, Eric Nelson, Steven Schamel, Richard Schweickert, Francis J. Turner, and Gian Gaspare Zuffa. The manuscript was given particularly careful reviews by Carrara, Engelder, Geiser, Kligfield, Schamel, and Schweickert. Financial support came from NSF Grants AG-39151, DES-73-06663, and EAR-76-84320, for NATO Research Grant 587, from the National Geographic Society, and from the Industrial Associates of Lamont-Doherty Geological Observatory.

Acknowledgments for 2004: I am greatly indebted to Enrico Tavarnelli for an excellent trip to Monte Reventino in 2004 after my very long absence, and for urging me to revise this very old manuscript for publication. I thank Ian Alsop and Robert Holdsworth for their encouragement as well, and Wouter Bleeker for useful suggestions. Enrico Tavarnelli and Domingo Aerden provided very useful reviews for the journal. I am grateful to Raffaele Spada and Agostino Gallo of Platania and Claudio Marasco of Decollatura for their efforts to protect Monte Reventino and to halt the grave environmental destruction that has occurred since the 1970s as a result of ecologically insensitive tourism and the construction of a huge gas pipeline passing exactly over the crest of the mountain.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsg.2005.05.012

References

Alvarez, W., 1978. Fold distortion: a new indicator of tectonic transport direction. Geology 6, 657–660.

Alvarez, W., 1991. Tectonic evolution of the Corsica–Apennines–Alps region studied by the method of successive approximations. Tectonics 10 (5), 936–947.

Alvarez, W., Cocozza, T., 1974. The tectonics of central–eastern Sardinia and the possible continuation of the Alpine chain to the south of Corsica. Rendiconti del Seminario della Facoltà di Scienze dell'Università di Cagliari Supplemento, 5–34.

Alvarez, W., Cocozza, T., Wezel, F.C., 1974. Fragmentation of the Alpine orogenic belt by microplate dispersal. Nature 248, 309–314.

Amodio-Morelli, L., Bonardi, G., Colonna, V., Dietrich, D., Giunta, G., Ippolito, F., Liguori, V., Lorenzoni, S., Paglionico, A., Perrone, V., Piccarreta, G., Russo, M., Scandone, P., Zanettin-Lorenzoni, E., Zuppetta, A., 1976. L'arco Calabro-Peloritano nell'orogene Appennico-Maghrebide. Società Geologica Italiana Memoria 17, 1–60.

Argentieri, A., Mattei, M., Rossetti, F., Argnani, A., Salvini, F., Funiciello, R., 1998. Tectonic evolution of the Amantea Basin (Calabria, southern Italy); comparing in-land and off-shore data. Annales Tectonicae 12 (1–2), 79–96.

Bonardi, G., Colonna, V., Dietrich, D., Giunta, G., Liguori, V., Lorenzoni, S., Paglionico, A., Perrone, V., Piccarreta, G., Russo, M., Scandone, P., Zanettin Lorenzoni, A., Zuppetta, A., 1976. L'Arco calabro-peloritano, Carta Geologica 1:500.000, Società Geologica Italiana, 68° Congresso.

Bonardi, G., Cavazza, W., Perrone, V., Rossi, S., 2001. Calabria–Peloritani terrane and northern Ionian Sea. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: the Apennines and adjacent Mediterranean Basins. Kluwer Academic Publishers, Dordrecht, pp. 286–306.

Bortolotti, V., Principi, G., Treves, B., 2001. Ophiolites, Ligurides and the tectonic evolution from spreading to convergence of a Mesozoic western Tethys segment. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publishers, Dordrecht, pp. 151–164.

Burton, A.N., 1970. Note on the Alpine Orogeny in Calabria, southern Italy. Quarterly Journal of the Geological Society of London 126 Part 3 (503), 369–381.

Butzer, K.W., 1964. Environment and Archeology. Methuen and Co, London.

Caggianelli, A., Prosser, G., Del Moro, A., 2000. Cooling and exhumation history of deep-seated and shallow level, late Hercynian granitoids from Calabria. Geological Journal 35 (1), 33–42.

Caire, A., Glangeaud, L., Grandjacquet, C., 1960. Les grands traits structuraux et l'évolution du territoire calabro-sicilien (Italie méridionale). Bulletin de la Société Géologique de France 72, 915–938.

Carrara, A., Merenda, L., 1976. Landslide inventory in northern Calabria, southern Italy. Geological Society of America Bulletin 87, 1153–1162.

Carrara, A., Zuffa, G.G., 1976. Alpine structures in northwestern Calabria, Italy. Geological Society of America Bulletin 87, 1229–1246.

Colonna, V., Piccarreta, G., 1975a. Metamorfismo di alta pressione/bassa temperatura nei micascisti di Zangarona-levoli-Monte Dondolo (Sila Piccolo, Calabria). Bollettino della Società Geologica Italiana 94 (1–2), 17–25.

Colonna, V., Piccarreta, G., 1975b. Schema strutturale della Sila Piccola Meridionale. Bollettino della Società Geologica Italiana 94 (1–2), 3–16.

Colonna, V., Piccarreta, G., 1977. Carta geologico-petrografica della zona compresa tra Serrastretta-Carlopoli-Gimigliano-Pianopoli (Sila Piccola, Calabria) 1:25,000. Istituto di Mineralogia e Petrografia, Bari.

Colonna, V., Paglionico, A., Piccarreta, G., Zirpoli, G., 1975. The Pomo River phyllitic unit (Calabria, southern Italy): geobarometric characteristics. Neues Jahrbuch für Mineralogie. Monatshefte 1975 (12), 556–563.

Cortese, E., 1895. Descrizione geologica della Calabria. Memorie Descrittive della Carta Geologica d'Italia 9, 1–310.

Cotecchia, V., Melidoro, G., 1974. Some principal geological aspects of the landslides of southern Italy. Bulletin of the International Association of Engineering Geology 9, 23–32.

Del Moro, A., Paglionico, A., Piccarreta, G., Rottura, A., 1986. Tectonic structure and post-Hercynian evolution of the Serre, Calabrian Arc, Southern Italy: geological, petrological and radiometric evidences. Tectonophysics 124, 223–238.

Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P., Biju-Duval, B., 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics 123, 241–315.

Dewey, J.F., Pitman III., W.C., Ryan, W.B.F., Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine system. Geological Society of America Bulletin 84, 3137–3180.

Di Pierro, M., Lorenzoni, S., Zanettin-Lorenzoni, E., 1973. Phengites and muscovites in Alpine and pre-Alpine phyllites of Calabria (Southern Italy). Neues Jahrbuch für Mineralogie. Abhandlungen 119 (1), 57–64.

Dietrich, D., 1976. La geologia della catena costiera calabra tra Cetraro e Guardia Piemontese. Società Geologica Italiana Memorie 17, 61–121.

Dietrich, D., 1988. Sense of overthrust shear in the Alpine nappes of Calabria (Southern Italy). Journal of Structural Geology 10 (4), 373–381.

Dietrich, D., Lorenzoni, S., Scandone, P., Zanettin-Lorenzoni, E., Di Pierro, M., 1976. Contribution to the knowledge of the tectonic units of Calabria. Relationships between composition of K-white micas and metamorphic evolution. Società Geologica Italiana Bollettino 95 (1–2), 1–25.

Dilek, Y., Robinson, P.T., 2003. Ophiolites in earth history. Geological Society Special Publication, London 218, 717.

Divi, R.R., Fyson, W.K., 1973. Folds and strain in Grenville metamorphic rocks, Bancroft, Ontario, Canada. Geological Society of America Bulletin 84 (5), 1607–1617.

Dubois, R., 1970. Phases de serrage, nappes de socle et métamorphisme alpin a la jonction calabre-apennin: la suture calabro-apenninique. Revue de Géographie Physique et de Géologie Dynamique 12 (3), 221–254.

Dubois, R., 1976. La suture calabro-apénninique Crétacé–Eocène et l'ouverture Tyrrhenienne Néogène: Étude pétrographique et structurale de la Calabre Centrale, Thèse d'Etat,vol. 3, Université Pierre et Marie Curie, Paris.

Graessner, T., Schenk, V., 2001. An exposed Hercynian deep crustal section in the Sila Massif of northern Calabria; mineral chemistry, petrology and a *P–T* path of granulite–facies metapelitic migmatites and metabasites. Journal of Petrology 42 (5), 931–961.

Grandjacquet, C., Glangeaud, L., Dubois, R., Caire, A., 1961. Hypothèse sur la structure profonde de la Calabre (Italie). Revue de Géographie Physique et de Géologie Dynamique 4 (3), 131–147.

Gueremy, P., 1972. La Calabre centrale et septentrionale—guide d'excursion géomorphologique. Travaux de l'Institut de Géographie de Reims 10, 1–128.

Haccard, D., Lorenz, C., Grandjacquet, C., 1972. Essai sur l'évolution tectogénétique de la liason Alpes-Apennins (de la Ligurie a la Calabrie). Società Geologica Italiana Memorie 11, 309–341.

Hansen, E., 1971. Strain Facies. Springer, New York.

Hsü, K.J., 1968. Principles of mélanges and their bearing on the Franciscan–Knoxville paradox. Geological Society of America Bulletin 79 (8), 1063–1074.

Ietto, A., Perri, E., letto, F., Rende, L., 1995. The sequence of Mount Cocuzzo (Catena Costiera, Calabria) in the dolomitic Trias of Southern Apennines. Bollettino della Società Geologica Italiana 114 (1), 215–244.

Irving, E., 1964. Paleomagnetism and its Application to Geological and Geophysical Problems. Wiley, New York.

Kastens, K., 1990. Proceedings of the Ocean Drilling Project, Scientific Results, v. 107: College Station, TX, Ocean Drilling Program, 772pp.

Kastens, K., Mascle, J., Auroux, C., Bonatti, E., Broglia, C., Channell, J., Curzi, P., Emeis, K.-C., Glacon, G., Hasegawa, S., Hieke, W., Mascle, G., McCoy, F., McKenzie, J., Mendelson, J., Muller, C., Rehault, J.-P., Robertson, A., Sartori, R., Sprovieri, R., Torii, M., 1988. ODP Leg 107 in the Tyrrhenian Sea: insights into passive margin and back-arc basin evolution. Geological Society of America Bulletin 100, 1140–1156.

Knott, S.D., 1994. Structure, kinematics and metamorphism in the Liguride Complex, Southern Apennines, Italy. Journal of Structural Geology 16 (8), 1107–1120.

Kusky, T.M., Hudleston, P.J., 1999. Growth and demise of an Archean carbonate platform, Steep Rock Lake, Ontario, Canada. Canadian Journal of Earth Sciences 36 (4), 565–584.

Lanzafame, G., Zuffa, G.G., 1975. Carta geologica del Bacino del Crati, Foglio 551 Bisignano (1:50,000), Consiglio Nazionale delle Ricerche. Istituto di Ricerca per la Protezione Idrogeologica, Cosenza.

Lanzafame, G., Zuffa, G.G., 1976. Geologia e petrografia del Foglio Bisignano (Bacino del Crati, Calabria), con carta geologica alla scala 1: 50.000. Geologica Romana 15, 223–270.

Limanowski, M., 1913. Bulletin International de l'Académie des Sciences de Cracovie, Classe des Sciences Mathématiques et Naturelles, Sér. A: Sciences Mathématiques 6a, 370–385.

Lockwood, J.P., 1971. Sedimentary and gravity-slide emplacement of serpentinite. Geological Society of America Bulletin 82 (4), 919–936.

Lorenzoni, S., Lorenzoni, E.Z., 1983. Note illustrative della carta geologica della Sila alla scala 1:200,000. Memorie di Scienze Geologiche (Padova) 36, 317–342.

Lorenzoni, S., Zanettin-Lorenzoni, E., 1975. The granitic unit of the Sila Piccola (Calabria, Italy). Its position and tectonic significance. Neues Jahrbuch für Geologie und Palaeontologie. Abhandlungen 148 (3), 233–251.

Lorenzoni, S., Zanettin-Lorenzoni, E., 1976. The granitic–kinzigitic klippe of Tiriolo–Miglierina (Catanzaro, southern Italy) and its significance in the interpretation of the geological history of Calabria. Neues Jahrbuch für Geologie und Palaeontologie. Monatshefte 1976 (8), 479–488.

Mascle, J., Kastens, K., Scientific Party Leg 107, 1988. A land-locked back-arc basin; preliminary results from ODP Leg 107 in the Tyrrhenian Sea. Tectonophysics 146, 149–162.

Mattei, M., Speranza, F., Argentieri, A., Rossetti, F., Sagnotti, L., Funiciello, R., 1999. Extensional tectonics in the Amantea Basin (Calabria, Italy); a comparison between structural and magnetic anisotropy data. Tectonophysics 307 (1–2), 33–49.

Mattei, M., Cipollari, P., Cosentino, D., Argentieri, A., Rossetti, F., Speranza, F., Di bella, L., 2002. The Miocene tectono-sedimentary evolution of the Southern Tyrrhenian Sea: stratigraphy, structural and paleomagnetic data from the on-shore Amantea basin (Calabrian arc, Italy). Basin Research 14, 147–168.

Nicolas, A., Boudier, F., 1975. Kinematic interpretation of folds in Alpine-type peridotites. Tectonophysics 25 (3–4), 233–260.

Ogniben, L., 1973. Schema geologico della Calabria in base ai dati odierni. Geologica Romana 12, 243–585.

Piccarreta, G., 1972. Presenza di lawsonite e di pumpellyite negli scisti verdi affioranti tra il M.te Reventino e Falerna (Calabria). Periodico di Mineralogia 41 (1), 153–161.

Piccarreta, G., 1973. Rapporti tra le metamorfiti affioranti nella zona compresa fra Castiglione, Nicastro, Conflenti e la bassa valle del Fiume Savuto (Calabria). Bollettino della Società Geologica Italiana 92 (2), 423–433.

Piccarreta, G., Zirpoli, G., 1969a. Le rocce verdi del Monte Reventino (Calabria). Bollettino della Società Geologica Italiana 88 (3), 469–488.

Piccarreta, G., Zirpoli, G., 1969b. Osservazioni geologico-petrografiche nella zona del M.te Reventino (Calabria). Rendiconti della Società Italiana di Mineralogia e Petrologia 25 (1), 121–144.

Piccarreta, G., Zirpoli, G., 1974. The barometric significance of the potassic white micas of the metapelites outcropping south of the low Savuto Valley (Calabria, Southern Italy). Neues Jahrbuch für Mineralogie. Monatshefte 1974, 454–461.

Piccarreta, G., Zirpoli, G., 1975. The meta-ophiolites outcropping south of the low Savuto Valley within the context of Alpine metamorphism in central and northern Calabria (southern Italy). Neues Jahrbuch für Mineralogie. Monatshefte 1975 (4), 145–162.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geological Society of America Bulletin 97, 1037–1053.

Platt, J.P., Compagnoni, R., 1990. Alpine ductile deformation and metamorphism in a Calabrian basement nappe (Aspromonte, South Italy). Eclogae Geologicae Helvetiae 83 (1), 41–58.

Quitzow, H.W., 1935. Der Deckenbau des Kalabrischen Massivs und seiner Randgebiete. Abhandlungen der Akademie der Wissenschaften in Goettingen. Mathematisch-Physikalische Klasse 13 (14), 63–179.

Ramberg, H., 1963. Evolution of drag folds. Geological Magazine 100 (2), 97–105.

Ramberg, H., 1964. Selective buckling of composite layers with contrasted rheological properties, a theory for simultaneous formation of several orders of folds. Tectonophysics 1 (4), 307–341.

Rossetti, F., Facenna, C., Goffe, B., Monie, P., Argentieri, A., Funiciello, R., Mattei, M., 2001. Alpine structural and metamorphic signature of the Sila Piccola Massif nappe stack (Calabria, Italy): insights for the tectonic evolution of the Calabrian Arc. Tectonics 20 (1), 112–133.

Rossetti, F., Faccenna, C., Goffè, B., Funiciello, R., Moniè, P., 2002. Tectono-metamorphic evolution of the high-*P*/low-*T*, ophiolite-bearing Gimigliano–Monte Reventino unit (Gimigliano, Sila Piccola). Insights for the tectonic evolution of the Calabrian Arc. Società Geologica Italiana Bollettino 121, 51–69.

Sartori, R., 2001. Corsica–Sardinia block and the Tyrrhenian Sea. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publishers, Dordrecht, pp. 367–374.

Scandone, P., 1982. Structure and evolution of the Calabrian Arc. Earth Evolution Sciences 3, 172–180.

Scandone, P., 1991. Structural model of Italy (6 sheets at 1:500,000). Consiglio Nazionale delle Ricerche, Roma.

Schenk, V., 1981. Synchronous uplift of the lower crust of the Ivrea Zone and of Southern Calabria and its possible consequences for the Hercynian orogeny of Southern Europe. Earth and Planetary Science Letters 56, 305–320.

Schenk, V., 1984. Petrology of felsic granulites, metapelites, metabasics, ultramafics, and metacarbonates from southern Calabria (Italy): prograde metamorphism, uplift, and cooling of a former lower crust. Journal of Petrology 25, 255–298.

Schenk, V., 1988. The exposed crustal cross section of southern Calabria, Italy: structure and evolution of a segment of Hercynian crust. In: Salisbury, M.H., Fountain, D.M. (Eds.), Exposed Cross Sections of the Continental Crust. Kluwer, Dordrecht, pp. 21–42.

Scott, W.H., Hansen, E., 1969. Movement directions and the axial-plane fabrics of flexural folds. Carnegie Institution of Washington, Year Book, 254–258.

Sorriso-Valvo, M., Sylvester, A.G., 1993. The relationship between geology and landforms along a coastal mountain front, northern Calabria, Italy. Earth Surface Processes and Landforms 18, 257–273.

Tavarnelli, E., Perrone, V., Alvarez, W., 2004. Structural geometry and tectonic evolution of an inverted extensional trough: The Longobucco Basin, northeastern Calabria, southern Italy. Online Abstracts of the 32nd International Geological Congress, Florence, August 2004.

Teale, T.C., 1988. In: Santantonio, M., Zuffa, G.G. (Eds.), Carta geologica dell'area Longobucco-Bocchigliero (1:25,000). Litografia Artistica Cartografica, Firenze.

Thomson, S.N., 1994. Fission track analysis of the crystalline basement rocks of the Calabrian Arc, southern Italy; evidence of Oligo-Miocene late-orogenic extension and erosion. Tectonophysics 238 (1–4), 331–352.

Thomson, S.N., 1998. Assessing the nature of tectonic contacts using fission-track thermochronology; an example from the Calabrian Arc, southern Italy. Terra Nova 10 (1), 32–36.

Vai, G.B., 1992. Il segmento calabro-peloritano dell'orogene ercinico. Disaggregazione palinspastica. Società Geologica Italiana Bollettino 111, 109–129.

Vezzani, L., 1969. La Formazione del Frido (Neocomiano-Aptiano) tra il Pollino ed il Sinni (Lucania). Geologica Romana 8, 129–176.

Wallis, S.R., Platt, J.P., Knott, S.D., 1993. Recognition of syn-convergence extension in accretionary wedges with examples from the Calabrian Arc and the Eastern Alps. American Journal of Science 293 (5), 463–494.

Watson, G.S., Irving, E., 1957. Statistical methods in rock magnetism. Monthly Notices of the Royal Astronomical Society, Geophysical Supplement 7, 289–300.