UC Berkeley
UC Berkeley Electronic Theses and Dissertations

Title
The Cenozoic Tectonic History of the Calabrian Orogen, Southern Italy

Permalink
https://escholarship.org/uc/item/2zf3q0p0

Author
Shimabukuro, David Haruo

Publication Date
2011

Peer reviewed|Thesis/dissertation

eScholarship.org Powered by the California Digital Library
University of California

The Cenozoic Tectonic History of the Calabrian Orogen, Southern Italy

By

David Haruo Shimabukuro

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Earth and Planetary Science

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Walter Alvarez, Chair
Professor Hans-Rudolf Wenk
Professor Richard A. Muller
Professor John Wakabayashi

Spring 2011

Abstract

The Cenozoic Tectonic History of the Calabrian Orogen, Southern Italy

by

David Haruo Shimabukuro

Doctor of Philosophy in Earth and Planetary Science

University of California, Berkeley

Professor Walter Alvarez, Chair

The Cenozoic accretionary wedge of Calabria, Southern Italy, consists of several units of continental and oceanic affinity accreted beneath the former continental margin of the Sardinia-Corsica block. Each of these units bears the imprint of blueschist-facies metamorphism, indicating that it has been subducted to high-pressure/low-temperature conditions during the Alpine Orogeny. Structurally higher units, having been accreted first, record the early metamorphic history of the orogen; lower units, which are accreted later, record correspondingly later sedimentary and metamorphic events.

In this dissertation, I use metamorphic petrology, structural geology, and geochronology, in the context of field relationships, to study several of the nappe units. The result is a new age and tectonic framework for the Calabrian orogen.

The Zangarona Schist, often the structurally highest unit in the accretionary wedge, records the early history of subduction in Calabria. I show that the high-pressure/high-temperature event recorded in these rocks did not occur at the beginning of Alpine-age subduction; instead, it was formed during an earlier event which took places in the Hercynian Orogen. The lack of a high-temperature metamorphic event, along with the considerable age of units at the time of their subduction, suggests that subduction started off in a cold thermal environment.

The Diamante-Terranova ophiolite unit is a metabasalt and associated sedimentary cover which was metamorphosed in the lawsonite-blueschist facies. It is generally considered to have a greenschist-facies overprint—one which is common in circum-Mediterranean orogens. I show that this greenschist-facies overprint does not exist and that the rocks followed a counterclockwise pressure-temperature-time history. The lack of a warm-overprint allows for Ar/Ar geochronology to be used on high-pressure phengites, indicating a crystallization age of about 48 Myr. This age links the rocks to a west-dipping subduction zone that led to volcanism in Sardinia.

The Frido Unit is a dominantly phyllite and quartzite unit which records changes in sedimentation during the approach of a unit of thinned continental crust to the Calabrian

subduction zone. Although much of it appears to be a coherent unit, I show that the upper levels of the unit include chaotic blocks of metabasalt and serpentinite, deposited as a sedimentary mélange. Many of the Calabrian ophiolite units, previously considered to be distinct nappe units, have similar block-in-matrix relationships and also may be sedimentary mélanges consisting of previously-subducted material which has been re-deposited into the trench by underwater slides.

Together, this re-evaluation of the Calabrian nappe stack indicates that subduction likely began in the Eocene in a cold thermal environment. Early-formed blueschist units were exhumed and re-deposited in the trench, eventually undergoing a second high-pressure metamorphic event. This same subduction zone exists today, to the southeast, as Ionian oceanic crust continues to subduct beneath Calabria.

This thesis is the culmination of many years of support from family, friends, and colleagues.

My cousin, Devin Iimoto, took me on my first hiking trip in the Sierra Nevada, at Kearsarge Pass. This was the first step in my lifelong love of mountains.

Josh Feinberg and Cathy Lee encouraged me to apply to graduate school at Berkeley. Although we have gone on separate paths, I still remember and appreciate their encouragement.

Dave K., Dave W., Johanna, Tim, Will, Connie, Amanda, and Edwin, have provided constant encouragement throughout the years.

The Locher and Alessio families of Cosenza, Italy, took in a wandering foreigner, providing a church and a home while I was working in Calabria.

Katharine King gave me a tremendous amount of support and the last bit of impetus for me to finish my dissertation.

I also want to thank my mother, Gail, and my sister, Pam, for their love and for tolerating my seemingly endless time in school.

My dissertation committee consisted of Rudy Wenk, Rich Muller, and John Wakabayashi. Rudy introduced me to mineralogy as an undergraduate. Rich taught me that it is okay to ask for crystal-clear answers in a multidisciplinary environment.

John Wakabayashi has truly been a mentor in subduction zones, high-pressure metamorphic rocks, mélanges, field geology, and IBUs. This thesis could not have been completed without him.

Finally, I would like to thank my dissertation supervisor, Walter Alvarez, for unwavering support throughout the years. Besides guiding me on the process of becoming a geologist and a scientist, he has given me the freedom to study whatever my intellectual passions have led me to. I am still looking forward to the adventures ahead.

Introduction

The Calabrian Arc of Southern Italy is a Cenozoic orogen developed over a west-dipping subduction zone. Geographically, it is a continuation of the carbonate- and flysch-dominated Apennine mountain belt which runs down the Italian Peninsula and curves westward into Sicily. Geologically, its rocks are more similar to those found in Alpine Corsica or the Western Alps, with the presence of high-pressure (HP) blueschist-facies crystalline rocks marking an ancient subduction system. It is a controversial mountain belt, as neither the number of subduction zones, their vergence, their age, nor the paleogeographic position of the individual units have been established with certainty. I hope to address some of these questions in this dissertation.

Geological Calabria can be divided into two geological regions, composed of smaller geographical subregions. The subregions are generally defined by basement topographic highs and separated by Neogene normal-fault bounded basins. Northern Calabria consists of the Sila and Catena Costiera, while Southern Calabria consists of the Serre, Aspromonte, and the Peloritani of Sicily. Although the two regions probably experienced the same orogenic event, high-pressure Alpine-aged subduction-related metamorphism is present in Northern Calabria, while in Southern Calabria, the orogenic event tends to be evidenced by thin-skinned amphibolites-facies tectonics. This dissertation will focus on the rocks of Northern Calabria where a more complete rock record exists.

The rocks in Northern Calabria can be broadly divided into two groups based on their tectonic role during the Alpine Orogen: upper plate and lower plate. Rocks which acted as the upper plate are older; most were previously involved in the ~300 Ma Hercynian Orogen. These rocks—named the Sila Unit—preserve a crustal cross-section from phyllitic upper crust down through mid-crustal granitoids into lower-crustal migmatites. These upper plate rocks were only weakly affected by Alpine-aged metamorphism.

These older rocks comprise the plate under which the lower nappes were subducted, in some cases to over 50 km depth. Most of the lower plate rocks are of oceanic derivation and are a mixture of ocean floor basalts, serpentinites, pelites, flysch, and carbonates which once were present in the Tethys Ocean. The main indication that these were involved in the Alpine Orogeny is the presence of blueschist-facies metamorphism throughout the lower plate units, indicative of a high-P/T subduction process.

Each of the following chapters studies a different unit in the accretionary wedge, emphasizing a different process which is important. In Chapter 1, I present a study of the Zangarona Schist, the highest unit of the Calabrian accretionary wedge, which indicates the subduction started off cold. In Chapter 2, I investigate the metamorphic history of metabasalts from the Diamante-Terranova unit, finding that they do not have a greenschist-facies overprint and were likely exhumed early on in the subduction zone history. In Chapter 3, I present a structural and geochronological study of the same Diamante-Terranova metabasalts, which shows that they are related to a west-dipping subduction zone. In Chapter 4, I show that the Frido Unit is likely to be a sedimentary mélange.

These four chapters, taken together, suggest that the west-dipping Calabrian subduction zone initiated in the Eocene in cold crust. As subduction progressed, blueschist-facies units were exhumed into the trench and re-subducted. The same subduction zone exists today, in the form of the Ionian trench southeast of Calabria.

Brief summaries of each of the chapters follow.

Chapter 1: Rock record of cold subduction initiation beneath a continental margin, Calabria, southern Italy

Subduction on earth can be broadly classified into two categories: subduction beneath ocean crust and subduction beneath continental crust. Although subduction is well understood as a steady-state process, how subduction zones form in either of these settings is not well understood.

Our only examples in the rock record of subduction initiation are from oceanic island arcs. In some cases, subduction begins along a pre-existing weakness in the ocean crust, such as a spreading center. In other instances, an initial extensional event is thought to create a new weakness in the crust. In both of these cases, young—and therefore hot—oceanic crust is subducted, leaving a distinctive high-temperature and high-pressure metamorphic signature on rocks.

In the case of subduction initiation beneath a continental margin, our information is limited because there are no known examples in the rock record. We know that starting a subduction zone here is difficult: although oceanic crust alongside continental margins is old and dense, it is also thick and strong. Yet the crust here must break, since subduction beneath continental margins leads to one of the first-order features of plate tectonics—the long volcanic arcs that ring the ocean basins.

In this chapter, I describe rock from a 45 million year old (Alpine-aged) subduction zone from Calabria, the toe of Italy. I believe that this subduction zone did not start out hot, as is common in oceanic subduction zones, but instead began in relatively cold conditions.

I offer two major arguments for this:

(1) If there was an initial hot event then the first rocks that were subducted would have been heated to high temperatures. We do not observe any evidence of high temperatures in the Alpine-aged rocks in Calabria. A high-temperature event does exist, but it occurred in a much older event.

(2) If subduction began along an extensional feature, such as a spreading center, then the first-subducted rocks would have been very young. Instead, our geochronological measurements indicate that all of the rocks in the orogen were at least 100 million years old when subducted; hence they were cold.

Thus, the cold conditions present at the beginning of the Calabrian subduction zone indicate that thermally-weakened crust was not important for subduction initiation in Calabria.

Instead, in the case of Calabria, the serpentinization of upper oceanic mantle due to water infiltration may have played an important role in weakening the crust so that subduction could start.

Chapter 2: Implications of a counterclockwise pressure-temperature-time path of blueschist-facies rocks in the Alpine Orogen of Calabria

Blueschist-facies* metamorphism, defined by the presence of lawsonite and glaucophane, is indicative of high pressure/low temperature conditions. This facies is produced in subduction zones where descending cold ocean crust creates a refrigeration effect on deep rocks. Blueschist-facies minerals are thermodynamically unstable at the surface of the earth, but they can be preserved if they are exhumed rapidly, in cool conditions, due to kinetic effects.

However, in many cases blueschist-facies minerals are not preserved. When subduction of ocean crust ceases due to a continental collision, temperatures rapidly increase as the cooling effect of the downgoing crust stops. Rocks brought to the surface during continental collision are exposed to warmer conditions, indicated by the growth of greenschist-facies minerals such as actinolite and epidote. These temperatures also destroy some of the more unstable blueschist-indicative minerals, such as lawsonite.

The Alpine Orogeny is a typical example of a collision belt, where continental collision has occurred and exhumed rocks have a greenschist-facies overprint. Because of this, lawsonite is rare, as it is only preserved when rocks are exhumed rapidly in cool conditions.

In this chapter, I describe blue and green rocks from Diamante, Calabria. These metabasalts contain one of the only occurrences of lawsonite in the Alps, which is surprising because they previously have been identified as having the warm, greenschist-facies metamorphism which destroys lawsonite.

I show that these rocks do not have the mineral assemblages indicative of a greenschist overprint. Instead, the green rocks at Diamante have been metamorphosed in the epidote-blueschist facies, a subclass of the blueschist facies. As epidote is a green mineral, these rocks are easy to mistake as greenschist-facies rocks in outcrop.

I suggest that the rocks at Diamante were exhumed early in the orogenic process, when thermal conditions were cool. This allowed the preservation of the delicate lawsonite-bearing mineral assemblages.

* A metamorphic facies is a characteristic assemblage of minerals which are stable at a particular pressure-temperature conditions. Blueschist-facies minerals (glaucophane and lawsonite) are stable at high-P/T conditions. Greenschist-facies minerals (actinolite and epidote) are stable at moderate-P/T conditions.

Chapter 3: Evidence for synchronous opposite vergence in the Calabria-Corsica orogenic trend from Diamante, Calabria

In this chapter, I present structural measurements and Ar/Ar geochronology from the lawsonite-blueschist outcrop at Diamante, Calabria. In the previous chapter I showed that these rocks have not been affected by a greenschist overprint, thus, they preserve early metamorphic events in the Calabrian subduction zone.

In addition to their well-preserved metamorphic history, these rocks bear unique structural indicators which record their direction of motion within the Calabrian subduction zone. The green layers are tilted in a manner similar to books on a bookshelf, indicating that they have been sheared in a top-to-the-southeast fashion. In addition, blueschist-facies minerals grow between the tilted blocks, indicating that the deformation took place in the high-pressure conditions of a subduction zone.

However, new observations presented in Chapter 4 suggest that the Diamante block may be a block in a sedimentary mélange. In that case, the structural and metamorphic history of the block may not be representative of the entire unit. Instead, the earliest stages of deformation recorded by the rock may have been formed in the early subduction zone, before it was exhumed and deposited as a block on the seafloor. Only the later stages of deformation, which indicate a top-to-the-east shear direction, are representative of the unit as a whole.

In order to aid in the interpretation of the structural fabrics, we used Ar/Ar geochronology to date white micas from the rocks at Diamante. Since they have not been affected by a greenschist overprint, the 46 Myr age of the rocks can be taken to be the crystallization age of the rocks and the subduction zone. This is the first clear date of the age of subduction in Calabria; previous radiometric dates in the literature date the process of exhumation.

This 46 Myr date is significant because it is synchronous with the start of subduction beneath Sardinia, indicating that the Diamante rocks formed in a west-dipping subduction zone. This date also implies that the deformation observed in Calabria was formed in a west-dipping subduction zone, consistent with the shear directions recorded in the rocks.

At the same time, north of Calabria, there was an east-dipping subduction zone present in Corsica. A transform fault is necessary to connect Corsica to the west-dipping subduction zone in Calabria.

Chapter 4: The Frido unit of Calabria, Southern Italy: Tectonic implications of a sedimentary mélange

A mélange is a type of rock fabric in which blocks are enclosed in a fine-grained matrix. The most common types of mélange are tectonic mélanges, in which a dense network of faults juxtaposes blocks against a matrix, and sedimentary mélanges, in which blocks are deposited in a fine-grained matrix. These two types of mélanges are easily confused with each other because later tectonic deformation can obscure the original relationship of the enclosed blocks to the matrix.

The Frido Unit of Calabria is a metamorphosed shale, sandstone, and carbonate unit. In the northern part of exposure, it is considered a mélange, as there are exotic blocks of basalt and lower continental crust present in the sedimentary sequence. Previous workers have considered it to be a tectonic mélange because of the strong shear deformation of the unit. In the southern part, it is considered to be a coherent sedimentary unit, as exotic blocks are not common.

In this chapter, I present new a new structural study of the southern part of the Frido Unit, near Monte Reventino, Calabria. In this area, the Frido has been considered to be a coherent unit, overlain by a sheet of Monte Reventino greenschist. My study of field relations indicates that the Monte Reventino rocks may instead be underwater landslide blocks (olistostromes) within the Frido sedimentary sequence, making the Frido a sedimentary mélange. This means that the metamorphic and structural history of the greenschist is not representative of the Frido Unit.

I then discuss other outcrops of the Frido Unit, located to the north, and find that they can best be understood as sedimentary mélanges. This framework help explain the diversity of lithologies (lower continental crust, granite, blueschist metabasalt, and pillow basalts) and metamorphic grades (“unmetamorphosed’ to lawsonite-blueschist) associated with the Frido Unit: each of the blocks has been deposited into a sedimentary basin.

If the entire Frido Unit is understood as a sedimentary mélange, then the variation in appearance from north to south may be due entirely to the types of sediment that reached the basin. In addition, the metamorphic and the ancient ages attributed to the Frido Unit may apply only to the blocks and not to the entire unit.

Responsibility for work

Each of these chapters, in revised form, will be submitted as a journal article. Below is a summary of the work I performed.

In Chapter 1, I identified the outcrops and collected the samples. The analyses were done at the UC Davis electron microprobe which is managed by Sarah Roeske. Su-chin Chang provided radiometric dates for the rocks. Walter Alvarez and John Wakabayashi reviewed several drafts of this chapter.

In Chapter 2, Francesca Liberi and I collected the rocks. We jointly analyzed the thin sections at the UC Berkeley electron microprobe, managed by Kent Ross, during Francesca’s visit to Berkeley. I followed up with additional microprobe on select sections. The metamorphic interpretation was performed by me. John Wakabayashi and Walter Alvarez reviewed several drafts of this chapter.

In Chapter 3, I originally identified the domino boudins, Francesca Liberi and I mapped the outcrop, I performed all of the structural analysis and interpretation, and Su-chin Chang provided the radiometric dates for rocks. Walter Alvarez and John Wakabayashi reviewed several drafts of this chapter.

In Chapter 4, I identified all the localities, collected the samples, and collected all the data for the geologic maps. John Wakabayashi and Walter Alvarez reviewed several drafts of this chapter.

In all chapters, the text is entirely my work.

Introduction to Chapter 1

Subduction on earth can be broadly classified into two categories: subduction beneath ocean crust and subduction beneath continental crust. Although subduction is well understood as a steady-state process, how subduction zones form in either of these settings is not well understood.

Our only examples in the rock record of subduction initiation are from oceanic island arcs. In some cases, subduction begins along a pre-existing weakness in the ocean crust, such as a spreading center. In other instances, an initial extensional event is thought to create a new weakness in the crust. In both of these cases, young—and therefore hot—oceanic crust is subducted, leaving a distinctive high-temperature and high-pressure metamorphic signature on rocks.

In the case of subduction initiation beneath a continental margin, our information is limited because there are no known examples in the rock record. We know that starting a subduction zone here is difficult: although oceanic crust alongside continental margins is old and dense, it is also thick and strong. Yet the crust here must break, since subduction beneath continental margins leads to one of the first-order features of plate tectonics—the long volcanic arcs that ring the ocean basins.

In this chapter, I describe rock from a 45 million year old (Alpine-aged) subduction zone from Calabria, the toe of Italy. I believe that this subduction zone did not start out hot, as is common in oceanic subduction zones, but instead began in relatively cold conditions.

I offer two major arguments for this:

(1) If there was an initial hot event then the first rocks that were subducted would have been heated to high temperatures. We do not observe any evidence of high temperatures in the Alpine-aged rocks in Calabria. A high-temperature event does exist, but it occurred in a much older event.

(2) If subduction began along an extensional feature, such as a spreading center, then the first-subducted rocks would have been very young. Instead, our geochronological measurements indicate that all of the rocks in the orogen were at least 100 million years old when subducted; hence they were cold.

Thus, the cold conditions present at the beginning of the Calabrian subduction zone indicate that thermally-weakened crust was not important for subduction initiation in Calabria.

Instead, in the case of Calabria, the serpentinization of upper oceanic mantle due to water infiltration may have played an important role in weakening the crust so that subduction could start.

CHAPTER 1

Rock record of cold subduction initiation beneath a continental margin, Calabria, southern Italy

ABSTRACT

Evidence for initiation of subduction beneath a continental margin has not been observed in any field setting, either in a present-day example, or in the historical record. We present data from Northern Calabria, in Southern Italy, which shows that subduction may have initiated beneath a continental margin east of the Corsica-Sardinia-Calabria block during the Eocene, in crust that was then over 100 Myr in age. There is no evidence of the amphibolite-facies metamorphism which is common in many examples of intraoceanic subduction initiation ("hot initiation"), implying that subduction began in old and cold lithosphere ("cold initiation"). Formation of a new subduction zone here suggests that serpentinized lithosphere may be important in weakening what is generally densest but also the strongest lithosphere in an ocean basin, at the edge of a continental margin.

INTRODUCTION

Although subduction of oceanic crust beneath continents is a first-order process in modern plate tectonics, how such subduction begins is poorly understood. Initiation of subduction beneath a continental margin presents a paradox—although oceanic crust adjacent to passive continental margins is old and dense, it is also rheologically strong and unlikely to break and allow subduction to initiate (Cloetingh et al. 1989). It is certain that the process occurs, however, since the long subduction zones along active continental margins are a major feature of plate tectonics. Study of this process has been hampered by the fact that no present or ancient examples of subduction initiation beneath passive margins have been reported from the field (Stern, 2004).

In contrast, the beginning of subduction within ocean basins is a well-studied process. In some examples from the geological record, such as the Franciscan Complex of California and the Samail Ophiolite of Oman, a new subduction zone is thought to have initiated in young, hot oceanic lithosphere, leaving a distinct high-pressure (HP), high-temperature (HT) sheet, or metamorphic sole, at the base of the upper-plate ophiolite ("hot initiation") (Wakabayashi, 1990; Brown, 1992; Dilek and Whitney, 1997; Hacker and Gnos, 1997; Smith et al., 1999; Guilmette et al., 2009; Wakabayashi et al., 2010). As this involves subduction of very young crust, the igneous protolith and amphibolite-facies metamorphic overprint have similar ages (Hacker and Gnos, 1997). This HT event is sometimes followed by a blueschist-facies overprint, as continuing subduction lowers the geothermal gradient (Wakabayashi, 1990; Dilek and Whitney, 1997). In the upper plate, a nascent arc also develops, either in new oceanic crust formed during slab rollback (Stern and Bloomer, 1992), or in older oceanic crust (Wakabayashi et al., 2010). There is one present-day example of subduction initiation, at the Puysegur trench of New Zealand, although it is a special situation at a restraining bend of a transform fault (Lebrun et al., 2003; Sutherland et al., 2006).

However, analogies with such intraoceanic settings may not be the best way to understanding the initiation of subduction beneath continental margins. Continental margins are adjacent to the oldest crust within ocean basins, areas with very low geothermal gradients. These cool conditions may prevent the formation of the high-temperature event seen in intraoceanic settings, making recognition of the subduction initiation process difficult. Instead, the first evidence of subduction-zone metamorphism may be standard blueschist-facies metamorphism of crust that was very old, and cold, at the time of subduction ("cold initiation")—one that lacks the early amphibolite-facies metamorphism common in intraoceanic examples.

In this paper, we present new petrological observations and Ar/Ar geochronology from the Cenozoic accretionary wedge in Northern Calabria, Southern Italy. These observations show that subduction appears to have initiated beneath a continental margin at least 100 million years old at the time, and to have begun with temperatures which were not high enough to cause amphibolite-facies metamorphism. This may be an example of "cold" subduction initiation.

REGIONAL GEOLOGY OF NORTHERN CALABRIA

The Calabrian Orogeny is a result of the complicated microcontinent tectonics taking place as a consequence of Africa-Europe convergence (Amodio-Morelli et al., 1976; Bonardi et al., 2001). Although geographically it is a link between the sedimentary-rock orogens of Italy (Apennines) and Sicily (Maghrebides), Calabria is dominated by igneous and metamorphic rocks and is considered to be a fragment of the Cenozoic Alpine chain, first displaced as part of the Sardinia-Corsica block during the back-arc opening of the Ligurian Sea in the Oligocene, then on its own as a microcontinent during Miocene opening of the Tyrrhenian Sea (Dewey et al., 1989). Movement of the Calabrian microcontinent was accommodated by consumption of oceanic crust of the Neotethys (the northwest continuation of the present Ionian Sea) and concurrent development of the Calabrian accretionary wedge (Dewey et al., 1989; Stampfli and Borel, 2002).

The direction of subduction beneath the Calabrian Arc has been controversial: models involving both a single west-dipping subduction zone (Knott, 1994; Rossetti et al., 2001, 2004), and two opposite-dipping subduction zones (Amodio-Morelli et al., 1976; Alvarez, 1991; Cello et al., 1994), are present in the literature. The information in the present paper does not directly bear on subduction vergence.

Two methods have previously been used to estimate the time of the start of subduction beneath Calabria. In the first, the presence of arc volcanism in Sardinia at 38.28 ± 0.26 Ma, plate velocities between 1 and 3 cm/yr, and partial melting of the downgoing slab at 80 km, it can be calculated that a west-dipping subduction must have existed by the 49-42 Ma age range (Lustrino et al., 2009). A second method, based on analogy to subduction in Corsica, indicates a beginning in the Paleocene-Eocene; however, these are only loosely constrained by radiometric ages from Calabria (Rossetti et al., 2001).

Geologic Calabria can be divided into Northern and Southern Calabria based on the presence, or absence, of blueschist-facies metamorphism (Bonardi et al, 2001)—in this paper, we will focus on the northern part of Calabria, where the blueschist-facies ophiolite remnants indicate that subduction has taken place. Here, the Calabrian orogenic wedge consists of several nappes, composed of material of both oceanic and continental affinity, emplaced beneath Hercynian-aged continental crust (Figure 1) (Amodio-Morelli et al., 1976).

The upper plate of the subduction zone is the Sila Unit, which preserves a cross section through the Paleozoic Hercynian Orogen (Graessner and Schenk, 2001). It can be considered the upper plate as it has not undergone blueschist-facies metamorphism during the Alpine-aged orogeny; instead, the Alpine burial metamorphism of these nappes is negligible. Although there is evidence of deformation, it has taken place entirely in the brittle field and most likely represents late, out-of-sequence thrusts (Acquafredda et al., 1994).

The nappes below the Sila Unit give the appearance of an inverted metamorphic sequence, with peak metamorphic grade varying from amphibolite facies in the uppermost Castagna Unit, to blueschist facies in the lowermost Frido and Verbicaro Units (Piccarreta, 1981). The uppermost unit that has undergone Cenozoic subduction—the Castagna Unit—has been locally divided into three members: an uppermost augen gneiss, a middle biotite gneiss, and a micaschist-dominated Zangarona Schist unit, each of which probably represent reactivated Hercynian-aged crust. None of the members are continuous throughout the orogen (Colonna and Piccarreta, 1975). Lower in the stack are ophiolite fragments, the quartzite and phyllite Frido Unit, and the carbonate platform Verbicaro Unit, all of which preserve Tethyan marine sedimentation (Amodio-Morelli et al., 1976).

Further to the north in Calabria, the well-defined napped structure transitions into a mélange resting on top of a metamorphosed carbonate platform. A crystalline upper plate, apparently eroded away, provided the overburden to cause blueschist-facies metamorphism (Monaco et al., 1995; Iannace et al., 2005; Tortorici et al., 2009). The mélange contains blocks of metabasalt and continental crust (Spadea, 1982). This mélange appears to have been roofed by either an ophiolite sheet, with Jurassic-aged sedimentary deposits, or continental crust which has been eroded away (Monaco et al., 1995). The tectonics in this region are fundamentally different than further to the south because, here, Calabria has collided with the Apulian carbonate platform which makes up much of Italy; to the south no collision has taken place.

FIELD LOCALITIES

Amphibolite-facies metamorphism does exist at the highest level of the Northern Calabrian subduction zone—the key question is whether this is related to the ~300 Ma Hercynian Orogeny, or to the more recent Alpine Orogeny. To determine this, we studied the uppermost units subducted during the Alpine stage in several places along strike: in the south, the Zangarona Schist member of the Castagna Unit is often the highest unit, whereas in the north, a serpentinite mélange contains a mafic block which experienced high-grade metamorphism. These two are the most likely to record the early history of the Calabrian subduction zone.

In the Sila Piccola region, the two uppermost members of the Castagna Unit are not present and the uppermost nappe unit experiencing Alpine-subduction related metamorphism is the Zangarona Schist member of the Castagna Formation, a garnet micaschist with uncommon blocks of garnet amphibolite metabasalt (Colonna and Piccarreta, 1976). We focused on two localities preserving metabasalt, near the towns of San Mango (Cozzo Volante, 39° 2'55.97"N, 16°10'28.73"E, WGS84) and San Fili (39° 2'55.07"N, 16°16'6.50"E). Electron microprobe analyses show that the amphibolite is comprised of low-Ti, high-Al blue-green amphiboles (edenite and pargasite) with almandine-grossular garnets. Late high-Al glaucophane rims the early amphiboles (Figure 2a). Ti-phases preserve rutile cores, with an intermediate ilmenite zone, surrounded by titanite rims (Figure 2b). These amphibolites have been interpreted as being Hercynian in age, based on regional relationships, but have not previously been dated using radiogenic geochronology (Colonna and Piccarreta, 1976).

The second locality, just below Timpa Pietrasasso (40° 0'0.40"N, 16°15'47.64"E) along the Calabria-Lucania border, preserves high-grade amphibolite blocks in a serpentine-matrix mélange, assigned either to the Frido Unit (Knott, 1987; Spadea, 1982), or to an unnamed mélange unit associated with an ophiolite fragment (Bonardi et al., 1988; Monaco et al., 1995). These blocks can be considered to be either tectonic slices or olistoliths; nevertheless, they are the best record of what remains of the upper plate (Knott, 1987, 1994). The amphibolite shows melt textures and leucosome segregations, indicating temperatures in excess of 650 ºC (Poli, 1993). Brown amphiboles are high-Ti, resulting in high equilibration temperatures based on the semi-quantitative thermobarometer (Ernst and Liu, 1989). These blocks have been interpreted to be Hercynian-aged lower crust, based on analogies with the diorite-kinzigite unit present throughout Calabria; again, they have not previously been radiometrically dated (De Roever, 1976; Spadea, 1982; Monaco et al., 1995).

GEOCHRONOLOGY

In order to investigate whether the amphibolites present in the highest nappes in Northern Calabria were related to “hot” Alpine-aged subduction initiation, or are remnants of Hercynian metamorphism, we selected samples from these outcrops to date with Ar/Ar geochronology: two from the Zangarona Schist unit, and a third from near the Calabria-Lucania border. One date in the Zangarona Schist resulted in a mixed age, possibly as a result of partial reheating during Tethyan rifting, while another gave a plateau age of 319 ± 4 Ma, and an isochron date of 304 ± 4 Ma (Figure 2c). This date is broadly consistent with a late Hercynian event (Schenk and Graessner, 2001). Previous geochronology done in the Sila Piccola on the Castagna Unit has shown mixed ages, attributed to partial reheating during a low-grade Alpine-aged event (Rossetti et al., 2001; Bonardi et al., 2008).

The Ar/Ar date on hornblendes from an amphibolite block in mélange from the Calabria-Lucania region gave a plateau age of 193 ± 2 Ma (Figure 2d). This is a relatively late date, unrelated to the Hercynian Orogeny, and is consistent with proto-Tethys extension that preceded the Jurassic rifting in this area (Piccardo, 2009).

For both of these dates it is notable that there is no evidence of a high temperature Alpine event resetting these old dates, as both show well-developed plateau ages. As hornblende closes to argon loss at 500-550 ºC (McDougall and Harrison, 1999), amphibolite-facies temperatures were not attained in these units.

The old age, at the time of subduction, of these units is further supported by the Tethyan-derivation of the ophiolite fragments in Northern Calabria (Spadea, 1994). For example, the well-studied Fuscaldo metabasalt is considered to be Jurassic in age, based on the presence of Calpionella (Tithonian-Neocomian) limestones in the cover sequence (De Roever, 1972).

All of these units were involved in the Alpine-aged subduction zone. In the Zangarona Schist, amphibole grains are rimmed with glaucophane, indicating metamorphism in subduction-related geothermal gradients (Figure 2a). In the Calabria-Lucania region, the mélange contains Alpine-aged lawsonite, blueschist, and Mg-carpholite (Monaco et al., 1995). The Fuscaldo ophiolite was metamorphosed in the lawsonite-albite facies during Alpine aged subduction (De Roever, 1972). Although none of these units were directly dated with radiogenic geochronology, we have obtained a new Ar/Ar date from the underlying Diamante-Terranova Unit which indicates an age of 46 Ma for syn-blueschist phengites, consistent with the existence of a volcanic arc in Sardinia at 38 Ma (Lustrino et al., 2009). We take this to be the age of the Alpine aged subduction zone.

The protolith ages, combined with the approximate metamorphic age, allow us to estimate the age of Tethyan crust beneath the Corsica-Sardinia continental margin: the Zangarona Schist was approximately 250 Myr in age, while the Timpa Sassopietra block was around 150 Myr in age when subducted (Figure 3). The ophiolite units of Calabria can be used as a further constraint—they too would have been 100 Myr old when subducted. In all cases, subduction would have begun in old and cold crust, in contrast with the relatively young material that would have been accreted at the beginning of subduction if the initiation had been “hot.” In the case of the Samail ophiolite, the metamorphic sole units were only 1 to 4 Ma at the time of subduction (Hacker and Gnos, 1997), while in the Franciscan Complex of California, the rocks were just a few million years old (Wakabayashi and Dumitru, 2007).

Although the Zangarona Schist may not represent the absolute top of the subduction zone, mineralogical evidence also supports the lack of a high-temperature event. There was on partial resetting of the Ar/Ar system in micas previously dated from other members of the Castagna Unit, indicating that temperatures stayed below 400 ºC during all phases of Alpine subduction (Rossetti et al., 2001; Bonardi et al., 2008). This is supported by our new dates for hornblendes, which show that amphiboles remained beneath the 500-550 ºC closure temperature (McDougall and Harrison, 1999).

To the south, in the Aspromonte region of Calabria, amphibolite-facies metamorphism exists; however, this is most likely related to the continental collision which has taken place between the Calabrian nappes and the Sicilian continental crust (Messina et al., 1990; Bonardi et al., 2008; Heymes et al., 2010). Only the paleogeographic accident of subduction being able to continue in Calabria, without a final continental collision, has allowed the early Alpine-aged metamorphic event to be preserved.

DISCUSSION

Two important results can be seen from Northern Calabria. First, all units in the orogenic stack were at least 100 Ma when subducted. Since oceanic crust reaches its maximum thickness after about 80 Ma, this implies that these units represent old and cold lithosphere, in contrast to intraoceanic examples of subduction initiation (Turcotte and Schubert, 1982). Secondly, there appears to have been no Alpine-aged amphibolite-facies metamorphism in Northern Calabria as temperature were not high enough for complete resetting of Rb/Sr or K/Ar in white micas, a point emphasized by several previous workers (Rossetti et al., 2001; Bonardi et al., 2008).

These observations show that, due to their low geothermal gradients, the initiation of subduction beneath continental margins may leave only subtle evidence—subduction may not begin hot, but may instead begin in a relatively cool environment. Since many models of subduction initiation involve subduction of young and hot crust (Mueller and Phillips, 1991; Williams and Smyth, 1973; Platt, 1975), an alternative mechanism is necessary to allow the old, strong crust to break. The particular geological situation in Calabria can be used comment on a couple of proposed models.

Some models assume that extensional rupture may have preceded the initiation of subduction (Stern and Bloomer, 1992; Kemp and Stevenson, 1996; Gurnis et al., 2004). An initial extensional phase is unlikely along the incipient Calabrian subduction zone as this would have produced a high geothermal gradient and resultant amphibolite-facies metamorphism at the beginning of subduction, which our observations exclude.

One possible regional feature which may have aided the beginning of subduction is the presence of serpentine and sedimentary ophicalcite bodies ophiolite fragments of the Monte Reventino Unit (Alvarez, 2005). These are common features where oceanic ridges were spreading slowly, and could not produce the partial melting need to generate a thick Penrose-style ophiolite sequence; they indicate that the uppermost mantle was serpentinized, and therefore weakened (Reston, 2009). This is a common feature, not only in Calabria, but in many of the Tethyan ophiolite belts (Whitmarsh et al., 1993; Lagabrielle and Lemoine, 1997; Manatschal and Bernoulli, 1999). This may indicate that Calabria was the locus of a magma-poor margin where water activity may have weakened the lithosphere, a possibility suggested by Stern (2004), and in a modified form by Regenauer-Lieb et al. (2001) and Hilairet et al. (2007).

ACKNOWLEDGEMENTS

I would like to thank Su-chin Chang for providing the radiometric dates. Walter Alvarez and John Wakabayashi provided comments on several drafts of this chapter. Francesca Liberi and Eugenio Piluso are thanked for their hospitality during my stay in Calabria.

REFERENCES

Alvarez, W., 1974, Fragmentation of the Alpine orogenic belt by microplate dispersal: Nature, v. 248, p. 309-314.

Alvarez, W., 1991, Tectonic evolution of the Corsica-Apennines-Alps region studied by the method of successive approximations: Tectonics, v. 10, p. 936-947.

Alvarez, W., 2005, Structure of the Monte Reventino greenschist folds: a contribution to untangling the tectonic-transport history of Calabria, a key element in Italian tectonics: Journal of Structural Geology, v. 27, p. 1355-1378.

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., and Zuppetta, A.,1976, L'arco Calabro-Peloritano nella'orogene Appenninico-Maghrebide: Memorie della Società Geologica Italiana, v. 17, p. 1-60.

Acquafredda, P., Lorenzoni, S. Lorenzoni, E.Z., 1994, The Bocchigliero Paleozoic sequence in the context of the Calabrian-Peloritan Hercynian Range (Italy): Geological Journal, v. 29, p. 45-58.

Bonardi, G., Cavazza, W., Perrone, V., and Rossi, S., 2001, Calabria-Peloritani Terrane and northern Ionian Sea, in, Anatomy of an Orogen, Vai, G.B., and Martini, J.P., eds., p. 287-306: Kluwer Academic, Norwell MA.

Bonardi, G., Amore, F.O., Ciamp, G., DeCapoa, P., Miconnet, P., and Perrone, V., 1988, Il complesso liguride auct.: Stato delle conoscenze e promblemi aperti sulla sua evoluzione pre-apenninica ed i suoi rapporti con l'arco calabro: Memorie della Società Geologica Italiana, v. 41, p. 17-35.

Bonardi, G., Compagnoni, R., Del Moro, A., Macaione, E., Messina, A., and Perrone, V., 2008, Rb-Sr age constraints on the Alpine metamorphic overprint in the Aspromonte Nappe (Calabria-Peloritani Composite Terrane, southern Italy): Bollettino della Società Geologica Italiana, v. 127, p. 173-190.

Brown, E.H., Wilson, D.L., Armstrong, R.E., and Harakal, R.L., 1982, Petrological, structural, and age relations of serpentine, amphibolite, and blueschist in the Shuksan Suite of the Iron Mountain-Gee Point area, North Cascades, Washington: Geological Society of America Bulletin, v. 93, p. 1087-1098.

Colonna, V., and Piccarreta, G., 1976, Contributo alla conoscenza dell'unita di Castagna in Sila Piccola: Rapporti tra micascisti, paragneiss e gneiss occhiadini: Bollettino della Società Geologica Italiana, v. 95, p. 1-10.

De Roever, E.W.F., 1972, Lawsonite-albite facies metamorphism near Fuscaldo, Calabria (Southern Italy), its geological significance and petrological aspects: Thesis, GUA Amsterdam, 171 p.

Dewey, J.F., Helman, M.L., Knott, S.D., Turco, E., and Hutton, D.H.W., 1989, Kinematics of the western Mediterranean, in, Coward, M.P., Dietrich, D., and Park, R.G., eds., Alpine Tectonics: Geological Society Special Publication, no. 45, p. 265-283.

Dilek, Y., and Whitney, D.L., 1997, Counterclockwise P—T—t trajectory from the metamorphic sole of a Neo-Tethyan ophiolite (Turkey): Tectonophysics, v. 280, p. 295-310.

Erickson, S.G., 1993, Sedimentary loading, lithospheric flexture, and subduction initiation at passive margins: Geology, v. 21, p. 125-128.

Ernst, W.G., and Liu, J., 1998, Experimental phase-equilibrium study o f Al- and Ti-contents of calcic amphbiole in MORB—A semiquantitative thermobarometer: American Mineralogist, v. 83, p. 952-969.

Graessner, T., and 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, v. 42, p. 931-961.

Guilmette, C., Hébert, R., Wang, C., and Valleneuve, M., 2009, Geochemistry and geochronology of the metamorphic sole underlying the Xigaze Ophiolite, Yarlung Zangbo Suture Zone, South Tibet: Lithos, v. 112, p. 149-162.

Gurnis, M., Hall, C., and Lavier, L., 2004, Evolving force balance during incipient subduction: Geochemistry, Geophysics, Geosystems, v. 5, Q07001, doi:10.1029/2003GC000681.

Hacker, B.R., and Gnos, E., The conundrum of Samail: Explaining the metamorphic history: Tectonophysics, v. 279, p. 215-226.

Heymes, T., Monié, P., Arnaud, N., Pêcher, A., Bouillin, J.-P., and Compagnoni, R., 2010, Alpine tectonics in the Calabrian-Peloritan belt (southern Italy): New 40Ar/39Ar data in the Aspromonte Massif area: Lithos, v. 114, p. 451-472.

Hilairet, N., Reynard, B., Wang, Y., Daniel, I., Merkel, S., Nishiyama, N., and Petitgirard, S., 2007, High-pressure creep of serpentine, interseismic deformation, and initiation of subduction: Science, v. 318, p. 1910-1913.

Iannace, A., Bonardi, G., D’Errico, M., Mazzoli, S., Perrone, V., and Vitale, S., 2005, Structural setting and tectonic evolution of the Apennine Units of northern Calabria: Comptes Rendus Geoscience, v. 337, p. 1541-1550.

Kemp, D.V., and Stevenson, D.J., 1996, A tensile, flexural model for the initiation of subduction: Geophysical Journal International, v. 125, p. 73-94.

Knott, S.D., 1994, Structure, kinematics and metamorphism in the Liguride Complex, southern Apennines, Italy: Journal of Structural Geology, v. 16, p. 1107-1120.

Lagabrielle, Y., and Lemoine, M., 1997, Alpine, Corsican and Apennine ophiolites: the slow-spreading ridge model: Comptes Rendus de l’Academie des Sciences, v. 325, p. 909-920.

Langone, A., Gueguen, E., Prosser, G., Caggianelli, A., and Rottura, A., 2006, The Curinga-Girifalco fault zone (northern Serre, Calabria) and its significance within the Alpine tectonic evolution of the western Mediterranean: Journal of Geodynamics, v. 42, p. 140-158.

Lebrun, J.-F., Lemarche, G., and Collot, J.-Y., 2003, Subduction initiation at a strike-slip plate boundary: The Cenozoic Pacific-Australian plate boundary, south of New Zealand: Journal of Geophysical Research, v. 108, doi:10.1029/2002JB002041.

Lustrino, M., Morra, V., Fedele, L., and Franciosi, L., 2009, Beginning of the Apennine subduction system in central western Mediterranean: Constraints from Cenozoic “orogenic” magmatic activity of Sardinia, Italy: Tectonics, v. 28, TC5016, doi:10.1029/2008TC002419.

Manatschal, G., and Bernoulli, D., 1999, Architecture and tectonic evolution of nonvolcanic margins: Present-day Galicia and ancient Adria: Tectonics, v. 18, p. 1099-1119.

McDougall, I., and Harrison, T.M., 1999, Geochronology and themochronology by the ^{40}Ar/^{39}Ar method: Oxford, Oxford University Press. 269 p.

Micheletti, F., Barbey, P, Fornelli, A., Piccarreta, G., and Deloule, E., 2007, Latest Precambrian to Early Cambrian U-Pb zircon ages of augen gneisses from Calabria (Italy), with inference to the Alboran micropalte in the evolution of the peri-Gondwana terranes: International Journal of Earth Sciences, v. 96, p. 843-860.

Monaco, C., Tortorici, L., Morten, L, Criteeli, S., and Tansi, C., 1995, Geologia del versante nord-orientale del massiccio del Pollino (confine Calabro-Lucano): Nota illustrative sintetica della carta geologica alla scalla 1:50.000: Bollettino della Società Geologica Italiana, v. 114, p. 277-291.

Mueller, S., and Phillips, R.J., 1991, On the initiation of subduction: Journal of Geophysical Research, v. 96, p. 651-665.

Nikolaeva, K., Gerya, T.V., and Marques, F.O., 2010, Subduction initiation at passive margins: Numerical modeling: Journal of Geophysical Research, v. 115, B03406, doi:10.1029/2009JB006549.

Piccardo, G.B., 2009, Geodynamic evolution of the Jurassic Ligurian Tethys viewed from the Mantle perspective: Bollettino della Società Geologica Italiana, v. 128, p. 565-574.

Piccarreta, G., 1981, Deep-rooted overthrusting and blueschist metamorphism in compressive continental margins. An example from Calabria (Southern Italy): Geological Magazine, v. 118, p. 539-544.

Platt, J.P., 1975, Metamorphic and deformational processes in the Franciscan Complex, California: Some insights from the Catalina Schist terrane: Geological Society of America Bulletin, v. 86, p. 1337-1347.

Poli, S., 1993, The amphibolite-eclogite transformation: An experimental study on basalt: American Journal of Science, v. 293, p. 1061-1107.

Regenauer-Lieb, K., Yuen, D.A., and Branlund, J., 2001, The initiation of subduction: Criticality by addition of water?: Science, v. 294, p. 578-580.

Reston, T.J., 2009, The structure, evolution and symmetry of the magma-poor rifted margins of the North and Central Atlantic: A synthesis: Tectonophysics, v. 468, p. 6-27.

Rossetti, F., Faccenna, C., Goffé, B., Monié, P, Argentieri, A., Funiciello, R., and 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, v. 20, p. 112-133.

Rossetti, F., Goffé, B, Monié, P, Faccenna, C., and Vignaroli, G., 2004, Alpine orogenic P-T-t-deformation history of the Catena Costiera area and surroudnign regions (Calabrian Arc, southern Italy): The nappe edifice of north Calabria revised with insights on the Tyrrhenian-Apennine system formation: Tectonics, v. 23, TC6011, doi:10.1029/2003TC001560.

Smith, C.A., Sisson, V.B., Avé Lallemant, H.G., and Copeland, P., 1999, Two contrasting pressure—temperature—time paths in the Villa de Cura blueschist belt, Venezuela: possible evidence for Late Cretaceous initiation of subduction in the Caribbean: Geological Society of America Bulletin, v. 111, p. 831-848.

Spadea, P., 1982, Continental crust rocks associated with ophiolites in Lucanian Apennine (Southern Italy): Ofioliti, v. 2/3, p. 501-522.

Spadea, P., 1994, Calabria-Lucania ophiolites: Bollettino di Geofisica Teorica ed Applicada, v. 36, p. 271-281.

Stampfli, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons: Earth and Planetary Science Letters, v. 196, p. 17-33.

Stern, R.J., 2004, Subduction initiation: spontaneous and induced: Earth and Planetary Science Letters, v. 226, p. 275-292.

Stern, R.J., and Bloomer, S.H., 1992, Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of American Bulletin, v. 104, p. 1621-1636.

Sutherland, R., Barnes, P., and Uruski, C., 2006, Miocene-Recent deformation, surface elevation, and volcanic intrusion of the overriding plate during subduction initiation, offshore southern Fiorland, Puysegur margin, southwest New Zealand: New Zealand Journal of Geology and Geophysics, v. 49, p. 131-149.

Tortorici, L., Catalano, S., and Monaco, C., 2009, Ophiolite-bearing mélanges in southern Italy: Geological Journal, v. 44, p. 153-166.

Turcotte, D.L., and Schubert, G., 1982, Geodynamics: New York, John Wiley & Sons, 450 p.

Wakabayashi, J., 1990, Counterclockwise P-T-t paths from amphibolites, Franciscan Complex, California: Relics from the earth stages of subduction zone metamorphism: Journal of Geology, v., 98, p. 657-680.

Wakabayashi, J., 2004, Tectonic mechanisms associated with P-T paths of regional metamorphism: alternatives to single-cycle thrusting and heating: Tectonophysics, v. 392, p. 193-218.

Wakabayashi, J., and Dumitru, T.A., 2007, ^{40}Ar/^{39}Ar ages from coherent high-pressure metamorphic rocks of the Franciscan Complex, California: Revisiting the timing of metamorphism of the world's type subduction complex: International Geology Review, v. 49, p. 873-906.

Wakabayashi, J., Ghatak, A., and Basu, A.R., 2010, Tectonic setting of supra subduction zone ophiolite generation and subduction initiation as revealed through geochemistry and regional field relationships: Geological Society of America Bulletin, v. 122, p. 1548-1568.

Whitmarsh, R.B., Manatschal, G., and Minshull, T.A., 2001, Evolution of magma-poor continental margins from rifting to seafloor spreading: Nature, v. 413, p. 150-154.

Williams, H., and Smyth, W.R., 1973, Metamorphic aureoles beneath ophiolite suites and alpine peridotits: Tectonic implications with West Newfoundland examples: American Journal of Science, v. 273, p. 594-621.

FIGURE CAPTIONS

Figure 1. Tectonic map of Northern Calabria modified from Alvarez (2005) and Alvarez and Shimabukuro (2009). Locations discussed in the text are boxed. The Zangarona Schist outcrops were near the towns of San Mango and San Fili in the Sila Piccola. The melange unit is near Timpa Pietrasasso, just west of the town of Terranova di Pollino. The lawsonite-albite facies ophiolite is exposed in the Catena Costiera (DeRoever, 1972).

Figure 2. a) Glaucophane rim on edenitic hornblende from the Cozzo Volante amphibolite of the Zangarona Schist. b) Ti-bearing phases from a garnet amphibolite at the San Fili locality: a rutile core, with an intermediate ilmenite zone and a sphene rim. This represents a HP Hercynian event, isothermal exhumation, and subduction during the Alpine event. c) Ar/Ar plateau age of 319 ± 4 for a glaucophane-rimmed hornblende from an amphibolite block in the Zangarona Schist at Cozzo Volante. d) Ar/Ar plateau age of 193 ± 2 Ma for a hornblende from an amphibolite block in the serpentine-matrix melange unit of Northern Calabria.

Figure 3. Age at time of subduction of the tectonic units of Northern Calabria. The Sila Unit represents the upper plate of an Alpine subduction system. All units of the accretionary complex bear evidence of blueschist-facies metamorphism. Each of the subducted units is at least Jurassic

in age, meaning that they were at least 100 Myr in age. This implies that subduction started in old and cold crust.

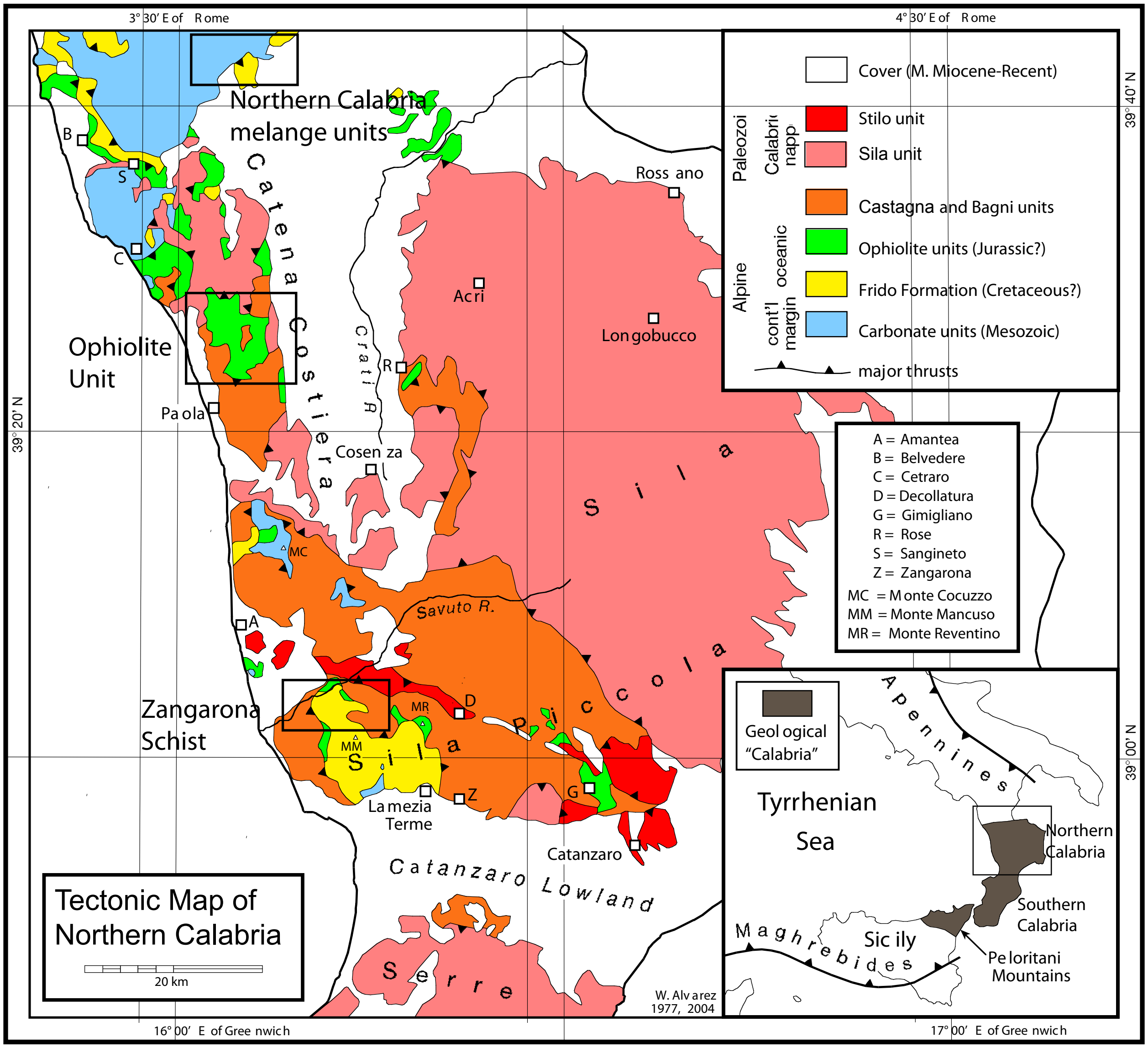


Figure 1. Tectonic map of Northern Calabria modified from Alvarez (2005) and Alvarez and Shimabukuro (2009). Locations discussed in the text are boxed. The Zangarona Schist outcrops were near the towns of San Mango and San Fili in the Sila Piccola. The melange unit is near Timpa Pietrasasso, just west of the town of Terranova di Pollino. The lawsonite-albite facies ophiolite is exposed in the Catena Costiera (DeRoever, 1972).

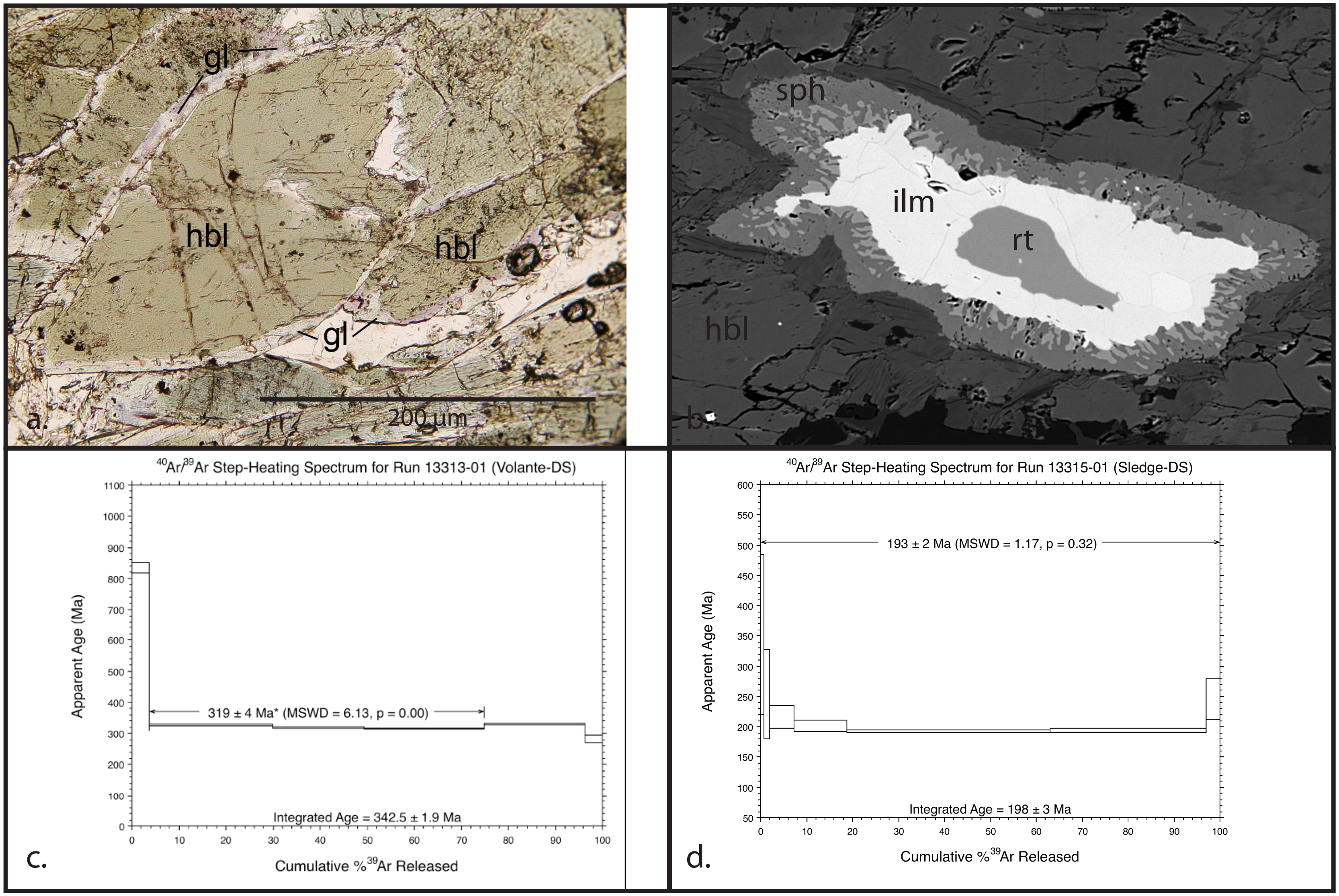


Figure 2. a) Glaucophane rim on edenitic hornblende from the Cozzo Volante amphibolite of the Zangarona Schist. b) Ti-bearing phases from a garnet amphibolite at the San Fili locality: a rutile core, with an intermediate ilmenite zone and a sphene rim. This represents a HP Hercynian event, isothermal exhumation, and subduction during the Alpine event. c) Ar/Ar plateau age of 319 ± 4 for a glaucophane-rimmed hornblende from an amphibolite block in the Zangarona Schist at Cozzo Volante. d) Ar/Ar plateau age of 193 ± 2 Ma for a hornblende from an amphibolite block in the serpentine-matrix melange unit of Northern Calabria.

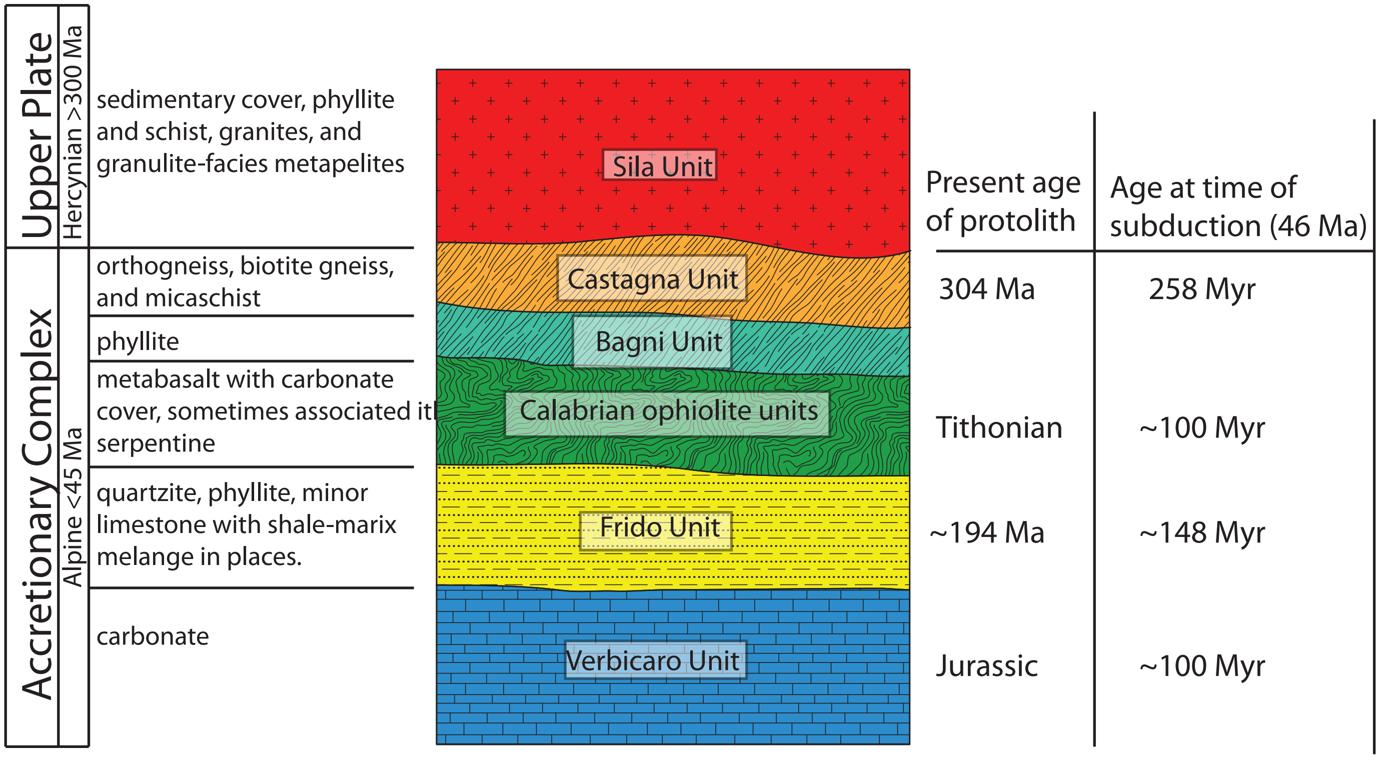


Figure 3. Age at time of subduciton of the tectonic units of Northern Calabria. The Sila Unit represents the upper plate of an Alpine subduction system. All units of the accretionary complex bear evidence of blueschist-facies metamorphism. Each of the subducted units is at least Jurassic in age, meaning that they were at least 100 Myr in age. This implies that subduction started in old and cold crust.

Introduction to Chapter 2

Blueschist-facies* metamorphism, defined by the presence of lawsonite and glaucophane, is indicative of high pressure/low temperature conditions. This facies is produced in subduction zones where descending cold ocean crust creates a refrigeration effect on deep rocks. Blueschist-facies minerals are thermodynamically unstable at the surface of the earth, but they can be preserved if they are exhumed rapidly, in cool conditions, due to kinetic effects.

However, in many cases blueschist-facies minerals are not preserved. When subduction of ocean crust ceases due to a continental collision, temperatures rapidly increase as the cooling effect of the downgoing crust stops. Rocks brought to the surface during continental collision are exposed to warmer conditions, indicated by the growth of greenschist-facies minerals such as actinolite and epidote. These temperatures also destroy some of the more unstable blueschist-indicative minerals, such as lawsonite.

The Alpine Orogeny is a typical example of a collision belt, where continental collision has occurred and exhumed rocks have a greenschist-facies overprint. Because of this, lawsonite is rare, as it is only preserved when rocks are exhumed rapidly in cool conditions.

In this chapter, I describe blue and green rocks from Diamante, Calabria. These metabasalts contain one of the only occurrences of lawsonite in the Alps, which is surprising because they previously have been identified as having the warm, greenschist-facies metamorphism which destroys lawsonite.

I show that these rocks do not have the mineral assemblages indicative of a greenschist overprint. Instead, the green rocks at Diamante have been metamorphosed in the epidote-blueschist facies, a subclass of the blueschist facies. As epidote is a green mineral, these rocks are easy to mistake as greenschist-facies rocks in outcrop.

I suggest that the rocks at Diamante were exhumed early in the orogenic process, when thermal conditions were cool. This allowed the preservation of the delicate lawsonite-bearing mineral assemblages.

---

* A metamorphic facies is a characteristic assemblage of minerals which are stable at a particular pressure-temperature conditions. Blueschist-facies minerals (glaucophane and lawsonite) are stable at high-P/T conditions. Greenschist-facies minerals (actinolite and epidote) are stable at moderate-P/T conditions.

CHAPTER 2

Implications of a counterclockwise pressure-temperature-time path of blueschist-facies rocks in the Alpine Orogen of Calabria

ABSTRACT

Calabria, in southern Italy, has generally been considered to be an extension of the Alpine orogenic belt, and therefore classified as part of a collisional orogen involving Adria and Europe. In this paper, we present petrological evidence from an outcrop of blue- and green-colored metabasalt at Diamante, Calabria, which shows that blueschist-facies rocks have not been overprinted by a retrograde greenschist-facies event, one which is ubiquitous in the rest of the Alpine orogen. Instead, rocks which are green in color are either epidote-blueschist facies metabasalts or they have undergone a retrograde pumpellyite-actinolite subgreenschist facies overprint during exhumation. This type of exhumation, via a counterclockwise P-T-t path, is more common in Franciscan-style subduction orogens. The existence of greenschist-facies rocks elsewhere in the same orogen means that exhumation within the Calabrian orogeny occurred via two distinct mechanisms: an early Franciscan-style cool exhumation, and a later Alpine-style warm exhumation.

INTRODUCTION

Calabria, the toe of Italy, is unique in the Alpine orogenic belt because subduction of the Neotethys, in the form of Ionian Sea crust, continues to today (Dewey et al., 1989; Stampfli et al., 1998). The historical record of this Cenozoic subduction is preserved in the accretionary wedge of Northern Calabria, where blueschist-facies fragments of oceanic crust are widely exposed (Amodio-Morelli et al., 1976). These dismembered ophiolites are significant because lawsonite—rare in the wider Alpine belt—is preserved at some places in Calabria (Spadea, 1982, 1994), although not at all, hinting at an unusual exhumation history.

The usual understanding of Calabrian blueschists is that they have undergone a regional greenschist retrograde overprint; when plotted on a P-T diagram with the P axis pointing upward, these burial histories trace out clockwise pressure-temperature-time (P-T-t) paths, a feature that is common in collisional belts (England and Thompson, 1984; Spear and Peacock, 1989). In this paper we report an occurrence from the Diamante-Terranova Unit in Northern Calabria of a lawsonite blueschist which has not undergone a greenschist overprint. Instead, green metabasaltic layers, previously reported to be of greenschist-facies, have instead been metamorphosed in the epidote-blueschist and pumpellyite-actinolite facies. Rocks in this outcrop stayed within the lawsonite stability field during exhumation, thus following a counterclockwise P-T-t path, a feature more common in Franciscan-style orogens (Ernst, 1988; Agard et al., 2009), where there has been no collision. Study of this outcrop allows us to observe metamorphic and structural features which are usually destroyed by mineralogical changes resulting from the high temperatures involved in exhumation through the greenschist facies.

This raises the fundamental question of how the blueschist was preserved. We will consider two possibilities: (1) that Calabria occupies a unique place in the Alpine Orogen where subduction is continuing and (2) that the rocks came up early, before slab-rollback of the Calabrian system began. In each of these possibilities, Diamante rocks would be exhumed within a tectonic setting with a low geothermal gradient.

REGIONAL SETTING

The rocks of Calabria make up a tight, oroclinal bend in the Apenninic-Maghribide mountain belt, which is a result of complicated microcontinent tectonics taking place between Africa and Europe (Dewey et al., 1989). Instead of the carbonate- and flysch-dominated units present in most of peninsular Italy and Sicily, crystalline basement rocks, mostly Hercynian, are widely exposed in Calabria (Amodio-Morelli et al., 1976; Bonardi et al., 2001).

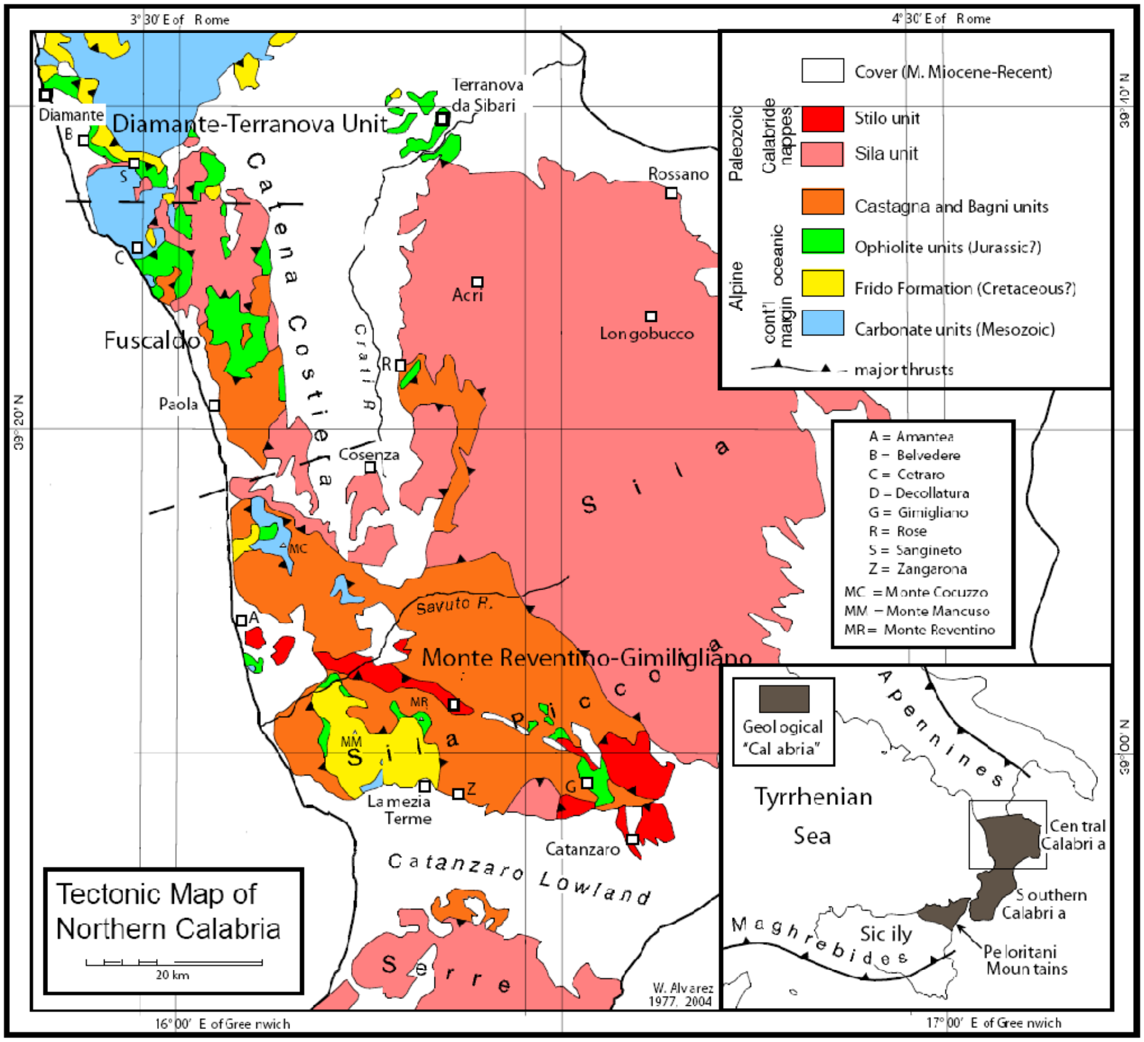


Figure 1. Tectonic map of Northern Calabria. The ophiolitic units can be broadly divided into three regions: the Monte Reventino-Gimigliano Unit in the southern part of the map area, the Fuscaldo and Malvito Units of the Catena Costiera of the central map area, and the Diamante-Terranova Unit in the northern part of the map. The present study focuses on the outcrop at Diamante.

The present study focuses on the northern part of Calabria, where Hercynian rocks form the upper plate of a Cenozoic subduction complex, separated from an underlying blueschist-facies Alpine-aged accretionary complex by a regional-scale fault (Piccarreta, 1981; Amodio-Morelli et al., 1976; Bonardi et al., 2001) (Figure 1). The accreted nappes are of diverse origins: the Castagna and Bagni Units near the top are fragments of Hercynian continental crust, reactivated during the Alpine Orogeny (Colonna and Piccarreta, 1975a, 1976), while a metabasaltic dismembered-ophiolite unit, the quartzite-and-phyllite Frido Unit, and the carbonate Verbicaro Unit, in descending order, are derived from the Tethyan marine realm (Amodio-Morelli et al., 1976; Piccarreta, 1981; Bonardi et al., 1988, 2001). All of the accreted nappe units were affected by blueschist-facies metamorphism during an Alpine-age event, as indicated by the growth of glaucophane in crystalline rocks (Piccarreta, 1981), and Mg-carpholite in pelitic and carbonate rocks (Rossetti et al., 2001, 2004; Iannace et al., 2007).

This chapter will focus on the Calabrian ophiolite unit, which represents off-scraped fragments of Tethyan ocean crust and sedimentary cover incorporated into the Calabrian accretionary wedge (Lanzafame et al., 1979; Liberi et al., 2006; Tortorici et al., 2009). The use of the term ophiolite is somewhat misleading, since they do not represent complete Penrose-style ocean crust sections. Instead, they consist of MORB-type basalt (Liberi et al., 2006), sometimes associated with serpentinite, or sedimentary cover. These are distinct from the coherent upper-plate ophiolites that are common in the circum-Mediterranean orogenies, such as the Troodos Ophiolite in Cyprus (Dilek, 2003; Beccaluva et al., 2004). We retain the use of the term ophiolite due to its wide usage in the published literature.

The Calabrian ophiolites can be divided into three geographic areas, based on metamorphic grade (refer to Figure 1): (1) the epidote-blueschist-facies rocks of the Monte Reventino-Gimigliano Unit in the southern region (Rossetti et al., 2001, 2002; Alvarez, 2005), (2) the lawsonite-albite-facies Fuscaldo metabasalts in the central region (De Roever, 1972; Liberi et al., 2006), and (3) the lawsonite-blueschist-facies Diamante-Terranova Unit in the northern region (Spadea et al., 1976; Cello et al., 1996) (Figure 1). The differences in metamorphic facies are not well understood, as all are in the same structural position—directly superposed on the phyllite and quartzite of the Frido Unit—and plausibly represent a continuous structural horizon of oceanic crust. It has been suggested that the different metamorphic facies may indicate different peak metamorphic pressures, due to different depths of subduction (De Roever, 1972; Spadea, 1982; Rossetti et al., 2001, 2004), or they may be due to differences in oxidation state between the units (Liberi et al., 2006).

The Diamante-Terranova Unit, the subject of the present study, is exposed in the northern part of Calabria in several discontinuous outcrops, with the majority of exposure near the towns of Diamante and Terranova da Sibari (De Roever, 1972; Spadea, 1994; Cello et al., 1996; Rossetti et al., 2004). Because of a combination of well-developed blueschist-facies metamorphism and good exposure in outcrop, this unit has played a key role in interpreting the subduction history of the orogen (Cello et al., 1996; Rossetti et al., 2004).

The tectonic history of the Alpine-aged orogen in Calabria is controversial, particularly regarding the number and dip-direction of subduction zones (Alvarez, 1991; Alvarez and Shimabukuro, 2009). One view argues for an early, east-dipping subduction zone, followed by the present-day west-dipping Ionian subduction zone (Alvarez et al., 1974; Amodio-Morelli et al., 1976; Cello et al., 1996; Bonardi et al., 2001). Another view considers the orogen to have been formed over a single, long-lasting, west-dipping subduction zone (Ogniben, 1973; Principi and Treves, 1984; Knott, 1987; Dewey et al., 1989; Rossetti et al., 2001, 2004; Langone et al., 2006). This controversy has not yet been fully resolved (Alvarez and Shimabukuro, 2009), although it is addressed in Chapter 3 of this thesis.

OUTCROP DESCRIPTION

The best outcrops of the Diamante-Terranova Unit are preserved on the Tyrrhenian coast about 2 km south of the city of Diamante, Calabria, along the waterfront at the La Guardiola locality (39°40'15.58"N, 15°49'37.87"E, WGS84) (Figure 1) (Cello et al., 1991, 1996; Rossetti et al., 2004; Liberi et al., 2006). Below a beachfront restaurant, a 200-m stretch of banded metabasalt and its sedimentary cover are spectacularly exposed along a stubby peninsula.

Figure 2. Green and blue layers in the metabasalt at Diamante, Calabria. The blue layers are lawsonite blueschist, while some of the green layers are pumpellyite-actinolite facies and others are epidote blueschist.

These banded metabasalts are foliated and interlayered blue- and green-colored schists (Figure 2). The green layers have been interpreted by previous authors as a greenschist-facies overprint (Cello et al., 1996; Rossetti et al., 2004; Liberi et al., 2006). However, the data obtained in the present study indicate that there is no retrograde greenschist overprint. Instead the banding is caused by alternation between green-colored epidote blueschist and blue-colored lawsonite blueschist, both formed during the same metamorphic episode. A late retrograde overprint does exist, but it is represented by the pumpellyite-actinolite facies instead of greenschist facies.

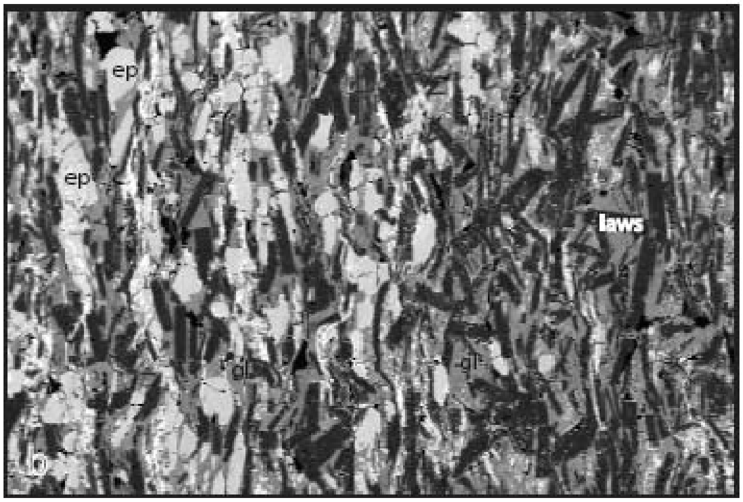


Figure 3. Electron backscatter image of the transition between an epidote-glaucophane assemblage on left and a lawsonite-glaucophne assemblage on right. Lawsonite is dark grey, glaucophane is light gray, while epidote is white. The image is 1.0 mm across.

The blue and green bands at Diamante are interlayered at different scales: mm-scale lamellae have strong mineralogical and color differences, with alternating green epidote-glaucophane-rich and blue lawsonite-glaucophane-rich layers (Figure 3). At cm-scales, the banding is often visible as green layers, sometimes boudinaged, surrounded by ductily-deformed blue layers (Chapter 3 of this thesis). Irregularly-shaped zones around late, high-angle faults are also green—in thin section, this seems to be due to a subgreenschist overprint, in the albite-lawsonite (de Roever, 1972), or pumpellyite-actinolite, facies (Frey et al., 1991). Although both epidote-glaucophane and pumpellyite-actinolite layers are green in color, the former are a brighter, pistachio green, while the latter are a more subdued, sea-green color.

METAMORPHIC EVENTS

The metamorphic history of these rocks reflects the tectonic history of the orogen; by reconstructing the metamorphic path, we can determine the thermal history to which the rocks have been exposed (Hacker et al., 2003).

The blue and green layers in the color-banded rocks at Diamante can be considered two separate chemical systems. Based on modal mineral composition, it is evident that the green layers are more oxidized than the blue layers, because they contain Fe^{3+}-bearing riebeckite instead of Fe^{2+}-bearing ferroglaucophane.

This is confirmed with bulk rock analyses of each of the layers, as the epidote layers are highly oxidized (Table 1) (See Supplementary Data). The blue layers—similar in composition to other metabasalts found in the Diamante-Terranova Unit (Spadea et al., 1976)—are slightly more reduced. Because of the fine interlayering between the green and blue metabasalt, it is likely that compositional layering inherited from the seafloor-metamorphosed basaltic protolith dominates the oxidation state of the system (Spooner and Fyfe, 1973), as opposed to variably oxidizing fluids (Matthews and Schliestedt, 1984; Getty and Selverstone, 1994).

The oxidation state of a rock is usually thought of in terms of oxygen fugacity or oxygen activity; however, in a closed system, oxygen activity is best represented by a fixed redox budget (Powell et al., 2005; Diener et al., 2010). This can be seen in calculated phase diagrams, which show the sensitive dependence of metamorphic mineral assemblage on the oxidation state of a metabasalt (Evans, 1990). The effect of oxidation state, as tracked by the Fe^{3+} /Fe^{2+} ratio in rocks, has also been explored using psuedosections produced in THERMOCALC by Diener et al. (2007, 2010).

In the Diamante rocks, the difference in bulk chemistry between layers resulted in a characteristic epidote-blueschist assemblage in the green layers and a lawsonite-blueschist assemblage in the blue layers. It appears that higher Fe^{3+}/Fe^{2+} has expanded the stability field of epidote, at the expense of lawsonite. A similar case of mm-scale interlayering due to variations in oxidation state, but instead involving greenschist- and blueschist-facies rocks, has been described from the Shuksan Schist of Washington (Dungan et al., 1983; Owen, 1989).

The metamorphic path can be represented by four metamorphic phases, M_1 through M_4, shown in Figures 5a and 5b; separate descriptions for the green and blue layers follow. Mineral identifications and chemical analyses were made with a combination of thin section petrography and electron microprobe analyses. Fe^{3+} in amphiboles was determined based on the method of Leake et al. (1997), where the maximum and minimum calculated Fe^{3+} was averaged.

GREEN LAYERS

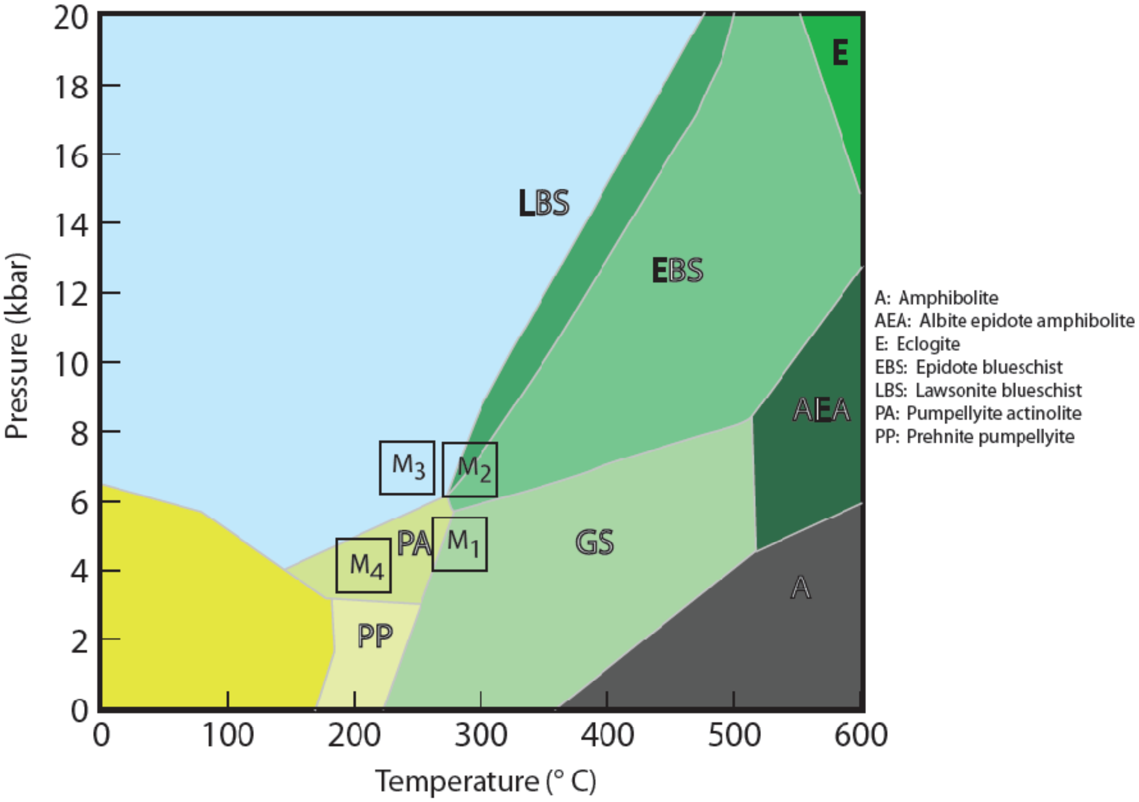


Figure 4. Pressure-temperature conditions of the green layers. The facies boundaries are from Figure 6f of Evans (1990) and are appropriate for oxidized assemblages containing Na-amphiboles of crossite composition.

In the green metabasalt layers, the full mineral assemblage consists of epidote + albite + Na-amphibole + quartz + calcite + titanite ± lawsonite ± pumpellyite ± actinolite ± aragonite. Because the green layers are more oxidized we plot the P-T path of the green layers on the facies diagrams from Figure 3 of Evans (1990) (Figure 4).

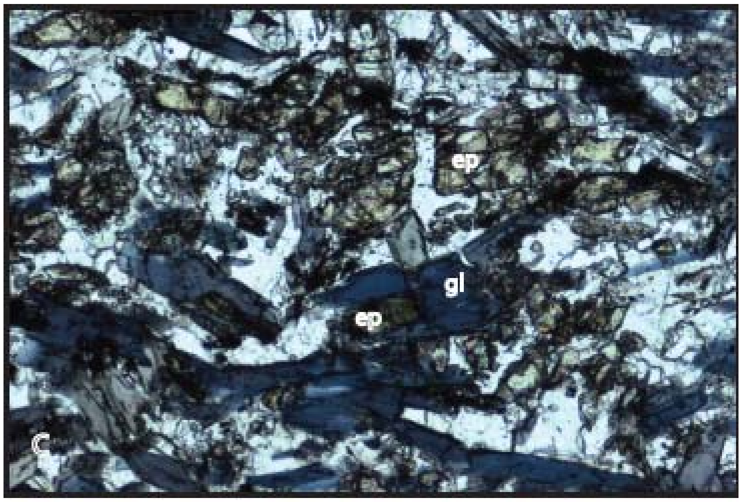


Figure 5. Plane-polar photomicrograph of early epidote at the core of Na-amphiboles. Late lawsonite is also present.

M_{green1} (prograde metamorphic event): Zoned Na-amphiboles have riebeckite-to-crossite cores, sometimes overgrowing an early epidote, indicative of growth in the epidote-blueschist facies (Figure 5). Although actinolite is not present, Al_2O_3 in Na-amphiboles of 4-6 % indicate minimum equilibration pressures of 5 kbar (Maruyama et al., 1986).

M_{green2} (peak metamorphic event): This event is defined by foliated Na-amphibole and epidote (Figure 3). Na-amphiboles are glaucophanic during this event, sometimes appearing as a mantle around M_{green1} cores, other times forming the core of the later, M_{green3}, metamorphic phase. In some samples, triple-zoned amphiboles, with crossite cores (M_{green1}), a glaucophane mantle (M_{green2}), and crossite rims (M_{green3}), preserve a more complete metamorphic history, indicating increasing, then decreasing, pressures (Figure 6, Figure 7) (Trzcienski et al., 1984; Murayama et al., 1986; Banno, 1998; Schulz et al., 2001). Thus, these zoned amphiboles may record the prograde burial path, and the beginning of a retrograde exhumation path (Figure 7). In addition, Al_2O_3 values in the Na-amphiboles indicating minimum pressures of 6-7 kbar for the glaucophane (Maruyama et al., 1986). Lawsonite is sometimes present; coexisting with epidote, this places the rocks in the narrow P-T space where both minerals are stable (Evans, 1990).

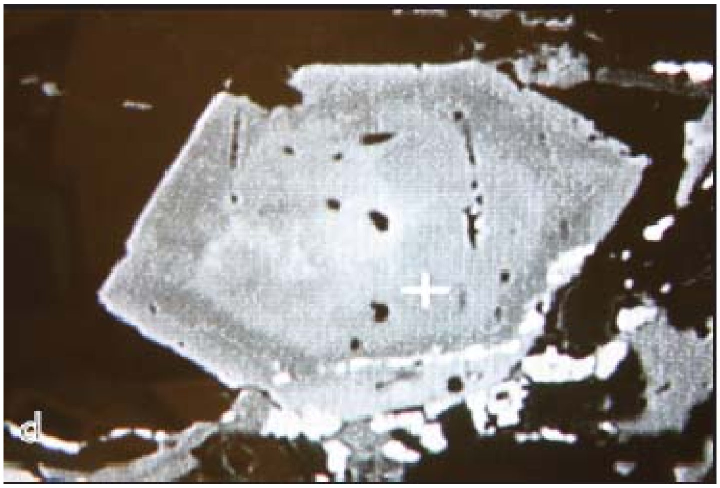


Figure 6. Backscatter image of a Na-amphibole from the lawsonite-blueschist layer showing triple zoning of crossite cores, a glaucophane mantle, and crossite rims. Image is 200 µm across.

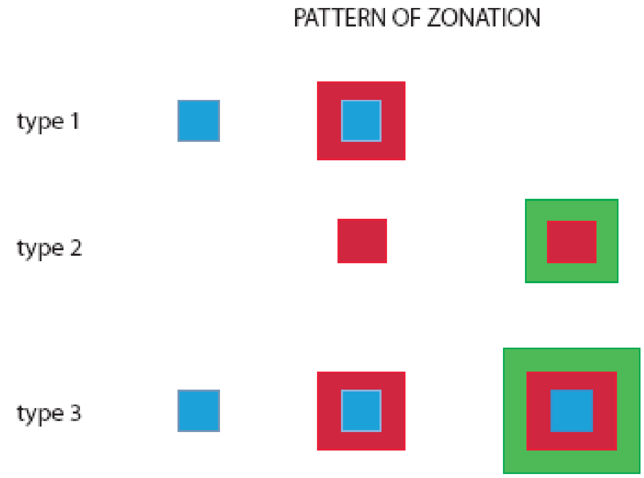
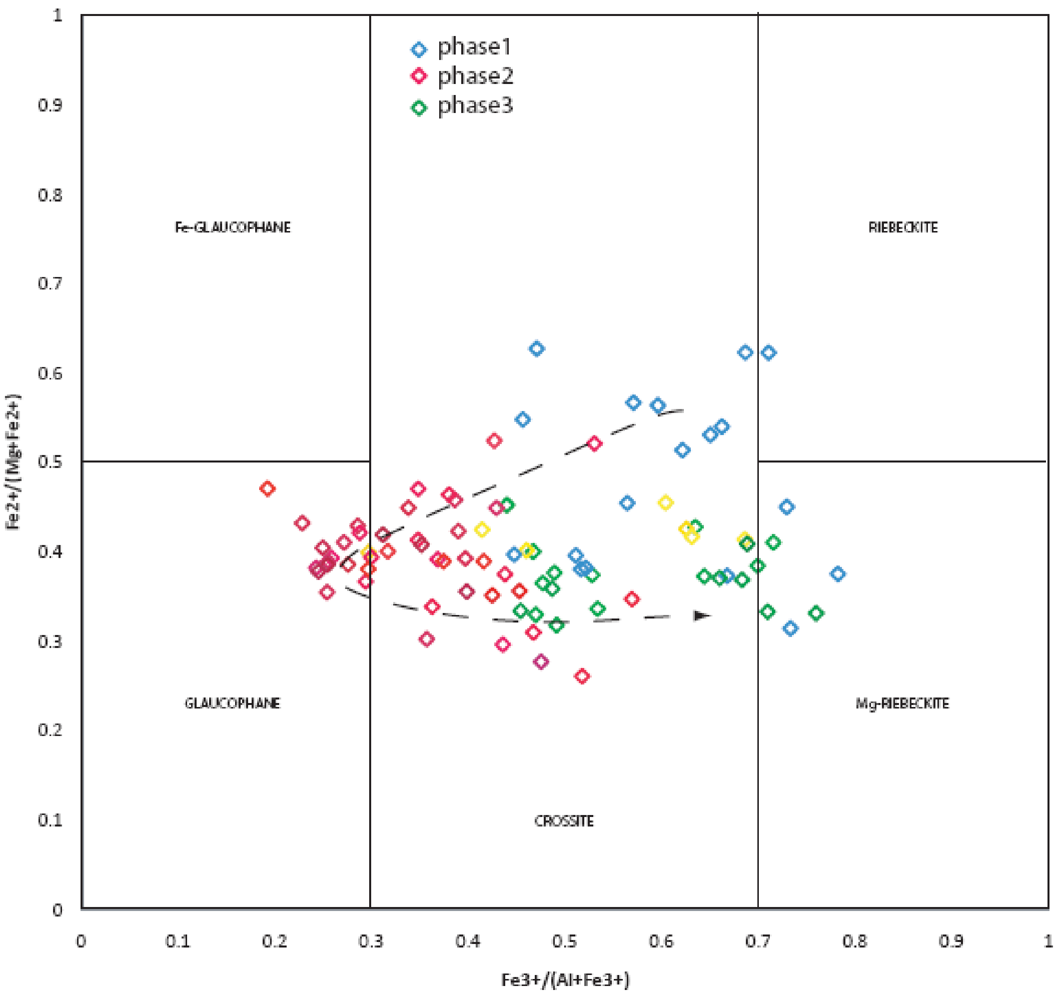


Figure 7. Chemical zonation of Na-amphiboles at Diamante. Three different metamorphic events are observed. The full history, consisting of riebeckite-crossite cores, with an intermediate glaucophane-crossite mantle, surrounded by crossite-Mg-riebeckite rims, is seen in some crystals. This is qualitatively indicative of increasing pressure followed by decreasing pressure.



M_{green3} (early retrograde event): This event is distinguished by lawsonite porphyroblasts which overgrow the previous foliation (Figure 5). The lawsonite is usually euhedral, unless sheared in a later event; in those cases rotated porphyroblasts develop. Poikiloblastic inclusions of Na-amphibole, generally of crossitic composition, are present within the lawsonite. Na-amphibole, ranging from crossitic to Mg-riebeckite in composition, also develops as a rim on earlier amphiboles (Figure 6, Figure 7). We place this event on the low temperature side of the lawsonite-in reaction (Evans, 1990; Ballevre et al., 2003; Zack et al., 2004).

M_{green4} (late retrograde event): A late, fine-grained mat of opaque minerals is associated with a pervasive crenulation. Microprobe analysis has identified pumpellyite, actinolite, lawsonite, and albite, placing this in the pumpellyite-actinolite facies (Powell et al., 1993; Banno, 1998).

BLUE LAYERS

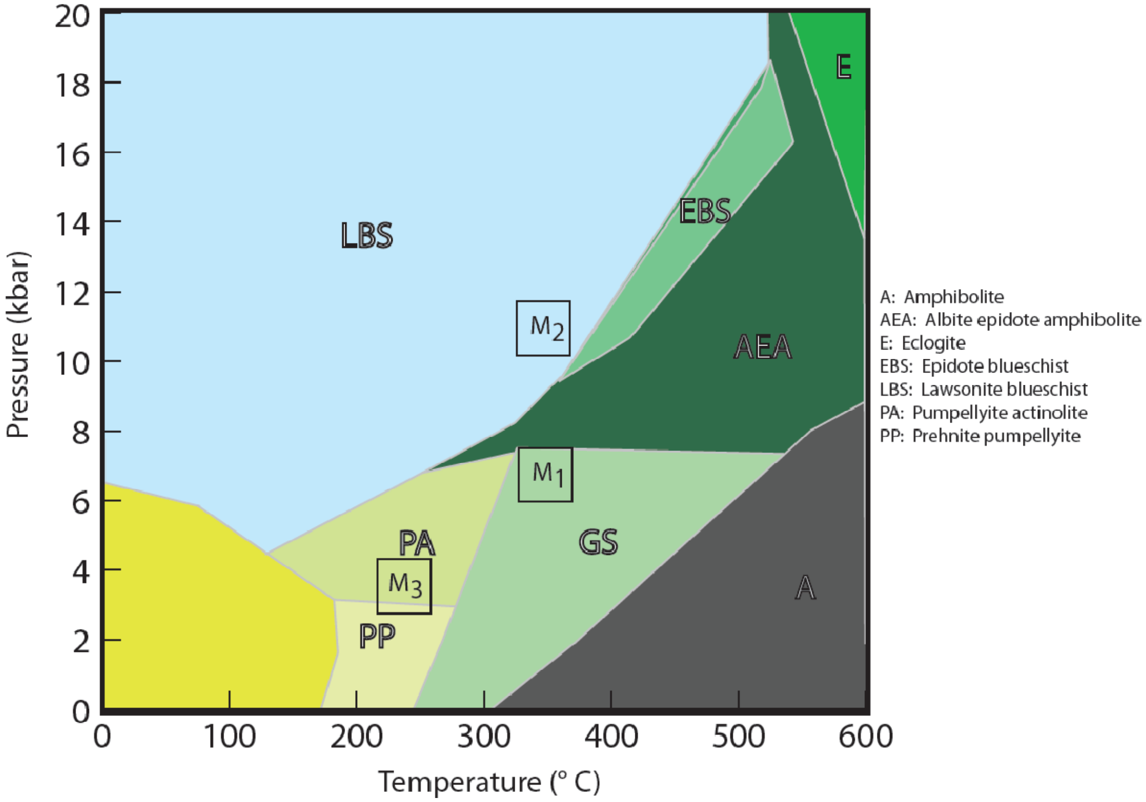


Figure 8. Pressure temperature path of blue layers. The facies boundaries for reduced systems are from Figure 6a of Evans (1990), appropriate for Na-amphiboles of glaucophanic composition.

Blue metabasalt layers are composed of Na-amphibole + lawsonite + omphacite + phengite + albite + quartz + calcite + titanite ± aragonite, with the Na-amphibole + lawsonite being the main assemblage. Since the blue layers are more reduced than the green layers (Supplementary Data), and the Na-amphibole in the peak assemblage is glaucophanic, it is appropriate to use Figure 1 of Evans (1990) to construct the phase diagram of Figure 8 of the present paper.

M_{blue1} (prograde metamorphic event): Cores of Na-amphiboles have riebeckite-to-crossite cores, sometimes in equilibrium with epidote, indicating growth in the epidote-blueschist facies. As in the green layers, Al_2O_3 values indicate pressures of at least 5 kbar, based on the Maruyama et al. (1986) geobarometer (Figure 7).

M_{blue2} (peak metamorphic event): The main foliation is defined by Na-amphibole + lawsonite ± phengite, indicating growth in the lawsonite-blueschist facies. The lack, or scarcity, of epidote is the defining characteristic of the blue layers during this event. Amphiboles are zoned, with this phase represented by crossite-glaucophane-rich compositions with high Al_2O_3 contents of up to 11% (Figure 7).

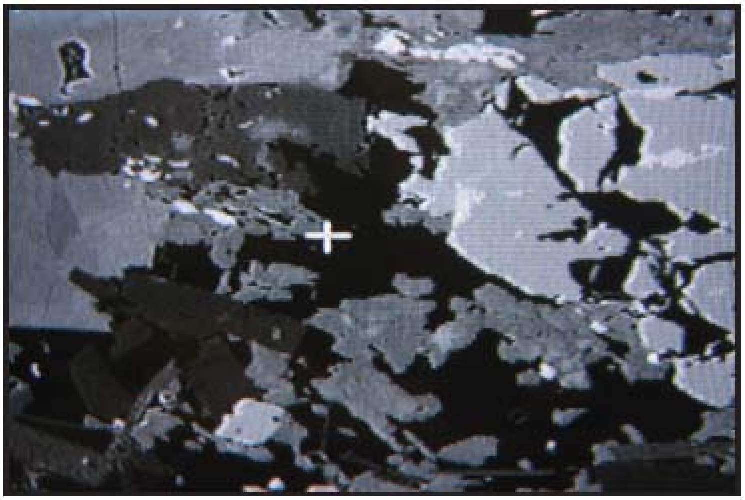


Figure 9. Electron backscatter image of omphacite in a lawsonite-glaucophane assemblage. Lawsonite is dark gray, glaucophane is light gray, and epidote is white. The image is 300 μm across.

Minimum pressures of 9-11 kbar (Liberi et al., 2006) can be estimated based on the jadeite content of Na-pyroxene of Jd=50% (Figure 9) (Holland, 1980). Although the equilibrium assemblage of Massonne and Schreyer (1987) is not present, Si^{4+} values of 3.5 atoms per formula unit were used by Liberi et al. (2006) to establish a minimum pressure of 9-11 kbar at a temperature of 350 ºC (Massonne and Szpurka, 1997). However, since the reaction was calibrated in the KMASH-system, and neither K-feldspar, nor biotite are present, these estimates are likely not valid (Wei and Powell, 2006). Instead, a different reaction of formation is needed.

For the rocks of Diamante, involving NCKFMASH-system metabasalts, THERMOCALC indicates that the phengite-forming reaction most likely involves either:

zoisite + muscovite + chlorite + quartz + water = lawsonite + celadonite

or

zoisite + muscovite + tremolite + quartz + water = lawsonite + celadonite.

Since these mineral assemblages, including lawsonite, are present in the rocks at Diamante, phengite can serve as a useful geobarometer (Wei and Powell, 2006). The extrapolated isobars of Si^{4+}-phengite in the omphacite + jadeite + paragonite + lawsonite field of Figure 8b of Wei and Powell (2006) indicate a pressure of 15 kbar at a temperature of 350 ºC. However, because this is only an estimate, we will use the pressure indicated by omphacite in the present study.

Figure 10. Plane-polar photomicrograph of late lawsonite overgowing a lawsonite-blueschist foliation.

M_{blue3} (early retrograde event): A late, euhedral lawsonite-bearing phase overgrows the main foliation, oftentimes at a high angle (Figure 10). This pokiloblastic lawsonite has inclusions trails of Ti-minerals and Na-amphibole which define the earlier principal foliation and indicate synkinematic crystallization of the lawsonite. Because of the lack of coexisting facies-defining minerals, it is difficult to determine the PT conditions of this metamorphic phase. We place this on the low-temperature side of the lawsonite-in reaction. Calculated pseudosections indicate that the passage between an epidote blueschist and lawsonite blueschist during decompression requires a cooling path (Ballevre et al., 2003; Davis and Whitney, 2006; Warren and Waters, 2006; Diener et al., 2010).

M_{blue4} (late retrograde event): Pumpellyite overgrows Na-amphibole in this subgreenschist-facies retrograde overprint. Actinolite is sometimes present on the rims of Na-amphiboles, always in contact with pumpellyite. Late phengite, with a Si^{4+} content of 3.20 to 3.32, indicates pressures of about 3 kbar (Liberi et al., 2006).

SYNTHETIC METAMORPHIC PATH

Although the blue and green layers record different metamorphic phases, it is obvious that they must have undergone the same P-T-t history since they are part of the same rock. We can attempt to produce a synthetic path, combining evidence from both of the layers (Figure 11, 12). The peak pressure conditions were best recorded by the blue layers, containing HP phengite and omphacite, while the retrograde conditions were best recorded by the green layers.

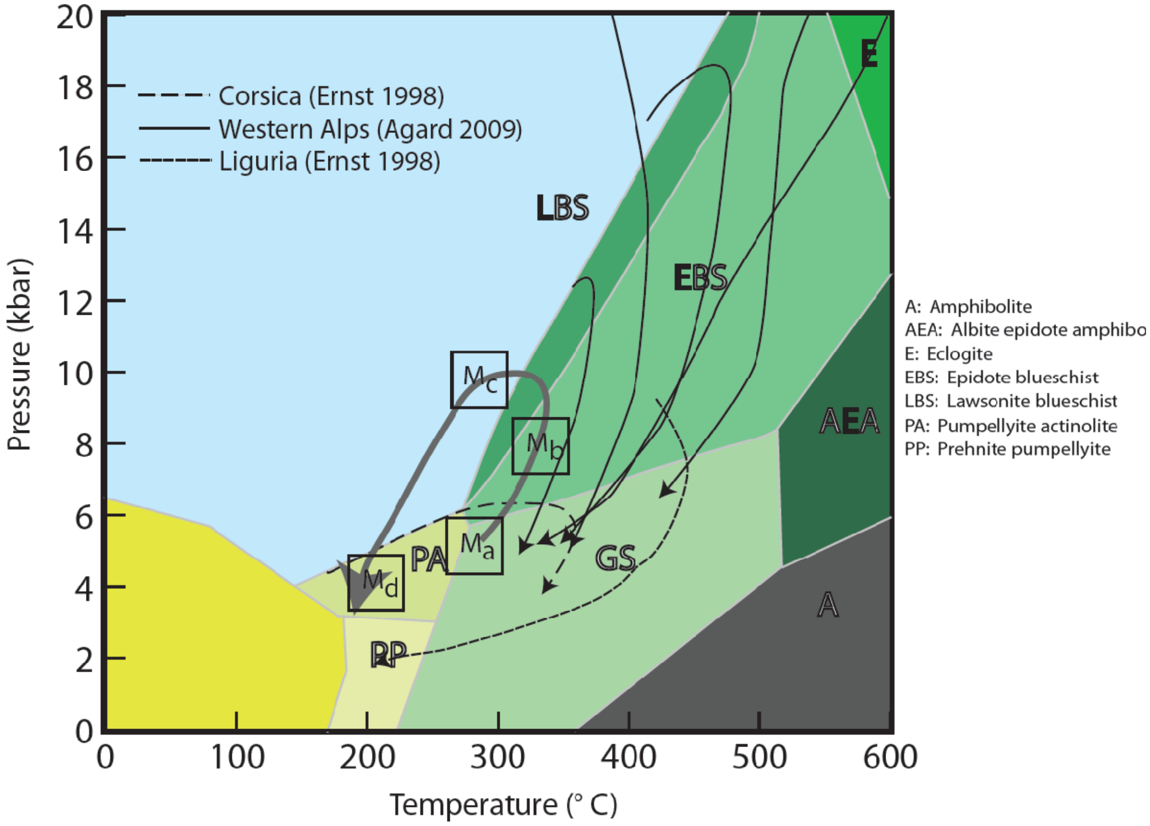


Figure 11. Comparison of Diamante metamorphic path with those found in the Alpine orogen. The clockwise shape of these P-T-t paths is generally due to near isothermal decompression causing a greenschist overprint on the rocks.

M_a(early prograde event): The prograde path was in the epidote-blueschist facies, as indicated by the presence of epidote in the cores of Na-amphibole of both layers.

M_b (peak pressure event): This event is represented by epidote blueschist in the green layers and lawsonite blueschist in the blue layers. This metamorphic event is synchronous with development of the foliation. Peak metamorphic conditions were best recorded in the blue layers, where omphacite indicates pressures of 9-11 kbar, while phengite suggest higher pressures of 15 kbar. Lawsonite in the blue layers indicates that temperature remained relatively low.

M_c (early retrograde event): Late lawsonite overgrows the foliation in both the green and blue layers. Although it is difficult to place a pressure estimate on this phase, the temperature must be on the lawsonite-in side of the facies boundary (Evans, 1990).

M_d(late retrograde event): This is a subgreenschist-facies overprint, consisting of lawsonite, pumpellyite, and actinolite.

These four phases form a counterclockwise, or hairpin, P-T-t path. Importantly, there is no evidence of a greenschist-facies overprint, and the presence of lawsonite indicates that temperatures decreased during exhumation. We will consider the implications of these two observations on Alpine tectonics.

LACK OF A GREENSCHIST OVERPRINT AND COUNTERCLOCKWISE P-T-t PATH AT DIAMANTE

Previous workers have reported a late greenschist overprint at Diamante and interpreted it as due to a change in convergence direction (Cello et al., 1991, 1996) or heating during exhumation (Rossetti et al., 2004). However, the greenschist-indicative minerals—epidote and actinolite—do not exist in equilibrium: epidote grew as an early phase, while actinolite came in as a late, retrograde phase, usually in contact with pumpellyite. The presence of pumpellyite limits temperatures during late stages of exhumation to the low-temperature side of the pumpellyite-out reaction, at temperatures of about 300º C (Frey et al., 1991; Banno, 1998). Together, actinolite and pumpellyite indicate that the retrograde metamorphism took place in the subgreenschist pumpellyite-actinolite facies (Coombs et al, 1976; Nakajima et al., 1977; Frey et al., 1991; Banno, 1998).

The absence of a greenschist overprint at Diamante is also consistent with the late growth of lawsonite (M_c), cutting the M_b foliation, and its preservation as euhedral crystals. In the broader Alpine Orogen, lawsonite is generally reported as pseudomorphs (Barnicoat and Fry, 1986; Gibbons et al., 1986; Ballevre et al, 2003; Clarke et al., 2006). This is because lawsonite is not stable during greenschist-facies retrogradation; instead, at those P-T conditions epidote becomes the more stable Ca-bearing phase (Evans, 1990). Since the P/T slope of the lawsonite-epidote transition is positive, cooling during exhumation is necessary to preserve lawsonite (Evans, 1990; Ballevre et al., 2003; Davis and Whitney, 2006; Clarke et al., 2006; Warren and Waters, 2006; Zhang et al., 2009; Diener et al., 2010). Only in Corsica have rare lawsonite-eclogite rocks escaped a greenschist facies overprint (Ravna et al., 2010); this is an anomaly, as a greenschist facies overprint is widespread in Corsica (Gibbons et al., 1986; Waters, 1989; Miller and Cartwright, 2006).

Another concurrent piece of evidence that confirms the lack of a greenschist overprint is the preservation of aragonite, as reported by Liberi et al. (2006). Since aragonite is only stable in cool conditions (Johannes and Puhan, 1971) it is rare in the Alps; its presence in circum-Pacific orogens indicates that geothermal gradients remained low throughout subduction and exhumation (Terabayashi and Maruyama, 1998).

When plotted, the metamorphic stages at Diamante from M_a to M_d define a counterclockwise P-T-t loop, representing the history of rocks which remained in low-temperature conditions during exhumation (Figure 11, 12). The key feature which defines this metamorphic path is a transition between epidote-stable and lawsonite-stable conditions—this requires cooling during exhumation (Evans, 1990).

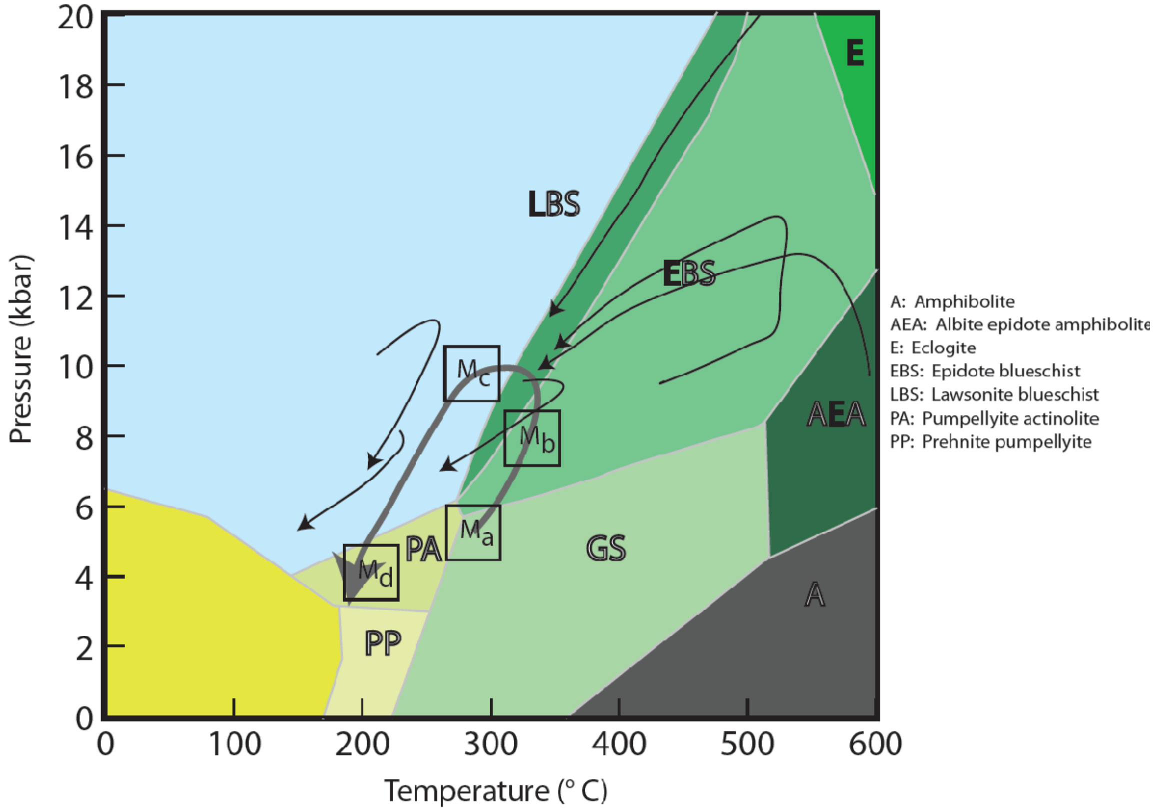


Figure 12. Comparison of Diamante metamorphic path (M$_a$-M$_d$) with those found in the Franciscan orogen (Agard, 2009). These counterclockwise paths are due to exhumation of the rocks during continued subduction.

TECTONIC SIGNIFICANCE OF PT PATHS AND COLD EXHUMATION

The rocks in Calabria are part of the broader Alpine Orogen, widely considered to be the world's prototypical collisional orogen. In these types of mountain belts involving continental collision, rapidly-buried rocks follow a P-T-t path that brings them to peak pressures before equilibrium with the regional geothermal gradient (England and Thompson, 1984; Spear and Peacock, 1989). When collision occurs, the cooling effect of the downgoing slab ceases. Subsequent exhumation often occurs rapidly and buried units are brought to the surface faster than heat can defuse out of them; this results in near-isothermal decompression and passage through the greenschist facies (Thompson and England, 1984). If this history is plotted on a P-T diagram it traces out a clockwise path (Figure 11) (Thompson and Ridley, 1987; Peacock, 1996; Ernst and Peacock, 1996; Ernst; 1998; Wakabayashi, 1990, 2004; Jolivet et al., 2003; Gerya and Stöckhert, 2006; Agard et al., 2009). Such a clockwise path can be enhanced by post-collisional processes involving the infiltration of hot asthenosphere beneath the orogen (Brouwer et al., 2004).

The rocks at Diamante do not follow this type of P-T-t history; instead, they underwent a counterclockwise P-T evolution, passing through the lawsonite-albite and pumpellyite-actinolite facies on their way to the surface (Figure 12). This type of thermal evolution is more similar to those observed in Franciscan-style non-collisional orogens, where the retrograde path takes place in much cooler conditions produced during the continued underflow of oceanic lithosphere (Platt, 1986; Ernst, 1988; Krogh et al., 1994; Wakabayashi, 2004) (Figure 12). Rocks in these situations can return to the surface along a similar path that they had descended, allowing for the retracing of a cool geothermal gradient back to the surface These P-T-t paths trace a hairpin, or counterclockwise, pattern on a P-T diagram (Ernst, 1988; Wakabayashi, 2004; Agard et al., 2009). However, in the case where subduction does cease, for example by conversion to a strike-slip margin and creation of a slab window, then a greenschist overprint will likely develop, even in a non-collisional system (Wakabayashi, 2004).

Could then the lack of continental collision explain the counterclockwise P-T-t path seen at Diamante? Northern Calabria occupies a unique place in the Apenninic chain where the underflow of cold oceanic crust continues to present day. A Wadati-Benioff Zone, linked to volcanism in the Eolian Islands, is present beneath Calabria (Chiarabba et al., 2008). However, in adjacent parts of the Apennine-Maghribide orogen, subduction has ceased. To the north, the southern Apennines have collided with the Apulian continental margin (Jolivet et al., 1993; Cello and Mazzoli, 1999; Scrocca et al., 2005; Mazzoli et al., 2008), while to the south, the Peloritani Mountains were formed during collision with the Sicily platform (Platt and Compagnoni, 1990; Messina et al., 2004; Vignaroli et al., 2008; Heymes et al., 2010). The continuation of subduction under Calabria is a consequence of historical contingency: the Jurassic rifting of Adria away from Africa created a narrow zone of oceanic crust, or thinned continental crust, between Sicily and Southern Italy; this crust continued to subduct even after adjacent parts of the orogen underwent continental collision (Catalano et al., 2001; Stampfli et al., 1998; Argnani, 2005; Schettino and Turco, 2006).

However, if continuing subduction was the primary reason that the Diamante blueschist was preserved, we would expect all exhumation histories in Calabria to be cold. Instead, we find greenschist-facies metamorphism reported from several areas of Northern Calabria. At Monte Reventino and Gimigliano (see Figure 1), a late greenschist-facies event consisting of co-existing epidote and actinolite overprints an earlier blueschist-facies metamorphic event (Colonna and Piccarreta, 1975b; Rossetti et al., 2001; Alvarez, 2005). The retrogradation here is so complete that significant amounts of Na-amphibole survive in only two outcrops: in a small block on the south face of Monte Reventino (Alvarez, 2005), and at Coreca, on the Tyrrhenian coast (De Roever, 1972).

Other ophiolitic metabasalt units of Northern Calabria have various degrees of greenschist-facies retrograde metamorphism. In the Fuscaldo region, De Roever (1972) reports the presence of a low-grade greenschist facies overprint on the albite-lawsonite facies metabasalts. This even is very low-grade, as lawsonite is often preserved. At Cetraro, the presence of chloritoid in phyllites indicates greenschist-facies conditions during exhumation (Rossetti et al, 2004; Iannace et al., 2007).

Hence, two styles of exhumation have taken place in Calabria: the cool path seen at Diamante and warm path observed in the Monte Reventino-Gimigliano Unit. Thus, it is clear that the metamorphic histories of the ophiolitic nappes in Calabria vary, not just in peak metamorphic pressure conditions (De Roever, 1972; Spadea, 1982), but also in thermal conditions of the retrograde metamorphic path. Continuing subduction beneath Calabria cannot be responsible for the preservation of Diamante blueschist, since within the same tectonic domain, both warm Alpine-style and cool Franciscan-style exhumation has occurred.

How then can we explain the two distinct styles of exhumation present in Calabria, one cool and one warm? The two styles of require different thermal conditions. Indeed, thermal conditions did change in Calabria beginning in the Miocene as the subduction zone rolled back and new oceanic crust developed in the forearc (Malinverno and Ryan, 1986; Brun and Faccenna, 2008). This suggests that thermal conditions may have changed from cool conditions to warm conditions, with exhumation taking place in two phases, one earlier and one later.

In the first phase of exhumation, as shown in the lawsonite-blueschist rocks at Diamante, rocks returned along a similar path that they had descended, allowing for the retracing of a cool geothermal gradient back to the surface, and resultant counterclockwise P-T-t history.

The second phase of exhumation may be shown by the rocks at Monte Reventino, with their extensive greenschist overprint. At this time, subduction rollback had led to increased thermal gradients in Calabria (Malinverno and Ryan, 1986; Brun and Faccenna, 2008).

Thus, the two types of exhumational paths suggests that at least two types of exhumation occurred in the Calabrian Arc during the Miocene: the blueschist may have been exhumed by an extrusional process during subduction, while the greenschist may have been exhumed during extension related to rollback of the subduction system, with the concurrent increase in heat flow (Wortel and Spakman, 2000; Brun and Faccenna, 2008; Malinverno and Ryan, 1986). Such different exhumation histories, within the same orogen, have also been observed in the Cyclades (Schmädicke and Will, 2003).

This hypothesis may explain a peculiar observation in Calabria. At Monte Reventino, the unit directly above the ophiolite is the Zangarona Schist, a pelitic schist and metabasalt unit. Both lawsonite and fine-grained glaucophane have been reported from this unit (Colonna and Piccarreta, 1975a), implying that it was exhumed in cool conditions, similar to the Diamante Unit. An early phase of exhumation could explain this feature, with the Zangarona being exhumed early—in cool condition—and the Monte Reventino Unit exhumed later, perhaps in a post-collisional process.

These new observations only apply to Calabria; however, they raise an important question about the wider Alpine orogen: Why is lawsonite blueschist not preserved in the Alps? The presence of greenschist in Calabria indicates that continuing subduction is not the main mechanism for the preservation of blueschist. Instead, early exhumation—in cool conditions—may be necessary for rocks to avoid later orogenic heating events. In the Alps, slab detachment is the main heating event; in Calabria, it is slab rollback. The timing of exhumation, even within dominantly collisional events, may play a large role in the preservation of HP minerals and fabrics.

ACKNOWLEDGEMENTS

I would like to thank Francesca Liberi for collaboration in analyzing thin sections and the petrological data. I thank Walter Alvarez, John Wakabayashi, and Eugenio Piluso for extensive discussion during the production of this chapter. I also thank Christine Waljeski and Sylvia Moses for assistance in the field, and the Locher and Alessio families of Cosenza for their warm hospitality.

REFERENCES

Agard, P., Yamato, P., Jolivet, L., and Burov, E., 2009, Exhumation of oceanic blueschists and eclogites in subduction zones: Timing and mechanisms: Earth-Science Reviews, v. 92, p. 53-79.

Alvarez, W., 1974, Fragmentation of the Alpine orogenic belt by microplate dispersal: Nature, v. 248, p. 309-314.

Alvarez, W., 1991, Tectonic evolution of the Corsica-Apennines-Alps region studied by the method of successive approximations: Tectonics, v. 10, p. 936-947.

Alvarez, W., 2005, Structure of the Monte Reventino greenschist folds: a contribution to untangling the tectonic-transport history of Calabria, a key element in Italian tectonics: Journal of Structural Geology, v. 27, p. 1355-1378.

Alvarez, W., and Shimabukuro, D.H., 2009, The geological relationship between Sardinia and Calabria during Alpine and Hercynian times: Bollettino della Società Geologica Italiana, v. 128, p. 257-268.

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., and Zuppetta, A., 1976, L'arco Calabro-Peloritano nella'orogene Appenninico-Maghrebide: Memorie della Società Geologica Italiana, v. 17, p. 1-60.

Argnani, A., 2005, Possible record of a Triassic ocean in the Southern Apennines: Bollettino della Società Geologica Italiana, v. 124, p. 109-121.

Ballevre, M., Pitra, P., and Bohn, M., 2003, Lawsonite growth in the epidote blueschists from the Ile de Groix (Armorican Massif, France): a potential geobarometer: Journal of Metamorphic Geology, v. 21, p. 723-735.

Banno, S., 1998, Pumpellyite-actinolite facies of the Sanbagawa metamorphism: Journal of Metamorphic Geology, v. 16, p. 117-128.

Barnicoat, A.C., and Fry, N., 1986, High-pressure metamorphism of the Zermatt-Saas ophiolite zone, Switzerland: Journal of the Geological Society, v. 143, p. 607-618.

Beccaluva, L., Coltorti, M., Giuna, G., and Siena, F., 2004, Tethyan vs. Cordilleran ophiolites: a reappraisal of distinctive tectono-magmatic features of supra-subudction complexes in relation to the subduction mode: Tectonophysics, v. 393, p. 163-174.

Bonardi, G., Amore, F.O., Ciampo, G., de Capoa, P., Miconnet, P., and Perrone, V., 1988, Il complesso Liguride Auct.: Stato delle conoscenze e problemi aperti sulla evoluzione Pre-Apenninica ed I suoi rapporti con l'arco Calabro: Memorie della Società Geologica Italiana, v. 41, p. 17-35.

Bonardi, G., Cavazza, W., Perrone, V., and Rossi, S., 2001, Calabria-Peloritani Terrane and northern Ionian Sea, in, Anatomy of an Orogen, Vai, G.B., and Martini, J.P., eds., p. 287-306: Kluwer Academic, Norwell MA.

Brouwer, F.M., van de Zedde, D.M.A., Wortel, M.J.R., and Vissers, R.L.M., 2004, Late-orogenic heating during exhumation: Alpine PTt trajectories and thermomechanical models: Earth and Planetary Science Letters, v. 220, p. 185-199.

Brun, J.-P., and Faccenna, C., 2008, Exhumation of high-pressure rocks driven by slab rollback: Earth and Planetary Science Letters, v. 282, p. 1-7.

Catalano, R., Doglioni, C., and Merlini, S., 2001, On the Mesozoic Ionian Basin: Geophysical Journal International, v. 144, p. 49-64.

Cello, G., De Francesco, A., and Morten, L., 1991, The tectonic significance of the Diamante-Terranova unit (Calabria, southern Italy) in Alpine evolution of the northern sector of the Calabrian Arc: Bollettino della Società Geologica Italiana, v. 110, p. 685-694.

Cello, G., Invernizzi, C., and Mazzoli, S., 1996, Structural signature of tectonic processes in the Calabrian Arc, southern Italy: Evidence from the oceanic-derived Diamante-Terranova unit: Tectonics, v. 15, p.187-200.

Cello, G., and Mazzoli, S., 1999, Apennine tectonics in southern Italy: a review: Journal of Geodynamics, v. 27, p. 191-211.

Chiarabba, C., De Gori, P., and Speranza, F., 2008, the southern Tyrrhenian subduction zone: Deep geometry, magmatism and Plio-Pleistocene evolution: Earth and Planetary Science Letters, v. 268, p. 408-423.

Clarke, G.L., Powell, R., and Fitzherbert, J.A., 2006, The lawsonite paradox: a comparison of field evidence and mineral equilibria modelling: Journal of Metamorphic Geology, v. 24, p. 715-725.

Colonna, V., and Piccarreta, G., 1975a, Metamorfismo di alta pressione/bassa temperatura nei micascisti di Zangarona-Ievoli-Monte Dondolo (Sila Piccola, Calabria): Bollettino della Società Geologica Italiana, v. 94, p. 17-25.

Colonna, V., and Piccarreta, G., 1975b, Schema strutturale della Sila Piccola Meridionale: Bollettino della Società Geologica Italiana, v. 94, p. 3–16.

Colonna, V., and Piccarreta, G., 1976, Contributo alla conoscenza dell'unita di Castagna in Sila Piccola: Rapporti tra micascisti, paragneiss e gneiss occhiadini: Bollettino della Società Geologica Italiana, v. 95, p. 1-10.

Coombs, D.S., Nakamura, Y., and Vaugnat, M., 1976, Pumpellyite-actinolite facies schists of the Taveyanne Formation near Loche, Valais, Switzerland: Journal of Petrology, v. 17, p. 440-471.

Davis, P.B., and Whitney, D.L., 2006, Petrogenesis of lawsonite and epidote eclogite and blueschist, Sivrihisar Massif, Turkey: Journal of Metamorphic Geology, v. 24, p. 823-849.

De Roever, E.W.F., 1972, Lawsonite-albite facies metamorphism near Fuscaldo, Calabria (Southern Italy), its geological significance and petrological aspects: GUA Papers in Geology, ser. 1, v. 3, 171 p.

Dewey, J.F., Helman, M.L., Knott, S.D., Turco, E., and Hutton, D.H.W., 1989, Kinematics of the western Mediterranean, in, Coward, M.P., Dietrich, D., and Park, R.G., eds., Alpine Tectonics: Geological Society Special Publication, no. 45, p. 265-283.

Diener, J.F.A., Powell, R., White, R.W., and Holland, T.J.B., 2007, A new thermodynamic model for clino- and orthamphiboles in the system Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O-O: Journal of Metamorphic Geology, v. 25, p. 631-656.

Diener, J.F.A., and Powell, R., 2010, Influence of ferric iron on the stability of mineral assemblages: Journal of Metamorphic Geology, v. 28, p. 599-613.

Dilek, Y., 2003, Ophiolite pulses, mantle plumes, and orogeny, in, Dilek, Y.,and Robinson, P.T., eds., Ophiolites in Earth History: Geological Society Special Publication, v. 218, p. 9-19.

Dungan, M.A., Vance, J.A., and Blanchard, D.P., 1983, Geochemistry of the Shuksan greenschists and blueschists, North Cascades, Washington: Variably fractionated and altered metabasalts of oceanic affinity: Contributions to Mineralogy and Petrology, v. 82, p. 131-146.

England, P.C., and Thompson, A.B., 1984, Pressure—temperature—time paths of regional metamorphism I. Heat transfer during the evolution of regions of thickened continental crust: Journal of Petrology, v. 25, p. 894-928.

Ernst, W.G., 1988, Tectonic history of subduction zones inferred from retrograde blueschist P-T paths: Geology, v. 16, p. 1081-1084.

Ernst, W.G., and Peacock, S., 1996, A thermotectonic model for preservation of ultrahigh-pressure mineralogic relics in metamorphosed continental crust: Geophysical Monographs, v. 96, p. 171–178.

Evans, B.W., 1990, Phase relations of epidote-blueschists: Lithos, v. 25, p. 3-23.

Fournier, M., Jolivet, L., Goffé, B., and Dubois, R., 1991, Alpine Corsica metamorpic core complex: Tectonics, v. 10, p. 1173-1186.

Frey, M., De Capitani, C., and Liou, J.G., 1991, A new petrogenetic grid for low-grade metabasites: Journal of Metamorphic Geology, v. 9, p. 497-509.

Gerya, T., and Stöckhert, B., 2006, Two-dimensional numerical modeling of tectonic and metamorphic histories at active continental margins: International Journal of Earth Sciences: v. 95, p. 250-274.

Getty, S.R., and Selverstone, J., 1994, Stable isotopic and trace element evidence for restricted fluid migration in 2 GPa eclogites: Journal of Metamorphic Geology, v. 12, p. 747-760.

Gibbons, W., Waters, C., and Warburton, J., 1986, The blueschist facies schistes lustrés of Alpine Corsica: A review, in Evans, B.W., and Brown, E.H., eds., Blueschists and eclogites: Geological Society of America Memoir 164, p. 301-311.

Hacker, B.R., Abers, G.A., and Peacock, S.M., 2003, Subduction factory 1. Theoretical mineralogy, densities, seismic wave speeds and H_2O contents: Journal of Geophysical Research B, v. 108, doi:10.1029/2001JB001127.

Hoffmann, C., 1970, Die Glaukophangesteine, ihre stofflichen Äquivalente und Umwandlungsprodukte in Nordcalabrien (Süditalien): Contributions to Mineralogy and Petrology, v. 27, p. 283-320.

Holland, T.J.B., 1980, The reaction albite=jadeite + quartz determined experimentally in the range 600-1200 °C: American Mineralogist, v. 65, p. 129-134.

Heymes, T., Monié, P., Arnaud, N., Pêcher, A., Bouillin, J.-P., and Compagnoni, R., 2010, Alpine tectonics in the Calabrian-Pelritan belt (southern Italy): New $^{40}Ar/^{39}Ar$ data in the Aspromonte Massif area: Lithos, v. 114, p. 451-472.

Iannace, A., Vitale, S., D'Errico, M., Mazzoli, S., Di Staso, A., Macaione, E., Massina, A., Reddy, S.M., Somma, R., Zamparelli, V., Zattin, M., and Bonardi, G., 2007, The carbonate tectonic units of northern Calabria (Italy): A record of Apulian palaeomargin evolution and Miocene convergence, continental crust subduction, and exhumation of HP-LT rocks: Journal of the Geological Society, v. 164, p. 1165-1186.

Jolivet, L., Faccenna, C., Goffé, B., Mattei, M., Rossetti, F. Brunet, C. Storti, F., Funiciello, R. Cadet, J.P., d'Agostino, N., and Parra, T., 1998, Midcrustal shear zones in postorogenic extension: Examples from the northern Tyrrhenian Sea: Journal of Geophysical Research B, v. 103, p. 12123-12160.

Jolivet, L., Faccenna, C., Goffé, B. Burov, E., and Agard, P., 2003, Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens: American Journal of Science, v. 303, p. 353-409.

Johannes, W., and Puhan, D., 1971, The calcite-aragonite transition, reinvestigated: Contributions to Mineralogy and Petrology, v. 31, p. 28-38.

Knott, S.D., 1987, The Liguride Complex of southern Italy—a Cretaceous to Paleogene accretionary wedge: Tectonophysics, v. 142, p. 217-226.

Krogh, E.J., Oh, C.W., and Liou, J.G., 1994, Polyphase and anticlockwise P-T evolution for Franciscan eclogites and blueschists from Jenner, California, USA: Journal of Metamorphic Geology, v. 12, p. 121-134.

Langone, A., Gueguen, E., Prosser, G., Caggianelli, A., and Rottura, A., 2006, The Curinga-Girifalco fault zone (northern Serre, Calabria) and its significance within the Alpine tectonic evolution of the western Mediterranean: Journal of Geodynamics, v. 42, p. 140-158.

Lanzafame, G., Spadea, P., and Tortorici, L., 1979, Mesozoic ophiolites of Northern Calabria and Lucanian Apennine (Southern Italy): Ofioliti, v. 4, p. 173-182.

Leake, B.E., Woolley, A.R., and others, 1997, Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names: Canadian Mineralogist, v. 35 p. 219-246.

Liberi, F., Morten, L., and Piluso, E., 2006, Geodynamic significance of ophiolites within the Calabrian Arc: Island Arc, v. 15, p. 26-43.

Malinverno, A., and Ryan, W.B.F., 1986, Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking in the lithosphere: Tectonics, v. 5, p. 227-245.

Maruyama, S., Cho, M., and Liou, J.G., 1986, Experimental investigations of blueschist-greenschist transition equilibria: Pressure dependence of Al_2O_3 contents in sodic amphiboles—A new geobarometer, in, Evans, B.W., and Brown, E.H., eds., Blueschists and Eclogites: Geological Society of America Memoir 164, p. 1-16.

Massonne, H.-J., and Schreyer, W., 1987, Phengite geobarometry based on the limited assemblage with K-felspar, phlogopite and quartz: Contributions to Mineralogy and Petrology, v. 96, p. 212-224.

Massonne, H.-J., and Szpurka, Z., 1997, Thermodynamic properties of white micas on the basis of high-pressure experiments in the systems K_2O-MgO-Al_2O_3-SiO_2-H_2O and K_2O-FeO-Al_2O_3-SiO_2-H_2O: Lithos, v. 41, p. 229-250.

Matthews, A., and Schliestedt, M., 1984, Evolution of the blueschist and greenschist facies rocks of Sifnos, Cyclades, Greece: Contributions to Mineralogy and Petrology, v. 88, p. 150-163.

Mazzoli, S., D'Errico, M., Aldega, L., Corrado, S., Invernizzi, C., Shiner, P., and Zattin, M., 2008, Tectonic burial and "young" (< 10 Ma) exhumation in the southern Apennines fold-and-thrust belt (Italy): Geology, v. 36, p. 243-246.

Messina, A., Somma, R. Macaione, E., Carbone, G., and Careri, G., 2004, Peloritani continental crust composition (southern Italy): Geological and petrochemical evidence: Bollettino della Società Geologica Italiana, v. 123, p. 405-441.

Miller, J.A., and Cartwright, I., 2006, Albite vein formation during exhumation of high-pressure terranes: a case study from alpine Corsica: Journal of Metmaorphic Geology, v. 24, p. 409-428.

Nakajima, T., Banno, S., and Suzuki, T., 1977, Reactions leading to the disappearance of pumpellyite in low-grade metamorphic rocks of the Sanbagawa metamorphic belt I Central Shikoku, Japan: Journal of Petrology, v. 18, p. 263-284.

Ogniben, L., 1973, Schema geologico della Calabria in base ai dati odiemi: Geologica Romana, v. 12, p. 243-585.

Owen, C., 1989, Magmatic differentiation and alteration in isofacial greenschists and blueschsits, Shuksan Suite, Washington—Statistical analysis of major-element variation: Journal of Petrology, v. 30, p. 739-761.

Peacock, S.M., 1996, Thermal and petrologic structure of subduction zones, in, Bebout, G.E., Scholl, D.W., Kirby, S.H., and Platt, J.P., eds., Subduction top to bottom: Geophysical Monographs, v. 96, p. 119-133.

Piccarreta, G., 1981, Deep-rooted overthrusting and blueschist metamorphism in compressive continental margins. An example from Calabria (Southern Italy): Geological Magazine, v. 118, p. 539-544.

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

Platt, J.P., and Compagnoni, R., 1990, Alpine ductile deformation and metamorphism in a Calabrian basement nappe (Aspromonte, south Italy): Eclogae geologicae Helvetiae, v. 83, p. 41-58.

Powell, W.G., Carmichal, D.M., and Hodgson, I., 1993, Thermobarometry in a subgreenschist to greenschist transition in metabasites of the Abitibi greenstone belt, Superior province, Canada: Journal of Metamorphic Geology, v. 11, p. 165-178.

Powell, R., Guiraud, M., and White, R.W., 2005, Truth and beauty in metamorphic phase equilibria: conjugate variables and phase diagrams: Canadian Mineralogist, v. 43, p. 21-33.

Principi, G., and Treves, B., 1984, Il sistema Corso-Appenninico come prisma d'accrezione. Riflessi sul problema generale del limite Alpi-Appennini: Memorie della Società Geologica Italiana, v. 28, p. 549-576.

Ravna, E.J.K., Andersen, T.B., Jolivet, L., and De Capitani, C., 2010, Cold subduction and the formation of lawsonite eclogite—constraints from the prograde evolution of eclogitizied pillow lava from Corsica: Journal of Metamorphic Geology, v. 28, p. 381-395.

Rossetti, F., Faccenna, C., Goffé, B., Monié, P., Argentier, A., Funiciello, R., and 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, v. 20, p. 112-133.

Rossetti, F., Faccenna, C., Goffé, B., Funiciello, R., and Monié, P., 2002, Tectono-metamorphic evolution of the ophiolite-bearing HP/LT Gimigliano-Monte Reventino unit (Gimigliano, Sila Piccola): Insights for the tectonic evolution of the Calabrian Arc: Bollettino della Società Geologica Italiana, v. 121, p. 51-67.

Rossetti, F., Goffé, B, Monié, P, Faccenna, C., and Vignaroli, G., 2004, Alpine orogenic P-T-t-deformation history of the Catena Costiera area and surrounding regions (Calabrian Arc, southern Italy): The nappe edifice of north Calabria revised with insights on the Tyrrhenian-Apennine system formation: Tectonics, v. 23, TC6011, doi:10.1029/2003TC001560.

Schettino, A., and Turco, E., 2006, Plate kinematics of the Western Mediterranean region during the Oligocene and Early Miocene: Geophysical Journal International, v. 166, p. 1398-1423.

Schmädicke, E., and Will, T.M., 2003, Pressure-temperature evolution of blueschist facies rocks from Sifno, Greece, and implications for the exhumation of high-pressure rocks in the Central Aegean: Journal of Metamorphic Geology, v. 21p. 799-811.

Schulz, B., Triboulet, C., Audren, C., Pfeifer, H.-R., and Gilg, A., 2001, Two-stage prograde and retrograde Variscan metamorphism of glaucophane-eclogites, blueschist and greenschists from Ile de Groix (Brittany, France): International Journal of Earth Sciences, v. 90, p. 871-889.

Scrocca, D., Carminati, E., and Doglioni, C., 2005, Deep structure of the southern Apennines, Italy: Thin-skinned or thick-skinned?: Tectonics, v. 24, TC3005, doi:10.1029/2004TC001634.

Spadea, P., 1982, Continental crust rocks associated with ophiolites in Lucanian Apennine (Southern Italy): Ofioliti, v. 7, p. 501-522.

Spadea, P., 1994, Calabria-Lucania ophiolites: Bollettino Geofisica Teorica Applicata, v. 36, p. 141-144.

Spadea, P., Tortorici, L., Lanzafame, G., 1976, Serie ofiolitifere nell'area fra Tarsia e Spezzano Albanese (Calabria): Stratigrapfia, petrografia, rapporti strutturali: Memorie della Società Geologica Italiana, v. 17, p. 135-174.

Spear, F.S., and Peacock, S.M., 1989, Metamorphic pressure-temperature-time paths: Short Course in Geology, American Geophysics Union, v. 7, 102 p.

Spooner, E.T.C., and Fyfe, W.S., 1973, Sub-sea-floor metamorphism, heat and mass transfer: Contributions to Mineralogy and Petrology, v. 42, p. 287-304.

Stampfli, G.M., Mosar, J., Marquer, D., Marchant, R., Baudin, T., and Borel, G., 1998, Subduction and obduction processes in the Swiss Alps: Tectonophysics, v. 296, p. 159-204.

Terabayashi, M., and Maruyama, S., 1998, Large pressure gap between the Coastal and Central Franciscan belts, northern and central California: Tectonophysics, v., 285, p. 87-101.

Thompson, A.B., and England, P.C., 1984, Pressure—temperature—time paths of regional metamorphism II. Their inference and interpretation using mineral assemblages in metamorphic rocks: Journal of Petrology, v. 25, p. 929-955.

Thompson, A.B., and Ridley, J.R., 1987, Pressure—temperature—time (P—T—t) histories of orogenic belts, in, Oxburgh, E.R., Yardley, B.W.D., and England, P.C., eds., Tectonic settings of regional metamorphism: Philosophical Transactions of the Royal Society of London, Series A, v. 321, p. 27-45.

Tortorici, L., Catalano, S., and Monaco, C., 2009, Ophiolite-bearing melanges in southern Italy: Geological Journal, v. 44, p. 153-166.

Trzcienski, W.E., Jr., Carmichael, D.M., and Helmstaedt, H., 1984, Zoned sodic amphibole: petrologic indicator of changing pressure and temperature during tectonism in the Bathurst Area, New Brunswick, Canada: Contributions to Mineralogy and Petrology, v. 85, p. 311-320.

Vignaroli, G., Rossetti, F., Bouybaouene, M., Massone, H.-J., Theye, T., Faccenna, C., and Funicello, R., 2005, A counter-clockwise P-T path for the Voltri Massif eclogites (Ligurian Alps, Italy): Journal of Metamorphic Geology, v. 23, p. 533-555.

Wakabayashi, J., 1990, Counterclockwise P-T-t paths from amphibolites, Franciscan Complex, California: relics from the early stages of subduction zone metamorphism: Journal of Geology, v. 98, p. 657-680.

Wakabayashi, J., 2004, Tectonic mechanisms associated with P-T paths of regional metamorphism: alternatives to single-cycle thrusting and heating: Tectonophysics, v. 392, p. 193-218.

Warren, C.J., and Waters, D.J., 2006, Oxidized eclogites and garnet-blueschists from Oman: P-T path modelling in the NCFMASHO system: Journal of Metamorphic Geology, v. 24, p. 783-802.

Waters, C.N., 1989, The metamorphic evolution of the Schistes lustrés ophiolite, Cap Corse, Corsica, in, Daly, J.S., Cliff, R.A., and Tarley, B.W.D., eds., Evolution of Metamorphic Belts: Geological Society, London, Special Publication, no. 43, p. 557-562.

Wei, C., and Powell, R., 2006, Calculated phase relations in the system NCKFMASH (Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3- SiO_2-H_2O) for high-pressure metapelites: Journal of Petrology, v. 47, p. 385-408.

Wiederkehr, M., Sudo, M., Bousquet, R., Berger, A., and Schmid, S.M., 2009, Alpine orogenic evolution from subduction to collisional thermal overprint: The ^{40}Ar/^{39}Ar age constraints from the Valaisan Ocean, central Alps: Tectonics, v. 28, TC6009, doi:10.1029/2009TC002496.

Wortel, W.J.R., and Spakman, W., 2000, Subduction and slab-detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910-1917.

Zack, T., Rivers, T., Brumm, R., and Kronz, A., 2004, Cold subduction of oceanic crust: Implications from a lawsonite eclogite from the Dominican Republic: European Journal of Mineralogy, v. 16, p. 909-916.

Zhang, L., Wang, Q., and Song, S., 2009, Lawsonite blueschist in Northern Qilian, NW China: P-T psudosections and petrologic implications: Journal of Asian Earth Sciences, v. 35, p. 354-366.

SUPPLEMENTAL DATA

Blueschist-facies metabasalts exposed in Calabria have different bulk chemistries that especially vary in oxidation state: Fe^{3+}/Fe^{2+} reported in the literature from several different outcrops range between 0.08 and 0.82 (Hoffman, 1970; De Roever, 1972; Spadea et al., 1976). This is a large enough range to significantly alter the pressure-temperature conditions of the transition between epidote-blueschist and lawsonite-blueschist facies (Evans, 1990; Diener et al., 2007, 2010).

In order to determine if oxidation state could explain the development of the blue and green layers, we separated a blue and a green layer in a hand specimen, and analyzed the bulk composition of each using x-ray fluorescence for major elements, and wet chemistry to determine the Fe^{3+}/Fe^{2+} ratio (Supplementary Data Table).

Although there are notable differences between the blue and green layers, notably in SiO_2,MgO, and total Fe, our measurements do not indicate different oxidations states in different layers. Fe^{3+}/Fe^{2+}, at 0.60, was identical in both layers. Measurements for an epidosite layer have a much higher Fe^{3+}/Fe^{2+}, as would be expected.

There is reason to think the measurements for blue and green are inaccurate. Lawsonite-blueschist layers are comprised of mainly of glaucophanic Na-amphibole, with little or no epidote or Na-pyroxene, leaving no place for the Fe^{3+} to reside, thus they should have low Fe^{3+}/Fe^{2+}. We suspect that the spatial resolution of the sampling may have blended two distinct bulk compositions together, as the blue and green layers are only several mm thick in places, while sampling took place on the cm scale. The coarse nature of cutting the samples from a hand specimen with a rocksaw may not have succeeded in isolated zones of a single composition.

Indeed, an epidote-rich layer, which was identical in appearance to the epidote-blueschist boudins, was measured along with the blue and green layers (Supplementary Data Table). A Fe^{3+}/Fe^{2+} ratio of 0.82—much more oxidized that the blue and green values—was obtained from this rock.

To overcome the spatial limitations of sampling for x-ray fluorescence analysis, we determined the modal percentage of minerals in both layers using electron-backscatter images. Using the composition of each phase, based on average microprobe analyses of minerals, we calculated the composition of each layer. Blue layers, represented by Na-amphibole, lawsonite, and epidote, are 47.9% SiO_2, 21.9% Al_2O_3, 6.1% FeO, 5.8 %

Fe_2O_3, 3.2% MgO, 11.7% CaO, 3.0% Na_2O, and 0.4% K_2O, in weight percent oxide. A simple calculation can be made to show that Fe^{3+}/Fe^{2+} is 0.46. In the case of the green epidote-blueschist layers, calculated compositions are 45.1% SiO_2, 20.9% Al_2O_3, 4.7% FeO, 9.7 % Fe_2O_3, 2.5% MgO, 14.4% CaO, 2.4% Na_2O, with a Fe^{3+}/Fe^{2+} of 0.65. This means that the epidote blueschist are more oxidized than the lawsonite blueschist layers, consistent with the idea that different oxidation states lead to different mineral assemblages.

Molar weight percentage of Calabrian metabasalts

	ep bs	lws bs	epidosite	P167	Rv-33-C	F162	H2	H11
Na2O	1.28	2.91	1.64	4.15	4.67	4.53	2.77	5.75
MgO	16.42	11.22	4.07	11.97	9.15	15.11	13.48	9.56
Al2O3	10.69	8.49	7.14	9.59	16.37	9.87	10.75	12.23
SiO2	45.78	54.78	58.42	54.55	56.30	53.21	52.07	55.25
K2O	0.91	0.30	0.05	0.25	1.68	0.50	0.05	1.96
CaO	12.39	12.04	21.81	10.05	4.71	7.62	11.85	5.72
TiO2	2.67	1.96	1.76	1.53	1.62	1.80	1.26	1.81
MnO	0.30	0.18	0.15	0.20	0.16	0.18	0.15	0.27
Fe2O3	4.12	3.51	3.45	1.86	3.63	1.40	0.33	2.51
FeO	5.44	4.62	1.50	5.84	1.71	5.78	7.30	4.94
Fe3+/Fe2+	0.60	0.60	0.82	0.39	0.81	0.33	0.08	0.50

ep bs = average of Diamante epidote blueschist
lws bs = average of Diamante lawsonite blueschist
P167 = lawsonite blueschist from Fonte Pippana (Spadea et al., 1976)
Rv-33-C = lawsonite and epidote metaporphyrite near Fuscaldo (De Roever, 1972)
F162 = spilite basalt from Vallone Forance (Spadea et al., 1976)
H2 = lawsonite blueschist from near Diamante (Hoffman, 1970)
H11 = lawsonite and epidote rock from near Diamante (Hoffman, 1970)

Supplementary Data Table 1. XRF measurements of Diamante blueschist and Calabria metabasalts from the literature.

Introduction to Chapter 3

In this chapter, I present structural measurements and Ar/Ar geochronology from the lawsonite-blueschist outcrop at Diamante, Calabria. In the previous chapter I showed that these rocks have not been affected by a greenschist overprint, thus, they preserve early metamorphic events in the Calabrian subduction zone.

In addition to their well-preserved metamorphic history, these rocks bear unique structural indicators which record their direction of motion within the Calabrian subduction zone. The green layers are tilted in a manner similar to books on a bookshelf, indicating that they have been sheared in a top-to-the-southeast fashion. In addition, blueschist-facies minerals grow between the tilted blocks, indicating that the deformation took place in the high-pressure conditions of a subduction zone.

However, new observations presented in Chapter 4 suggest that the Diamante block may be a block in a sedimentary mélange. In that case, the structural and metamorphic history of the block may not be representative of the entire unit. Instead, the earliest stages of deformation recorded by the rock may have been formed in the early subduction zone, before it was exhumed and deposited as a block on the seafloor. Only the later stages of deformation, which indicate a top-to-the-east shear direction, are representative of the unit as a whole.

In order to aid in the interpretation of the structural fabrics, we used Ar/Ar geochronology to date white micas from the rocks at Diamante. Since they have not been affected by a greenschist overprint, the 46 Myr age of the rocks can be taken to be the crystallization age of the rocks and the subduction zone. This is the first clear date of the age of subduction in Calabria; previous radiometric dates in the literature date the process of exhumation.

This 46 Myr date is significant because it is synchronous with the start of subduction beneath Sardinia, indicating that the Diamante rocks formed in a west-dipping subduction zone. This date also implies that the deformation observed in Calabria was formed in a west-dipping subduction zone, consistent with the shear directions recorded in the rocks.

At the same time, north of Calabria, there was an east-dipping subduction zone present in Corsica. A transform fault is necessary to connect Corsica to the west-dipping subduction zone in Calabria.

CHAPTER 3

Evidence for synchronous opposite vergence in the Calabria-Corsica orogenic trend from Diamante, Calabria

ABSTRACT

Oftentimes, vergence directions recorded by structural indicators in orogenic belts are difficult to interpret. This is because at outcrop scale, the main indicator of vergence is simple-shear deformation of rocks. Since simple-shear strain can result from either extension or shortening, and can reverse on alternating limbs of major folds, the sense of thrust vergence in an orogenic belt can be difficult to determine without careful structural and petrological work relating the phases of deformation with metamorphic stages. In the Calabrian Orogen of Southern Italy, the vergence direction of the orogenic belt has been controversial. Features in single outcrops have been interpreted by different authors as indicating either shortening or extension, leading to proposals that the tectonics of Calabria are dominated by either east vergent, or west vergent, tectonics. In this chapter, we present new structural mapping and geochronology from an outcrop at Diamante, on the Tyrrhenian Coast of Northern Calabria, which has been cited as an evidence for both east-vergent compression and west-vergent extension. New observations, presented in Chapter 4, indicate that the Diamante outcrop is likely a block in an orogen-scale mélange. Thus, the first two stages of deformation may not be related to the current position of the Diamante Unit and may record the history of early subduction beneath Calabria. Even though the structural data is difficult to interpret, the ~46 Ma age for phengitic mica can be linked with the early stages of the west-dipping subduction zone beneath Sardinia indicating the existence of an east-vergent orogen in Calabria. This age occurs simultaneously with the west-vergent blueschist-facies metamorphism in Corsica. The synchronicity in opposite vergences in adjacent parts of an orogenic belt implies the existence of a transform fault between the two segments.

INTRODUCTION

In Calabria, the toe of the Italian boot, there has been considerable disagreement about the vergence of the Alpine-aged orogenic belt. Workers have reported the existence of either a single orogenic event, or two orogenic events, leading to two models of the pre-Miocene tectonic history of Calabria (Alvarez and Shimabukuro, 2009). In the first model, Calabria represents a microcontinent which originally collided with Sardinia during a west-vergent orogenic episode over an east-dipping subduction zone (Alvarez, 1974). After a collisional event, subduction ceased, and a new east-vergent orogenic belt developed above a west-dipping subduction zone (Figure 1a). In this model, Calabria can be thought of as an amalgamation of two separate orogens, one which is Cretaceous in age, and the other which occurred during from the Oligocene to present (Alvarez, 1974; Amodio-Morelli et al., 1976; Cello et al., 1996; Bonardi et al., 2001; Liberi et al., 2006). This model, involving a subduction polarity flip, has been applied to the wider Alpine orogen, usually involving the “AlKaPeCa” (Alboran-Kabylie-Peloritani-Calabria) microcontinent (Michard et al., 2002; Guerrera et al., 2005; Molli et al., 2006).

In a second model, Calabria represents an original piece of the Corsica-Sardinia continental margin (Figure 1b). In this case, west-dipping subduction initiated beneath Calabria, and continues to today, creating an east-vergent orogen (Dietrich, 1988; Knott, 1994; Rossetti et al., 2001, 2004). This model, involving a single-subduction zone, has been applied the other areas of the Alpine belt (Principi and Treves, 1984; Dewey et al., 1989; Zeck, 1996).

A key piece of evidence for distinguishing between these two theories comes from shear indictors in metamorphic rocks. Shear directions are often difficult to interpret in a regional context since, in isolation, they do not indicate shortening or extension, only principal strain directions (Butler and Freeman, 1996). Thus, it can be difficult to interpret a structural event as being related to burial, or exhumation. Only in the context of a metamorphic pressure-temperature path can shear directions be used to interpret a tectonic history.

In the Calabrian orogen, structural evidence from a single critical outcrop, near the town of Diamante in Northern Calabria, has been interpreted in terms of both west-vergent (Cello et al., 1991, 1996; Liberi et al., 2006) and east-vergent compression (Rossetti et al., 2004), and in terms of west-vergent extension (Rossetti et al., 2004). There are two points of contention about this outcrop: the first is the direction of shear sense recorded by the SC-fabrics and the second is the metamorphic facies in which the deformation took place. In this paper we present new structural mapping which shows new shear indicators which developed in the blueschist facies. We also present a new Ar/Ar date on phengitic mica which chronologically links the deformation at Diamante to subduction volcanism in Sardinia. Although new observations, presented in Chapter 4, indicate that the Diamante metabasalt is most likely a block in a sedimentary mélange, the geochronological data is most consistent with a single, long-lasting, west-dipping subduction zone beneath Calabria.

OUTCROP DESCRIPTION

The Apenninic Orogen of Italy is a Cenozoic subduction system resulting from closure of a branch of the Neotethys, followed by partial subduction of the Adria continental margin (Dewey et al., 1989). It consists of carbonate and flysch sequences along much of its length on the Italian peninsula; however, in Calabria, this trend is interrupted by a crystalline-basement terrane (Bonardi et al., 2001). Unlike the rest of the Apennines, where continental collision ended subduction, subduction of oceanic crust continues in Calabria to today (Wortel and Spakman, 2000; Chiarabba et al., 2009). The age of the start of subduction is poorly known—some argue for an earlier, Cretaceous age (Amodio-Morelli et al., 1976; Cello et al., 1996) while others consider the subduction system to be a relatively late feature, perhaps Eocene in age (Rossetti et al., 2001, 2004).

Geologically, Calabria can be divided into two segments which record different histories—Northern Calabria and Southern Calabria (Bonardi et al., 2001; Alvarez and Shimabukuro, 2009). Northern Calabria preserves high-pressure/low-temperature (HP/LT) Alpine metamorphic units, some of which are dismembered ophiolites, and is much different than Southern Calabria, including the Peloritani Mountains of northeast Sicily, which lacks these HP/LT units and instead has large exposures of Hercynian-aged crust (Platt and Compagnoni, 1990; Messina et al., 2004). The present study focuses on the more complete record preserved in Northern Calabria (Figure 2).

Here, a cross-section through both the upper and lower plate of an Alpine-aged accretionary system is exposed (Amodio-Morelli et al., 1976; Bonardi et al., 2001). The upper plate of the subduction zone consists of the Herycnian-aged Sila Unit consisting of migmatitic lower crust, a batholithic layer, and upper-crustal schists and phyllites (Graessner and Schenk, 2001) (Figure 3). A thin Mesozoic sedimentary succession is deposited above these crystalline rocks. These units underwent only minor deformation and metamorphism during the Alpine even. Beneath the Sila Unit is a mylonitic zone metamorphic pressure discontinuity; units below all have the blueschist-facies metamorphism characteristic of Alpine-aged subduction (Langone et al., 2006; Piccarreta, 1981).

The uppermost units that were subducted during the Alpine-aged orogen, the Bagni and Castagna Units, are made up of Herycnian-aged protoliths (Amodio-Morelli et al., 1976; Dietrich et al., 1976). These two units probably represent pieces of thinned continental crust which were the first-subducted units of the Calabrian system. Both have an Alpine-aged blueschist overprint (Colonna and Piccarrea, 1975; Piccarreta, 1981; also Chapter 1 and 2 of this thesis).

Below are the blueschist-metamorphosed Calabrian ophiolite units (De Roever, 1972; Spadea, 1994; Tortorici et al., 2009). Although they are referred to as ophiolites, they do not represent complete ophiolite sequences; instead, they are dismembered fragments of serpentinite, metabasalt, and sedimentary cover that were scraped off the downgoing Tethyan plate and are more similar to Franciscan-style ophiolites (Dilek, 2003). They are exposed at the same structural level across the 130-km long orogen, however, due to difference in metamorphic grade, they have been given several different names: in the north, the Diamante-Terranova Unit (Spadea et al., 1976), in the central part, the Fuscaldo and Malvito Units (De Roever, 1972; Dietrich, 1976; Liberi et al., 2006), and in the south, the Monte Reventino-Gimigliano Unit (Piccarreta and Zirpoli, 1969; Alvarez, 2005). No agreement exists on their relationship with each other, although their peak metamorphic grade seems to be similar, varying between lawsonite-blueschist and albite-lawsonite facies, with peak pressures of ~1.0 GPa (Rossetti et al., 2001, 2004; Liberi et al., 2006).

The lowest unit of the subduction stack is the Verbicaro Unit, a group of Triassic-Jurassic platform carbonates outcropping in several tectonic windows in Northern Calabria (Amodio-Morelli et al., 1976; Iannace et al., 2005, 2007). It is not clear whether these are isolated basement blocks (Rossetti et al., 2001, 2004), or whether they are fensters into a mostly-buried section of the Adria microplate (Chiarabba et al., 2008). The presence of Mg-carpholite phyllite sequence overlying the carbonates indicates that they were buried to blueschist-facies conditions (Iannace et al., 2005).

This present study focuses on the Diamante-Terranova Unit, which is regarded as the highest-grade of the Calabria ophiolite units (De Roever, 1972; Spadea et al., 1976; Liberi et al., 2006). Because of its excellent exposure, both in seaside outcrops near Diamante, and along ravines near Terranova da Sibari, this unit has been studied by several previous groups who agree on its peak blueschist-facies metamorphic grade, but disagree on the interpretation of the structural history of the outcrop (top-to-the-NW compression, as in Cello et al. (1991, 1996) and Liberi et al., (2006), or top-to-the-NE compression followed by top-to-the-NW extension, as in Rossetti et al. (2004)).

The best outcrops of the Diamante-Terranova Unit are preserved about 2 km south of the town of Diamante, Calabria, along the waterfront at the La Guardiola locality (39°40'15.58"N, 15°49'37.87"E, WGS84). Below a beachfront restaurant, a 200-m section of metabasalt and its sedimentary cover is exposed along a small peninsula. These metabasalts are banded, with deep blue lawsonite blueschist interlayered with pistachio-green epidote blueschist. Along the margins, the carbonate and metapelitic cover of the metabasalt unit is exposed.

METAMORPHIC FRAMEWORK

The metabasalts at Diamante consist of alternating blue- and green-colored bands. These bands are composed of different mineral assemblages, indicating metamorphism in different metamorphic facies (Chapter 2 of this thesis). The blue layers, metamorphosed in the lawsonite-blueschist facies, are made up of Na-amphibole + lawsonite + omphacite + phengite + albite + quartz + calcite + titanite ± aragonite (Cello et al., 1996; Liberi et al., 2006). Green layers are epidote blueschist; they are made of Na-amphibole + epidote + albite + quartz + calcite + titanite ± lawsonite ± pumpellyite ± actinolite ± aragonite. Some of these layers are composed nearly entirely of epidote.

The two distinct metamorphic facies in the rock are due to different compositions in blue and green layers. Blue layers tend to be more reduced—indicated by the lack of Fe^{3+}-bearing phases, such as epidote and riebeckite—while green layers are more oxidized, as indicated by the presence of Fe^{3+}-bearing epidote. The compositional variation was likely inherited from the seafloor-metamorphosed basaltic protolith.

As discussed in Chapter 2, we have inferred a sequence of metamorphic events for these rocks based on petrological work on the lawsonite-blueschist- and epidote-blueschist-layers. The 4-stage metamorphic history is summarized here (Figure 4).

M_a, early prograde phase: This event is attested to by relic epidote in riebeckite-to-crossite cores of Na-amphibole, indicating epidote-blueschist conditions.

M_b, peak pressure phase: This event took place in the lawsonite-blueschist facies in the blue layers and epidote-blueschist facies in the green layers. Zoned Na-amphiboles, which may indicate both prograde burial and the beginning of retrograde exhumation, have Al_2O_3 values of up to 11% (Chapter 2). Omphacite (Jd=50%) and phengite (Si^{4+}=3.5) are present in blue layers, allowing for the estimation of 9-11 kbar peak metamorphic pressures, at temperatures around 350 ºC (Liberi et al., 2006).

M_c, early retrograde metamorphic event: In this event, coarse-grained lawsonite overgrew both Na-amphibole and epidote crystals. The poikiloblastic lawsonite encloses shear bands indicating syn-kinematic growth. This event takes place in the lawsonite-albite facies of De

Roever (1972), or in the more widely used pumpellyite-actinolite subgreenschist facies (Banno, 1998; Evans, 1990).

M_d, late retrograde metamorphic event: A late coarse, opaque mat, composed of pumpellyite, albite, lawsonite, and actinolite, indicates a low-temperature metamorphic event, probably also in the pumpellyite-actinolite facies. Actinolite, when present, is in equilibrium with pumpellyite. Based on Si^{4+} in phengite, conditions are likely to be around 3 kbar (Liberi et al., 2006).

We have not found the greenschist overprint previously reported by other workers at Diamante (Cello et al., 1996; Rossetti et al., 2004). The distinctive green-blue banding visible in outcrop is due to alternating green epidote-blueschist and blue lawsonite-blueschist layers, not due to interlayering between greenschist and blueschist (Chapter 2). Green-colored pumpellyite-actinolite-facies metamorphism is widespread, especially along late crenulations and shear bands. Late actinolite is present as part of the pumpellyite-actinolite facies; the presence of pumpellyite in equilibrium with actinolite places the P-T path to the low-temperature side of the sub-greenschist to greenschist facies boundary (Banno, 1998).

A cool exhumation path is consistent with the presence of lawsonite and aragonite, formed during the peak and retrograde metamorphic phases. Since these minerals cannot survive temperatures associated with greenschist-facies exhumation, the rocks at Diamante probably came to the surface in the subduction channel, retracing the P-T path by which they were buried (Ballevre et al., 2003).

The metamorphic P-T-t path shown in Figure 4 has a slightly counterclockwise P-T-t path, with the retrograde exhumation taking place in cool conditions. This is different from the general exhumation pattern observed in the wider Alpine Orogen, where clockwise P-T paths resulting from a late greenschist-facies overprint are common (Ernst, 1988; Agard et al., 2009).

This counterclockwise P-T path is important in interpreting structural and geochronological observations at Diamante. If structural fabrics can be correlated with individual metamorphic events, then it may be possible to interpret structural directions in terms of burial or exhumation. In addition, the lack of a greenschist overprint means that the Ar/Ar system in white micas will record the age of blueschist-facies metamorphism, which will aid in interpreting the deformation in a regional context.

STRUCTURAL OBSERVATIONS

The outcrop at La Guardiola, 2 km south of Diamante town, was mapped at a scale of 1:1000, with special emphasis on the ductile and brittle-ductile deformation features (Figures 5a-5c). The base map was traced from an aerial photo of the Diamante area. As this photo was taken near high tide, several outcrops that were occasionally visible throughout a two-week period were not present in the photograph. Because of difficulty of access and poor exposure, these outcrops, which were often underwater, were not mapped. Previous metamorphic petrology and structural work was done by Cello et al. (1996, 2001), Rossetti et al. (2004), and Liberi et al. (2006). Rossetti et al. (2004) included a rough sketch map with several structural data points.

We divided the structural history of the Diamante outcrop into four structural phases, which are not necessarily coincident with the four metamorphic phases (Figure 6). The structural data were plotted with the computer program GEOrient, v. 9.4.4, by Rod Holcombe. As the deformational phases are similar in the metabasalts and the carbonate cover, we will describe them together.

Protolith: The protolith of a majority of rocks exposed at Diamante was ocean floor basalt, interbedded in places with minor carbonates (Liberi et al., 2006). The basalts were compositionally variable, especially with respect to oxidation state; this led to epidote-rich layers and lawsonite-rich layers forming during later subduction (Chapter 2 of this thesis). The compositional variation may be due to hydrothermal alteration of seafloor basalts or hyaloclastites (Spooner and Fyfe, 1973; Cello et al., 1996). A calcschist unit is in depositional contact with the south edge of outcrop; however, no stratigraphic-up indicators have been observed in this unit. Thus, it is not possible to determine if the calcschist is above or below the metabasalt.

The original lithological layering defines S0 bedding; these same planar units are deformed during D1. Isoclinal fold hinges can be seen in metabasalts in outcrop (Figure 7a), in thin section (Liberi et al., 2006), and as cm-scale rootless fold-hinges in the calcareous schist which covers the metabasalt (Figure 7b; Cello et al., 1996).

D1: At Diamante, the main structural fabric in the metabasalts is a LS-tectonite (Figure 7c). The main foliation in the metabasalts, S1, dips to the SE, and is defined by interlayered lawsonite-blueschist and epidote-blueschist (Figure 6, S1). In the metacarbonate cover, the foliation is defined by a spaced cleavage of phengitic mica, which demarcates calcite-rich domains. In both cases, the foliation was developed subparallel to compositional layering.

A strong mineral lineation, L1, is present on the lawsonite-blueschist surfaces, in the form of aligned Na-amphiboles trending NW-SE (Figure 7d) (Figure 6, L1). The lineation is particularly well developed in the coarse-grained layers, which have been interpreted as metamorphosed diabase dikes (Cello et al, 1996; Liberi et al., 2006). L1 is less obvious in epidote-blueschist layers because of the lack of shape-anisotropic minerals—Na-amphibole is rarely visible at the outcrop and epidote is equant and is not pulled into parallelism with strain axis.

The S1 fabric is axial planar to F1 folds, as indicated by rare transposed fold limbs in thin section (Liberi et al., 2006), and rootless folds in the metacarbonate cover (Figure 7b). Since we only rarely observed F1 fold hinges in the metabasalts (Figure 7a), it was not possible to test whether the lineation present on the foliation surface wraps around the fold hinges. Therefore, by parsimony, we will assume that the lineation originated at the same time as the S1 foliation, and term it L1.

The prograde fabric of D1 developed in M_b blueschist-facies conditions. Depending on layer composition, metamorphism took place in the lawsonite-blueschist or epidote-blueschist facies (M_b). Since it seems to be the result of progressive deformation and transposition of an original planar structure (S0) resulting in appressed fold hinges, it is likely that this is a compressional phase.

Although a SW-NE mineral lineation in the carbonate cover was reported in Cello et al. (1996, their Figure 3b), it appears that this is actually an intersection lineation between a later SW-NE trending crenulation, D3, and the S1 foliation surface.

D2: During this phase, epidote-blueschist layers formed during M_b, were broken into sub-rectangular blocks, which are turn rotated in a sense of motion consistent with top-to-the-southeast shear (Figure 8a-8d). As these are similar in appearance to tilted books on a bookshelf, they are known as bookshelf boudins, or domino boudins (Simpson and De Paor, 1993; Goscombe and Passchier, 2003; Passchier and Trouw, 2007).

In the majority of cases the boudin is flush with the adjacent boudin (Figure 8a); in a minority, an extensional component allowed for mineral growth between the boudins (Figure 8b-8d), defining a second stretching direction, L2 (Figure 6, L2). This shear direction is sub-parallel to the earlier NW-SE mineral lineations present as L1. Importantly, there is a strong asymmetry in broken boudins, which allows the determination of a top-to-the-southeast sense of shear. A small area of the southern part of the outcrop records a top-to-the-north sense of shear; this is discussed in the D4 structural phase.

As asymmetrical boudins can be confused with other features, Goscombe and Passchier (2003) offer several criteria to evaluate whether the boudins are reliable determinants of shear sense. Our boudin axes are perpendicular to the stretching lineation in the rock, the boudin shape corresponds to domino-shaped boudins, and they are foliation parallel, thus indicating that these boudins indicate a sense of shear.

In addition to L2 direction, the mineral growth in some of the boudin veins offers another benefit—although most are calcite, glaucophane and lawsonite are often present, indicating that deformation took place in lawsonite-blueschist facies conditions (M_b) (Figure 9a, 9b). The presence of lawsonite, in particular, limits temperatures to the low temperature side of the epidote-lawsonite equilibrium (Figure 9b) (Evans, 1990). In addition, the Na-amphiboles from the veins are zoned, varying from glaucophane-rich in the cores to crossite-rich at the rims (Figure 9c). This decrease in Al^{3+} content is qualitatively indicative of decreasing pressures (Trzcienski et al., 1984; Murayama et al., 1986; Banno, 1998; Schulz et al., 2001).

Since the shear directions, and metamorphic conditions, of this deformational episode are the same as the previous deformation, D1, it is useful to consider whether it is a distinct stage of deformation. The sheared boudins are composed of epidote-blueschist-facies metabasalt, while the surrounding matrix is lawsonite blueschist metabasalt. Both of these layers are foliated, and the foliation is cut by a later veins associated with boudin formation, usually filled with calcite in spaces created by rotation of the rigid blocks (Figure 8b). For this to have occurred, the shear event must have taken place after the formation of the epidote-blueschist and lawsonite-blueschist main foliation (S1) because a rheological difference between the boudin and the enclosing matrix was necessary for the formation of the boudins.

D3: This phase of deformation is represented by penetrative crenulation associated with meter-scale folds (Figure 6, L3, F3) (Figure 10a). The fold axes and the crenulation axes trend ~NW-SE. This is consistent with a SW-NE shortening direction—different from main tectonic direction indicated by D2. In places, the crenulation has a distinct top to-the-east asymmetry (Figure 10b), while in other places, the folds do not give a good sense of vergence.

Shear bands, consisting of both SC- and SC'-tectonites, rotate glaucophane and lawsonite during this phase of deformation (Figure 11). We believe these are the shear bands that Cello et al. (1996) identified as an SC-tectonites, using them to infer a top-to-the-west sense of shear. However, we have reviewed the original thin section set from that study and observe similar features with both top-to-the-east and top-to-the west senses of shear (Figure 11). Because both vergences exist on such small scales, these are most likely parasitic folds on opposite limbs of larger folds (Ramsay and Huber, 1987; Frehner and Schmalholz, 2006). Because of this inconsistency in directions, it is impossible to determine a predominant shear direction.

This phase of deformation was synchronous with the late, pumpellyite-actinolite facies overprint seen in the outcrop (metamorphic phase M_d).

D4: Instead of the top-to-the-southeast D2 sense of shear observed in boudins in the northern part of the outcrop, boudins in the southern part of the outcrop indicate a top-to-the-north sense of shear (Figure 5b). We will briefly consider two possibilities to explain this anomalous sense of shear and late phase of deformation.

1. A vertical-axis rotation may have affected a fault-bounded block. In this case, the top-to-the-southeast vergent shear directions would have been rotated counterclockwise by about 120°. However, this would have led to a rotation of all early-formed features, including crenulations and fold directions. Such a rotation is not observed—crenulations, and fold axes, maintain a similar direction throughout the outcrop.
2. The beach area may represent an overturned limb of a recumbent fold. In this case, the shear directions may have been overturned and inverted. However, the foliation of the rocks can be traced nearly continuously across the outcrop and there is no place where foliation overturns and stays that way.

Further mapping, at a regional scale, will be needed to understanding this stage of deformation.

AGE OF DEFORMATION USING AR/AR GEOCHRONOLOGY

In order to determine the age of deformation, we collected coarse-grained phengite from the metabasalt near the northern end of the outcrop for Ar/Ar dating. The micas were sampled from a pod in the S1 foliation which was formed in lawsonite-blueschist-facies conditions (Figure 10c).

The geochronology was performed by Su-chin Chang at AGES (Argon Geochronology for the Earth Sciences) at Columbia University's Lamont-Doherty Earth Observatory. The mica, along with bracketing standards of Fish Canyon sanidine with an age of 28.2 Ma (Kuiper et al., 2008), was irradiated for 8 hours at the USGS TRIGA reactor in Denver, CO, USA (Renne et al., 1998). After irradiation, all standards and samples were degassed using an automated CO_2 laser-based extraction system and analyzed with a Micromass VG 5400 mass spectrometer.

Two separate aliquots of the sample were run in the mass spectrometer: the first contained a single large mica flake, while the second consisted of five smaller grains. For the first aliquot, the age spectrum did not yield a well-defined plateau; we instead determined an integrated age of 46.7 ± 0.4 Ma (Figure 12). Since only seven heating steps were used, it is possible that a plateau is hidden in the data. In fact, heating steps 5 and 7 would form a plateau, except for the excursion in heating step 6. This may be due to an inclusion in the mica.

There is evidence for slight metamorphic reheating of the sample—the low temperature ages are slightly younger than the high temperature ages. The inverse isochron from this sample was not useful, as all heating steps had the same ratio of radiogenic argon to non-radiogenic argon.

The second aliquot, consisting of the smaller micas, also lacked a plateau, giving an integrated age of 36.18 ± 0.08 Ma, along with an isochron age of 35.4 ± 1.6 Ma (Figure 12b). The spectrum starts out with a lower age, rising toward a higher age as more Ar is released. This may indicate that a late episode of heating slightly perturbed the system. Note, in comparing Figures 12a and 12b, that the non-plateau steps of the smaller micas is confined to an interval of only 4 Myr.

Due to the younger ages, we interpret the smaller micas to represent a later crystallization event, taking place in blueschist-facies conditions. This is consistent with the observation by Liberi et al. (2006) of two generations of phengite in the Diamante blueschist. The discussion that follows will focus on the larger mica, with a date of 46.7 ± 0.4 Ma.

In high-pressure rocks exhumed in collisional belts, Ar/Ar dates on phengitic micas are often interpreted to be the age of exhumation (Brocker et al., 2004). This is because the temperature of greenschist-facies retrograde metamorphism common in collisional orogens is higher than the Ar closure temperature of 350 ± 50 ºC in white micas. However, at Diamante, petrological evidence indicates that the rocks were never subject to greenschist conditions (Chapter 2). Instead, temperatures remained in the lawsonite- and aragonite-stable zone—below 350 º—during their exhumation path (Liberi et al., 2006; Chapter 2 of this thesis). Indeed, there is the possibility that temperatures remained much lower: a zircon fission-track age from the Malvito Unit, one of the Calabrian blueschist units, records an age of 136 ± 20 Ma, indicating have remained below ~260 ºC since the formation of the Tethyan basaltic protolith (Thomson, 1994, 1998). These low retrograde temperatures mean that the Ar/Ar dates from phengites at Diamante can be interpreted as the crystallization age of the mica, and therefore the age of blueschist-facies metamorphism.

The 46 Ma date is Alpine in age, and somewhat older than ages that have been determined in recent studies. Rossetti et al. (2001, their Figure 13), using the Ar/Ar system on phengites in the Gimigliano Unit, measured total gas ages of 30.8 ± 0.1 Ma and 33.5 ± 0.1 Ma. As the age spectra of these measurements had a stair-step pattern, they inferred the presence of two thermal events: one, an original crystallization event, and the other a perturbation by a later heating event (Rossetti et al., 2001). This is consistent with their estimates of peak metamorphic of 400 ºC ("low-grade greenschist"), which was based on the lack of aragonite in pelites and marbles and the presence of epidote. This metamorphic temperature is near the closure temperature of Ar/Ar in white mica (Rossetti et al., 2001). They note that temperatures were not high enough during exhumation to fully reset the Ar system in the micas.

Our date is consistent with biostratigraphy from the Terranova sector of the Diamante-Terranova Unit. In a gully, just outside of the town of Terranova da Sibari, limestone breccias bearing Discocyclines nummulites of Lutetian age (48.6-40 Ma) are overthrust by blueschist-facies nappes (Bouillin, 1984; Wallis et al., 1993). The presence of Lutetian fauna in the subducted material indicates that the unit was subducted after ~48 Ma.

Our new radiometric date of 46 Ma can help us interpret the structural data in the context of regional tectonics. Arc-related volcanism in Sardinia is as old as 38.26 Ma, indicating that at that time, subduction existed beneath Sardinia (Lustrino et al., 2009). Based on subduction velocities of 1 to 3 cm/yr, at a 45º angle, and an 80 km depth of melting, these ages of volcanism indicate that Apennine subduction must have begun by 49 to 42 Ma (Lustrino et al., 2009).

This Sardinia volcanism continued through the Miocene (Savelli, 1988); at that time a west-dipping subduction zone had been established; thus, the early Sardinia volcanics must be part of the same west-dipping subduction zone (Lustrino et al., 2009). If these rocks were accreted as part of a west-dipping subduction system, they are most likely associated with an east-vergent orogeny. Thus, we can interpret the structural deformation at Diamante as taking place in an east-vergent orogenic belt. The date is not consistent with the rocks at Diamante representing a Cretaceous-aged west-vergent system (Cello et al., 1996).

STRUCTURAL INTERPRETATION

This structural study was done with the hope using the D2 shear directions indicated by domino boudins to determine the direction of orogenic transport. However, observations presented in Chapter 4, from other ophiolite-bearing localities in Calabria, suggest that the block at Diamante may be a block within an orogen-scale mélange.

Because of poor rock exposure, determining the relationship of the Diamante metabasalt to the rocks surrounding it requires studying analogous outcrops. Exposures of metabasalt near Terranova da Sibari are considered to be equivalent to those at Diamante (Amodio-Morelli et al., 1976; Spadea et al., 1976; Liberi et al., 2006). At these localities, the metabasalt does not represent a coherent unit; instead, it appears to be dismembered blocks in a calcschist matrix, alongside pillow basalt, chert, and granite (Chapter 4 of this thesis) (Spadea et al., 1976; Tortorici et al., 2009). The calcschist encloses many of these blocks, indicating that they are sedimentary blocks, likely emplaced by underwater landslides onto the seafloor (Tortorici et al., 2009). In that case, the blocks most likely preserve a metamorphic and structural history distinct from their surrounding matrix.

Indeed, our new geochronology supports the idea that the Diamante block is recycled from an earlier stage of subduction. The large micas record an age of ~48 Ma, while the small micas were formed at ~36 Ma. If these dates are taken to be the age of rocks at Terranova da Sibari, they must be understood in the context of the Lutetian (48.6-40.4 Ma) fossils found to overlie the unit (Bouillin, 1984). Neither extensional nor contractional tectonics does a good job of explaining the map relations between the units; however, they are readily explained if the Diamante block was metamorphosed at 48 Ma, exhumed onto the seafloor, covered with Eocene sediment, then re-subducted (see Chapter 4). Similar multi-cycle episodes of subduction are increasingly being recognized in other orogens (Wakabayashi, 2011a, 2011b; also Chapter 4 of this thesis).

If the mélange fabric observed at Terranova da Sibari extends to Diamante, then our D1 and D2 structural measurements may not be indicative of deformation in the orogen. Instead, they may have been inherited from an earlier phase of subduction, previous to their exhumation and re-deposition within a trench. The only distinctive indicator in the Diamante block relevant to its current position may be the D3 top-to-the-east overturned folds, based on their metamorphism in the lawsonite-albite facies—same as the surrounding matrix.

Indeed, these D3 shear directions at Diamante are consistent with several other studies of the Calabrian Arc. Rossetti et al. (2001, 2004) report ENE-shear directions from ophiolite units across the orogen. Dietrich (1988) used mineral lineations to determine shear directions, finding NE-directed shear in the Gimigliano and Malvito Units. Several studies from the Frido Unit indicate the presence of NE-directed shear indicators (Knott, 1987; Monaco, 1993; Monaco and Tortorici, 1995; Monaco et al., 1998). These studies must be interpreted cautiously, as the deformation was not always clearly linked with a metamorphic event; hence, they may indicate either shortening or extension.

The final stage of deformation, D4, took place in the brittle-ductile field. It is not clear what the tectonic cause of this deformation is. Cello et al. (1996) suggest that exhumation took place along transpressional faults, perhaps as pop-up, or flower, structures. There is, however, the added complication of shear directions which locally are top-to-the-north which highlights the structural complications at this outcrop.

In summary, the first two phases of deformation, D1 and D2, may record events which took place much earlier in the history of the subduction zone. The final two phases, D3 and D4, likely represent the deformation which affected the entire Diamante-Terranova Unit. Even without clear structural indicators, we can use the geochronology to help us interpret the orogenic belt.

DISCUSSION AND CONCLUSIONS: HOW DOES CALABRIA CONNECT TO THE REST OF THE ALPINE SUBDUCTION ZONE?

Our conclusion from the geochronology presented is that west-dipping subduction existed beneath Calabria at 46 Ma; this is earlier than has been suggested in other studies. At that time, before Tyrrhenian rifting began, Calabria was part of the Corsica-Sardinia continental margin. The subduction zone beneath Calabria continued, in some form, along-strike northward into the blueschist-facies Schiste Lustrés nappe of Corsica and the western Alps (Alvarez, 1974; Alvarez, 1991; Rosenbaum and Lister, 2005; Argnani, 2009).

Most of the evidence regarding the early history of the Apennine-Calabria subduction system has come from Corsica, due to the good exposures of blueschist- and eclogite-facies rocks (Gibbons et al., 1986; Waters, 1989). These rocks contain early, west-vergent fabrics that have been interpreted to have been formed in a Cretaceous, east-dipping subduction zone (Jolivet et al., 2003; Molli et al., 2006; Molli, 2008). Although it is clear that these west-vergent fabrics passed northward into the western Alps there is disagreement—as discussed in the present paper—as to whether they passed southward into Calabria.

The difficulty in structural interpretation is partially due to the poor age constraints for the rocks in Corsica: Sm-Nd ages on garnet from eclogites in Corsica indicate a Cretaceous age for the subduction system (Cohen et al., 1981; Lahondère and Guerrot, 1997; Molli et al., 2006). However, these may be spurious ages, as nummulite fossils present in blueschist-facies rocks indicate Eocene upper-age bounds for these rocks (Brunet et al., 2000). As a consequence, many workers instead regard high-pressure metamorphism in Corsica as Eocene in age (Brunet et al., 2000; Molli and Tribuzio, 2004; Molli, 2008).

It is not clear how the west-vergent Corsican orogeny links up to the Calabria subduction system. This represents a classic problem in Western Mediterranean tectonics and several solutions have been proposed. We will briefly review and discuss them:

(1) In one view, Calabria, and the Nebbio nappe of Corsica, are part of a microcontinent which first collided with Europe over an east-dipping subduction zone, then underwent a subduction polarity flip, leading to an east-vergent orogen over a west-dipping subduction zone (Alvarez, 1974; Alvarez, 1991; Bonardi et al., 2001; Guerrera et al., 2005) (refer to Figure 1a). This view is not consistent with the synchronous west-vergent orogeny in Corsica, and east-vergent orogeny in Calabria, both active at about 46 Ma.
(2) In another view, Calabria and Corsica are part of a long-lasting east-vergent subduction system, which developed over a west-dipping subduction zone (refer to Figure 1b) (Principi and Treves, 1984; Alvarez, 1991). This idea considers the Apennines to be ancient—possibly as old as Cretaceous—and continuous with the Corsica belt. However, the lack of Cretaceous metamorphism in Calabria is not consistent with this idea.
(3) In a third view, Calabria is a bivergent subduction system, with blueschist-facies metamorphism present in the west-vergent retro-wedge of a dominantly east-vergent orogen (Rossetti et al., 2001, 2004) (Figure 14a). This view is based primarily on evidence from Corsica-Tuscany transect, where two structural vergences are visible. However, in Calabria there are no west-vergent fabrics that developed in the blueschist-facies. It is possible that a west-vergent retro-wedge was not preserved, having been destroyed by the Miocene rifting of the Tyrrhenian Sea (Kastens et al., 1988; Sartori et al., 2004).
(4) A recent view proposed by Argnani (2009) considers east-vergent Calabrian tectonics to have been active at the same time as west-vergent Corsican tectonics (Figure 14b). These two domains would have been separated by a transform fault, which would have grown as convergence continued. In the north, the west-vergent Corsican system would have flipped after the Eocene collision with Corsica occurred, resulting in the start of the east-vergent Apenninic orogeny.

The synchronous two-vergence model of Argnani (2009) solves the fundamental problem of having west-vergent Corsica tectonics active at the same time as east-vergent Calabrian orogen (Figure 15). This model also allows a west-vergent convergence in the Alps to continue at the same time as east-vergence convergence in the Apennines, as long as the two orogens are separated by a transform fault (Principi and Treves, 1984; Knott, 1987).

It is important to note that this model is not compatible with Cretaceous metamorphic ages for rocks in Corsica. Both subduction zones involve subduction of the Neotethys; thus, the initiation of subduction in the east-vergent Calabrian orogen must occur at the same time as the initiation of subduction in the west-vergent Calabrian orogen. Since the only evidence in Calabria indicates the subduction existed in the Eocene, this suggests the northern section of the subduction zone, in Corsica, may have also begun in the Eocene (Figure 15). Indeed, this is consistent with a new evaluation of the geochronological data from the Schistes Lustrés units in the Western Alps which considers the Pennides to be Eocene in age; earlier dates are considered spurious (Brunet et al., 2000; Bowtell et al., 1994; Duchêne et al., 1997; Cliff et al., 1998). Thus, the Calabria-Corsica-western Alps represented a continuous trend, with two separate vergences separated by a transform fault, where subduction leading to high-pressure metamorphism may have started in the Eocene (Rosenbaum and Lister, 2005).

ACKNOWLEDGEMENTS

I would like to thank Francesca Liberi for help collecting data in the field and Su-chin Chang for providing the geochronology. Walter Alvarez and John Wakabayashi reviewed several drafts of this chapter. I also want to thank the Locher and Alessio families of Cosenza for their kindness during my stay in Calabria.

REFERENCES

Agard, P., Yamato, P., Jolivet, L., and Burov, E., 2009, Exhumation of oceanic blueschists and eclogites in subduction zones: Timing and mechanisms: Earth-Science Reviews, v. 92, p. 53-79.

Alvarez, W., 1974, Fragmentation of the Alpine orogenic belt by microplate dispersal: Nature, v. 248, p. 309-314.

Alvarez, W., 1991, Tectonic evolution of the Corsica-Apennines-Alps region studied by the method of successive approximations: Tectonics, v. 10, p. 936-947.

Alvarez, W., and Shimabukuro, D.H., 2009, The geological relationships between Sardinia and Calabria during Alpine and Hercynian times: Bollettino della Società Geologica Italiana, v. 128, p. 257-268.

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., and Zuppetta, A.,1976, L'arco Calabro-Peloritano nella'orogene Appenninico-Maghrebide: Memorie della Società Geologica Italiana, v. 17, p. 1-60.

Argnani, A., 2009, Plate tectonics and the boundary between Alps and Apennines: Bollettino della Società Geologica Italiana, v. 128, p. 317-330.

Ballevre, M., Pitra, P., and Bohn, M., 2003, Lawsonite growth in the epidote blueschists from the Ile de Groix (Armorican Massif, France): a potential geobarometer: Journal of Metamorphic Geology, v. 21, p. 723-735.

Banno, S., 1998, Pumpellyite-actinolite facies of the Sanbagawa metamorphism: Journal of Metamorphic Geology, v. 16, p. 117-128.

Bonardi, G., Cavazza, W., Perrone, V., and Rossi, S., 2001, Calabria-Peloritani Terrane and northern Ionian Sea, in, Anatomy of an Orogen, Vai, G.B., and Martini, J.P., eds., p. 287-306: Kluwer Academic, Norwell MA.

Bosse, V., Féraud, G., Ballèvre, M., Peucat, J.-J., and Corsini, M., 2005, Rb-Sr and ^{40}Ar/^{39}Ar ages in blueschists from the Ile de Groix (Armorican Massif, France): Implications for closure mechanism in isotopic systems: Chemical Geology, v. 220, p. 21-45.

Bouillin, J.-P., 1984, Nouvelle interprétation de la liaison Apennin-Maghrébides en Calabre; conséquences sur la paléogéographie téthysienne entre Gibraltar et les Alpes: Revue de Géologie Dynamique et de Géographie Physique, v. 25, p. 321-338.

Bowtell, S.A., Cliff, R.A., and Barnicoat, A.C., 1994, Sm-Nd isotopic evidence on the age of eclogitization in the Zermatt-Saas ophiolite: Journal of Metamorphic Geology, v. 12, p. 187-196.

Brocker, M., Bieling, D., Hacker, B., and Gans, P., 2004, High-Si phengite records the time of greenschist facies overprint: implications for models suggesting megadetachments in the Aegean Sea: Journal of Metamorphic Geology, v. 22, p. 427-442.
Brun, J.-P., and Faccenna, C., 2008, Exhumation of high-pressure rocks driven by slab rollback: Earth and Planetary Science Letters, v. 282, p. 1-7.

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

Butler, R.W.H., and Freeman, S., 1996, Can crustal extension be distinguished from thrusting in the internal parts of mountain belts? A case history of the Entrelor shear zone, Western Alps: Journal of Structural Geology, v. 18, p. 909-923.

Cello, G., Morten, M., De Francesco, A.M., 1991, The tectonic significance of the Diamante-Terranova Unit (Calabria, Southern Italy) in the Alpine evolution of the northern sector of the Calabrian Arc: Bolletino della Società Geologica Italiana, v. 110, p. 685-694.

Cello, G., Invernizzi, C., and Mazzoli, S., 1996, Structural signature of tectonic processes in the Calabrian Arc, southern Italy: Evidence from the oceanic-derived Diamante-Terranova unit: Tectonics, v. 15, p.187-200.

Chiarabba, C., De Gori, P., and Speranza, F., 2008, the southern Tyrrhenian subduction zone: Deep geometry, magmatism and Plio-Pleistocene evolution: Earth and Planetary Science Letters, v. 268, p. 408-423.

Cliff, R.A., Barnicoat, A.C., and Inger, S., 1998, Early Tertiary eclogite facies metamorphism in the Monviso Ophiolite: Journal of Metamorphic Geology, v. 16, p. 447-455.

Cohen, C.R., Schweickert, R.A., Odom, A.L., 1981, Age of emplacement of the Schistes Lustrés nappe, Alpine Corsica: Tectonophysics, v. 72, p. 267-284.

Colonna, V., and Piccarreta, 1975, Metamorfismo di alta pressione/bassa temperature nei micascisti di Zangarona-Ievoli-Monte Dondolo (Sila Piccola, Calabria): Bollettino della Società Geologica Italiana, v. 94, p. 17-25.

De Roever, E.W.F., 1972, Lawsonite-albite facies metamorphism near Fuscaldo, Calabria (Southern Italy), its geological significance and petrological aspects: GUA Papers in Geology, ser. 1, v. 3, 171 p.

Dewey, J.F., Helman, M.L., Knott, S.D., Turco, E., and Hutton, D.H.W., 1989, Kinematics of the western Mediterranean, in, Coward, M.P., Dietrich, D., and Park, R.G., eds., Alpine Tectonics: Geological Society Special Publication, no. 45, p. 265-283.

Dietrich, D., 1976, La geologia della Catena Costiera tra Cetraro e Guardia Piemontese: Memorie della Società Geologica Italiana, v. 17, p. 61-121.

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

Dilek, Y., 2003, Ophiolite pulses, mantle plumes, and orogeny, in, Dilek, Y.,and Robinson, P.T., eds., Ophiolites in Earth History: Geological Society Special Publication, v. 218, p. 9-19.

Duchêne, S., Lardeaux, J.M., and Albarède, F., 1997, Exhumation of eclogites: insights from depth-time path analysis: Tectonphysics, v. 280, p. 125-140.

Ernst, W.G., 1988, Tectonic history of subduction zones inferred from retrograde blueschist P-T paths: Geology, v. 16, p. 1081-1084.

Evans, B.W., 1990, Phase relations of epidote-blueschists: Lithos, v. 25, p. 3-23.

Faure, M., 1980, Microtectonique et charriage Est-Ouest des nappes alpines profondes de Sila (Calabre-Italie meridionale): Revue de Géologie Dynamique et de Géographie Physique, v. 22, p. 135-146.

Frehner, M., and Schmalholz, S.M., 2006, Numerical simulations of parasitic folding in multilayers: Journal of Structural Geology, v. 28, p. 1647-1657.

Frey, M., De Capitani, C., and Liou, J.G., 1991, A new petrogenetic grid for low-grade metabasites: Journal of Metamorphic Geology, v. 9, p. 497-509.

Gibbons, W., Waters, C., and Warburton, J., 1986, The blueschist facies schistes lustrés of Alpine Corsica: A review, in Evans, B.W., and Brown, E.H., eds., Blueschists and eclogites: Geological Society of America Memoir 164, p. 301-311.

Goscombe, B.D., and Passchier, C.W., 2003, Asymmetric boudins as shear sense indicators—an assessment from field data: Journal of Structural Geology, v. 25, p. 272-589.

Graessner, T., and 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, v. 42, p. 931-961.

Guerrera, F., Martín-Martín, M., Perrone, V., and Tramontana, M., 2005, Tectono-sedimentary evolution of the southern branch of the Western Tethys (Maghrebian Flysch Basin and Lucanian Ocean): consequences for Western Mediterranean geodynamics: Terra Nova, v. 17, p. 358-367.

Iannace, A., Bonardi, G., D'Errico, M., Mazzoli, S., Perrone, V., and Vitale, S., 2005, Structural setting and tectonic evolution of the Apennine Units of northern Calabria: Comptes Rendus Geoscience, v. 337, p. 1541-1550.

Iannace, A., Vitale, S., D'Errico, M., Mazzoli, S., Di Staso, A., Macaione, E., Massina, A., Reddy, S.M., Somma, R., Zamparelli, V., Zattin, M., and Bonardi, G., 2007, The carbonate tectonic units of northern Calabria (Italy): A record of Apulian palaeomargin evolution and Miocene convergence, continental crust subduction, and exhumation of HP-LT rocks: Journal of the Geological Society, v. 164, p. 1165-1186.

Jolivet, L., Faccenna, C., Goffé, B., Burov, E., and Agard, P., 2003, Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean Orogens: American Journal of Science, v. 303, p. 353-409.

Kastens, K., Mascle, J., and others, 1988, ODP Leg 107 in the Tyrrhenian Sea: Insights into passive margin and back-arc basin evolution: Geological Society of America Bulletin, v. 100, p. 1140-1156.

Knott, S.D., 1987, The Liguride Complex of Southern Italy—a Cretaceous to Paleogene accretionary wedge: Tectonophysics, v. 142, p. 217-226.

Knott, S.D., 1994, Structure, kinematics and metamorphism in the Liguride Complex, southern Apennines, Italy: Journal of Structural Geology, v. 16, p. 1107-1120.

Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., and Wijbrans, J.R., 2008, Sychronizing rock clocks of Earth history: Science, v. 320, p. 500-504.

Lahondère, D., and Guerrot, C., 1997, Datation Nd-Sm du mètamorhpisme éclogitique en Corse alpine: un argument pour l'existence, au Crétacé supérieur, d'une zone de subduction active localisée le long du block corse-sarde: Géologie de la France, v. 3, p. 3-11.

Langone, A., Gueguen, E., Prosser, G., Caggianelli, A., and Rottura, A., 2006, The Curinga-Girifalco fault zone (northern Serre, Calabria) and its significance within the Alpine tectonic evolution of the western Mediterranean: Journal of Geodynamics, v. 42, p. 140-158.

Liberi, F., Morten, L., and Piluso, E., 2006, Geodynamic significance of ophiolites within the Calabrian Arc: Island Arc, v. 15, p. 26-43.

Lustrino, M., Morra, V., Fedele, L., and Franciosi, L., 2009, Beginning of the Apennine subduction system in central western Mediterranean: Constraints from Cenozoic "orogenic" magmatic activity of Sardinia, Italy: Tectonics, v. 28, TC5016, doi:10.1029/2008TC002419.

Malavieille, J., Chemenda, A., and Larroque, C., 1998, Evolutionary model for Alpine Corsica: mechanism for ophiolite emplacement and exhumation of high-pressure rocks: Terra Nova, v. 10, p. 317-322.

Malinverno, A., and Ryan, W.B.F., 1986, Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking in the lithosphere: Tectonics, v. 5, p. 227-245.

Marroni, M., and Treves, B., 1998, Hidden terranes in the Northern Apennines, Italy: A record of Late Cretacous-Oligocene transpressional tectonics: Journal of Geology, v. 106, p. 149-162.

McDougall, I., and Harrison, T.M., 1999, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method: New York, Oxford University Press, 269 p.

Messina, A., Somma, R. Macaione, E., Carbone, G., and Careri, G., 2004, Peloritani continental crust composition (southern Italy): Geological and petrochemical evidence: Bollettino della Società Geologica Italiana, v. 123, p. 405-441.

Michard, A., Chalouan, A., Feinberg, H., Goffé, B., and Montgny, R., 2002, How does the Alpine belt end between Spain and Morocco?: Bulletin de la Société de France, v. 173, p. 3-15.

Molli, G., and Tribuzio, R., 2004, Shear zones and metamorphic signature of subducted continental crust as tracers of the evolution of the Corsica/Northern Apennine orogenic system, in, Alsop, I., Holdsworth, R. E., McCaffrey, J. W., and Hand, M., eds.: Flow Process in Faults and Shear Zones, Geological Society of London, Special Publication, v. 224, p. 321–335.

Molli, G., Tribuzio, R., and Marquer, D., 2006, Deformation and metamorphism at the eastern border of the Tenda Massif (NE Corsica): a record of subduction and exhumation of continental crust: Journal of Structural Geology, v. 28, p. 1748-1766.

Molli, G., 2008, Northern Apennine-Corsica orogenic system: an updated overview, in, Siegesmund, S., Fügenschuh, B., and Froitzheim, N., eds., Tectonic Aspects of the Alpine-Dinaride-Carphathian System: Geological Society, London, Special Publication, v. 298, p. 413-442.

Monaco, C., 1993, Le unità Liguridi nel confine Calabro-Lucano (Appennino Meridionale): Revisione del dati esistenti, nuovi dati ed interpretazione: Bollettino della Società Geologica Italiano, v. 112, p. 751-769.

Monaco, C., and Tortorici, L., 1995, Tectonic role of ophiolite-bearing terranes in the development of the Southern Apennines orogenic belt: Terra Nova, v. 7, p. 153-160.

Monaco, C., Tortorici, L., and Paltrinieri, W., 1998, Structural evolution of the Lucanian Apennines, southern Italy: Journal of Structural Geology, v. 20, p. 617-638.

Passchier, C.W., and Truow, R.A.J., 2007, Microtectonics: Spring-Verlag, Berlin. 366 p.

Piccarreta, G., 1981, Deep-rooted overthrusting and blueschist metamorphism in compressive continental margins. An example from Calabria (Southern Italy): Geological Magazine, v. 118, p. 539-544.

Piccarreta, G., and Zirpoli, G., 1969, Osservationi geologico-petrografiche nella zona del M.te Reventino (Calabria): Rendiconti della Società Geological Italiana di Mineralogia e Petrologia: v. 25, p. 121-144.

Platt, J.P., 1993, Exhumation of high-pressure rocks: A review of concepts and processes: Terra Nova, v. 5, p. 119-133.

Platt, J.P., and Compagnoni, R., 1990, Alpine ductile deformation and metamorphism in a Calabrian basement nappe (Aspromonte, south Italy): Eclogae Geologicae Helvetiae, v. 83, p. 41-58.

Principi, G., and Treves, B., 1984, Il sistema Corso-Appenninico come prisma d'accrezione. Riflessi sul problema generale del limite Alpi-Appennini: Memorie della Società Geologica Italiana, v. 28, p. 549-576.

Ramsay, J.G., and Huber, M.I., 1987, The techniques of modern structural geology. Volume 2: Folds and Fractures. Academic Press, London.

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in Ar^{40}/Ar^{39} dating: Chemical Geology, v. 145, p. 117-152.

Rosenbaum, G., and Lister, G.S., 2005, The Westerns Alps from the Jurassic to Oligocene: spatio-temporal constraints and evolution reconstructions: Earth-Science Reviews, v. 69, p. 281-306.

Rossetti, F., Faccenna, C., Goffé, B., Monié, P., Argentier, A., Funiciello, R., and 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, v. 20, p. 112-133.

Rossetti, F., Goffé, B, Monié, P, Faccenna, C., and Vignaroli, G., 2004, Alpine orogenic P-T-t-deformation history of the Catena Costiera area and surrounding regions (Calabrian Arc, southern Italy): The nappe edifice of north Calabria revised with insights on the Tyrrhenian-Apennine system formation: Tectonics, v. 23, TC6011, doi:10.1029/2003TC001560.

Sartori, R., Torelli, L., Zitellini, N., Carrara, G., Magaldi, M., and Mussoni, P., 2004, Crustal features along a W-E Tyrrhenian transect from Sardinia to Campania margins (Central Mediterranean): Tectonophysics, v. 383, p. 171-192.

Savelli, C., 1988, Late Oligocene to Recent episodes of magmatism in and around the Tyrrhenian Sea: implications for the processes of opening in a young inter-arc basin of intra-arc-orogenic (Mediterranean) type: Tectonophysics, v. 146, p. 163-181.

Schulz, B., Triboulet, C., Audren, C., Pfeifer, H.-R., and Glig, A., 2001, Two-stage prograde and retrograde Variscan metamorphism of glaucophane-eclogites, blueschists and greenschsits from Ile de Groix (Brittany, France): International Journal of Earth Sciences, v. 90, p. 871-889.

Simpson, C., and De Paor, D.G., 1993, Strain and kinematic analysis in general shear zones: Journal of Structural Geology, v. 15, p. 1-20.

Spadea, P., Tortorici, L., and Lanzafame, G., 1976, Serie ofiolitifere nell'area fra Tarsia e Spezzano Albanese (Calabria): Stratigrafic, petrografic, rapporti strutturali: Memorie della Società Geologica Italiana, v. 17, p. 135-174.

Spadea, P., 1994, Calabria-Lucania ophiolites: Bollettino Geofisica Teorica Applicata, v. 36, p. 141-144.

Spooner, E.T.C., and Fyfe, W.S., 1973, Sub-sea-floor metamorphism, heat and mass transfer: Contributions to Mineralogy and Petrology, v. 42, p. 287-304.

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, v. 238, p. 331-352.

Thomson, S.N., 1998, Assessing the nature of tectonics contacts using fission-track thermochronology: An example from the Calabrian Arc, southern Italy: Terra Nova, v. 10, p. 32-36.

Tortorici, L., Catalano, S., and Monaco, C., 2009, Ophiolite-bearing mélanges in southern Italy: Geological Journal, v. 44, p. 153-166.

Trzcienski, W.E., Jr., Carmichael, D.M., and Helmstaedt, H., 1984, Zoned sodic amphibole: petrologic indicator of changing pressure and temperature during tectonism in the Bathurst Area, New Brunswick, Canada: Contributions to Mineralogy and Petrology, v. 85, p. 311-320.

Wakabayashi, J., 2011a, Mélanges of the Franciscan Complex, California: Diverse structural setting, evidence for sedimentary mixing, and their connection to subduction processes, in, Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of Formation and Societal Significance: Geological Society of America Special Paper.

Wakabayashi, J., 2011b, Subducted sedimentary serpentinite mélanges: Record of multiple burial exhumation cycles and subduction erosion: submitted to Tectonophysics.

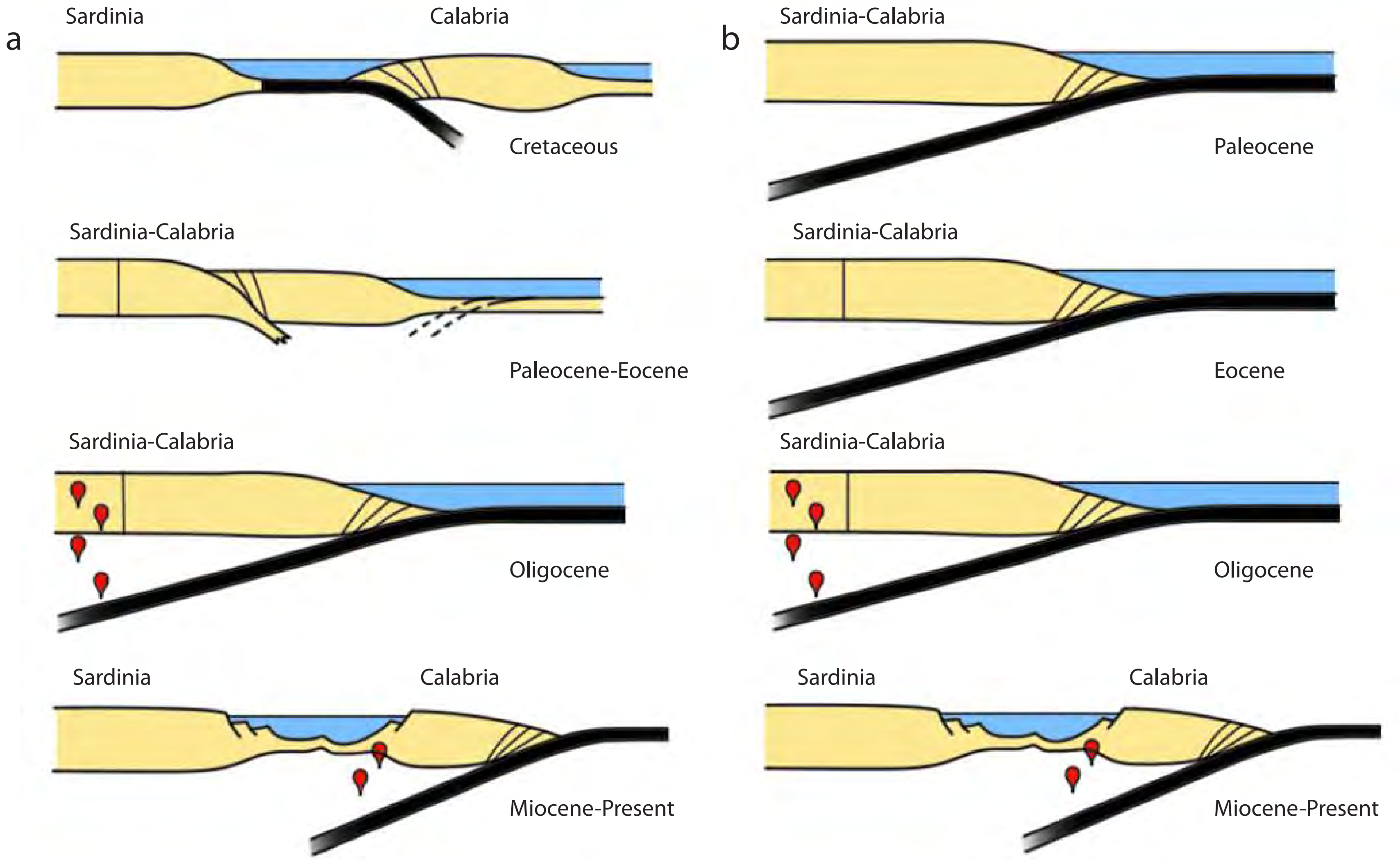
Wallis, S.R., Platt, J.P., and Knott, S.D., 1993, Recognition of syn-convergent extension in accretionary wedges with examples from the Calabrian Arc and the Eastern Alps: American Journal of Science, v. 293, p. 463-495.

Waters, C.N., 1989, The metamorphic evolution of the Schistes lustrés ophiolite, Cap Corse, Corsica, in, Daly, J.S., Cliff, R.A., and Tarley, B.W.D., eds., Evolution of Metamorphic Belts: Geological Society, London, Special Publication, no. 43, p. 557-562.

Wortel, W.J.R., and Spakman, W., 2000, Subduction and slab-detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910-1917.

Zeck, H.P., 1996, Betic-Rif orogeny: subduction of Mesozoic Tethys lithosphere under easterward drifting Iberia, slab detachment shortly before 22 Ma, and subsequent uplit and extensional tectonics: Tectonophysics, v. 254, p. 1-16.

Figure 1. There are two popular models for the tectonic history of Calabria. a) In the first, there was an east-dipping subduction zone beneath Calabria until it collided with the Corsica-Sardinia margin. After a flip in subduction polarity, a volcanic arc developed in Sardinia, above a west-dipping subduction zone. b) An alternative model considers Calabria to be the long-lasting continentla margin of the Corsica-Sardinia-Calabria block, until its Miocene rifting during formation of the Tyrrhenian Sea.



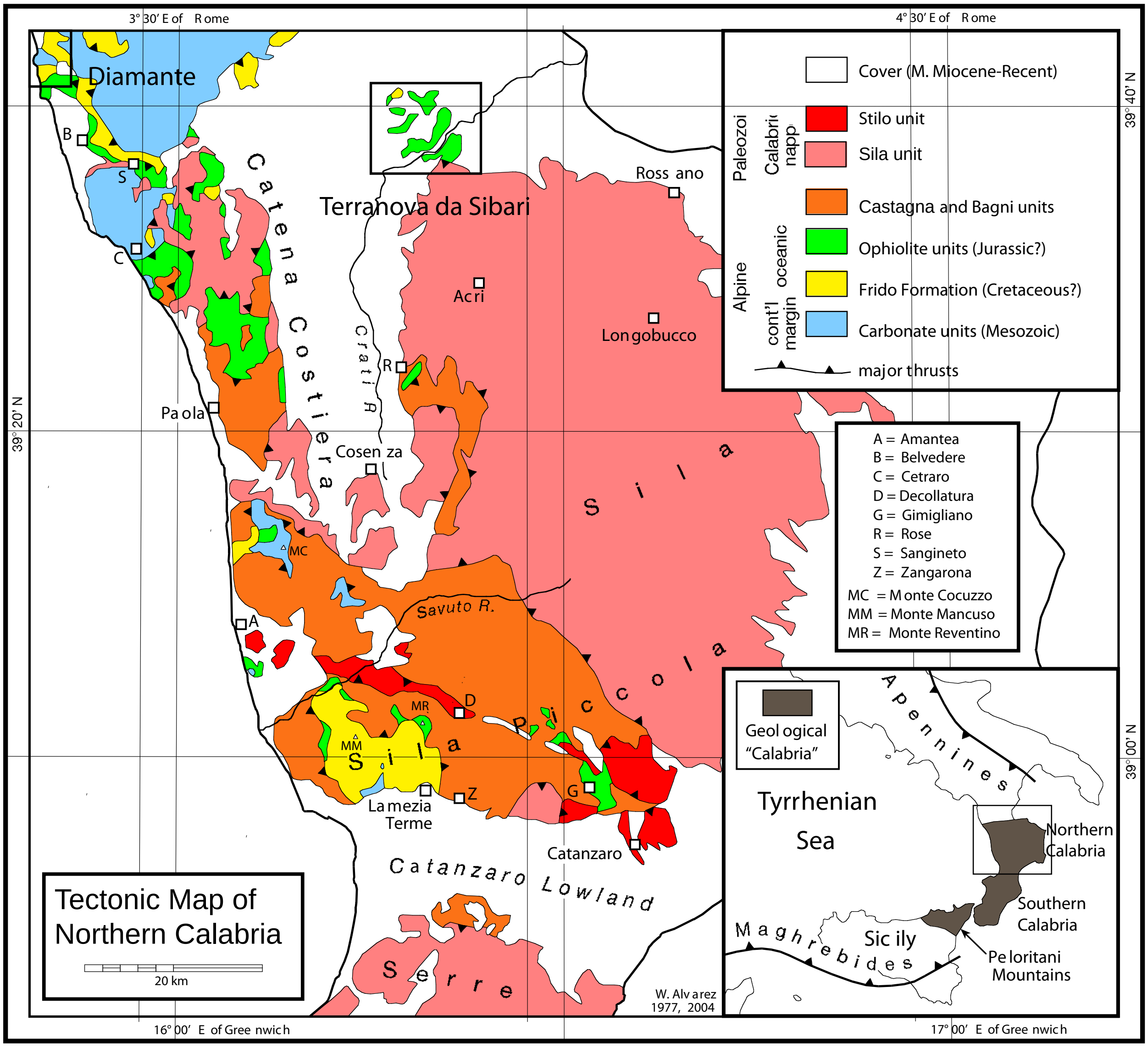


Figure 2. Tectonic map of Northern Calabria. Locations discussed in the text are boxed. The Diamante-Terranova blueschist unit is best exposed near the eponymous towns of Diamante, which was strucutrally mapped in the present study, and Terranova da Sibari.

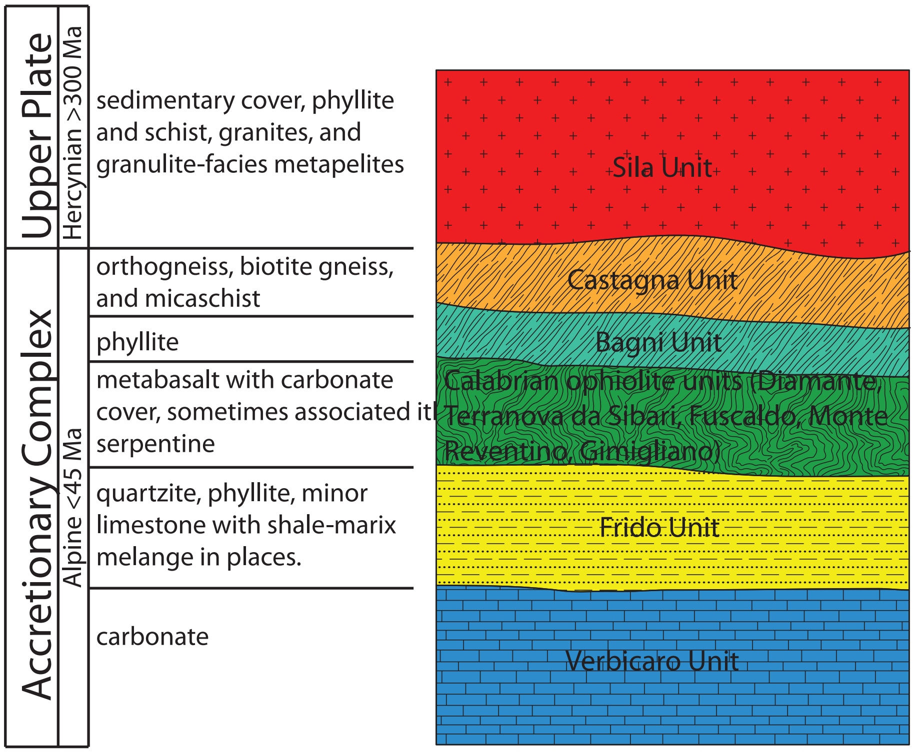
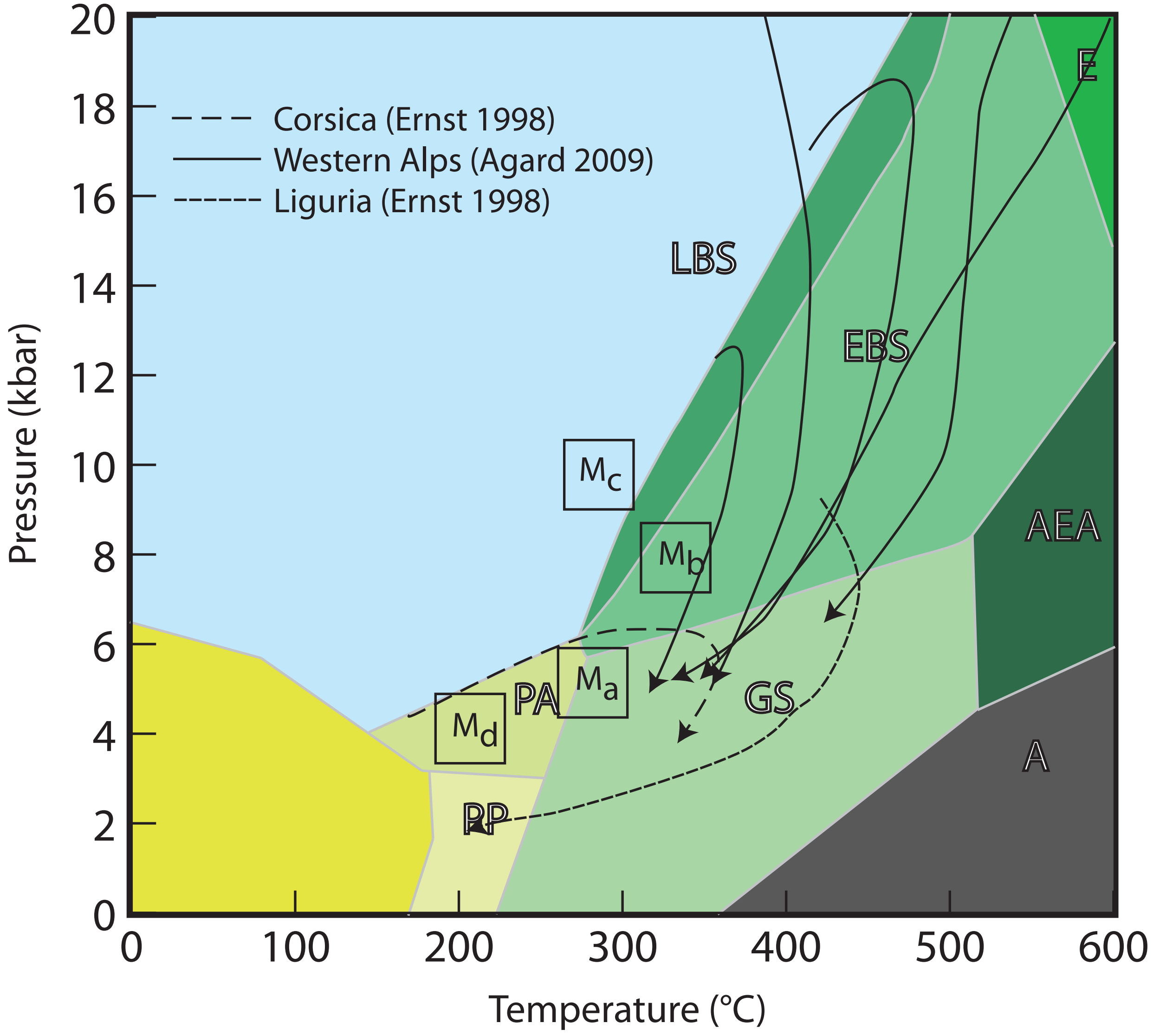


Figure 3. Tectonostratigraphy of the Calabrian Orogeny.

Figure 4. A comparison of the four metamorphic stages (Ma to Md) found in the blueschist rocks of Diamante. Sample metamorphic paths from the Alpine orogen are displayed showing the unusual hairpin/counterlcockwise pressure-temperature path takens by the Diamante blueschist.

A: Amphibolite
AEA: Albite epidote amphibolite
E: Eclogite
EBS: Epidote blueschist
LBS: Lawsonite blueschist
PA: Pumpellyite actinolite
PP: Prehnite pumpellyite



Facies boundaries from Evans (1990)

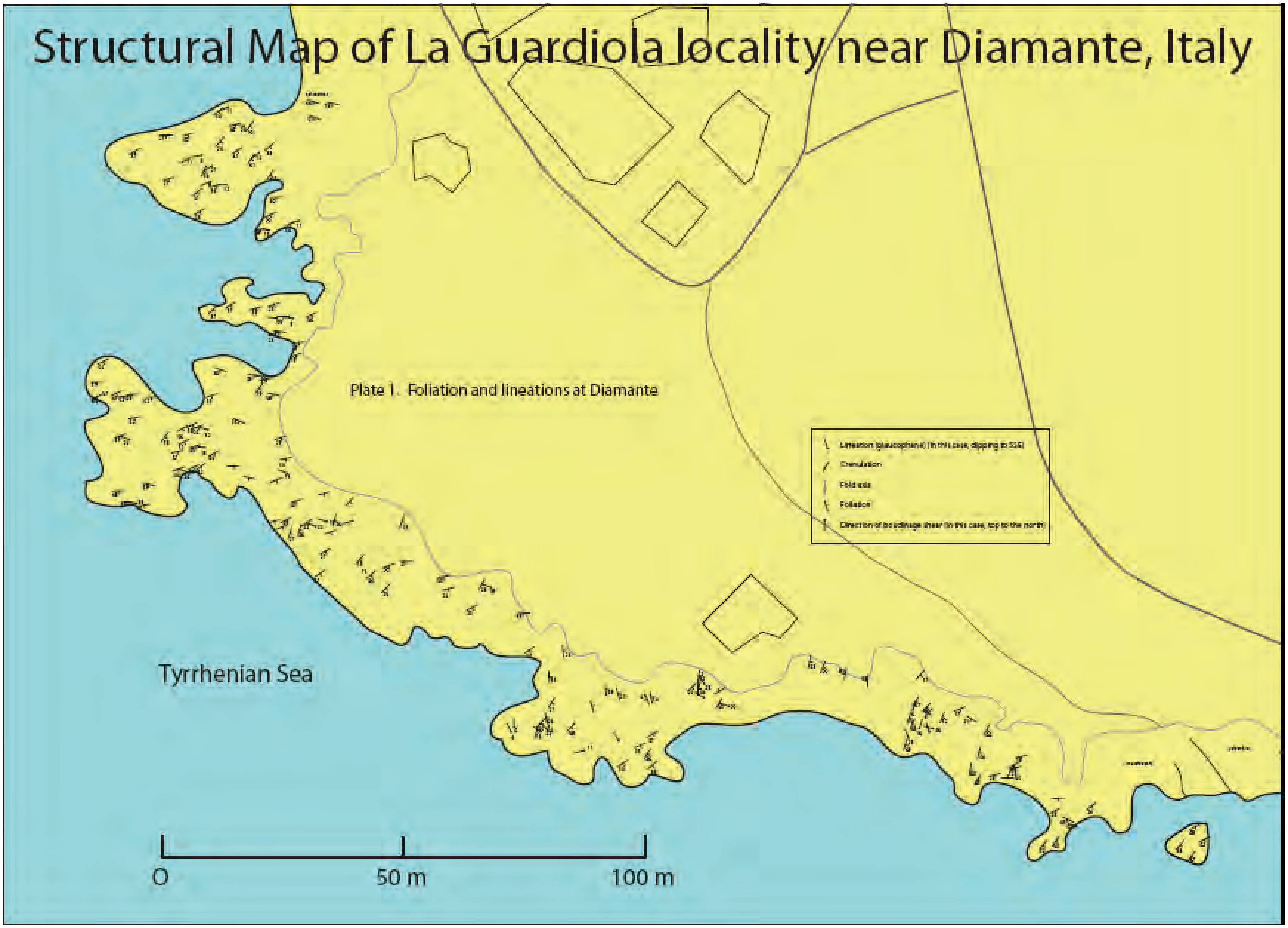


Figure 5a. Foliation and lineations at Diamante. See Plate 1 for full-sized version.

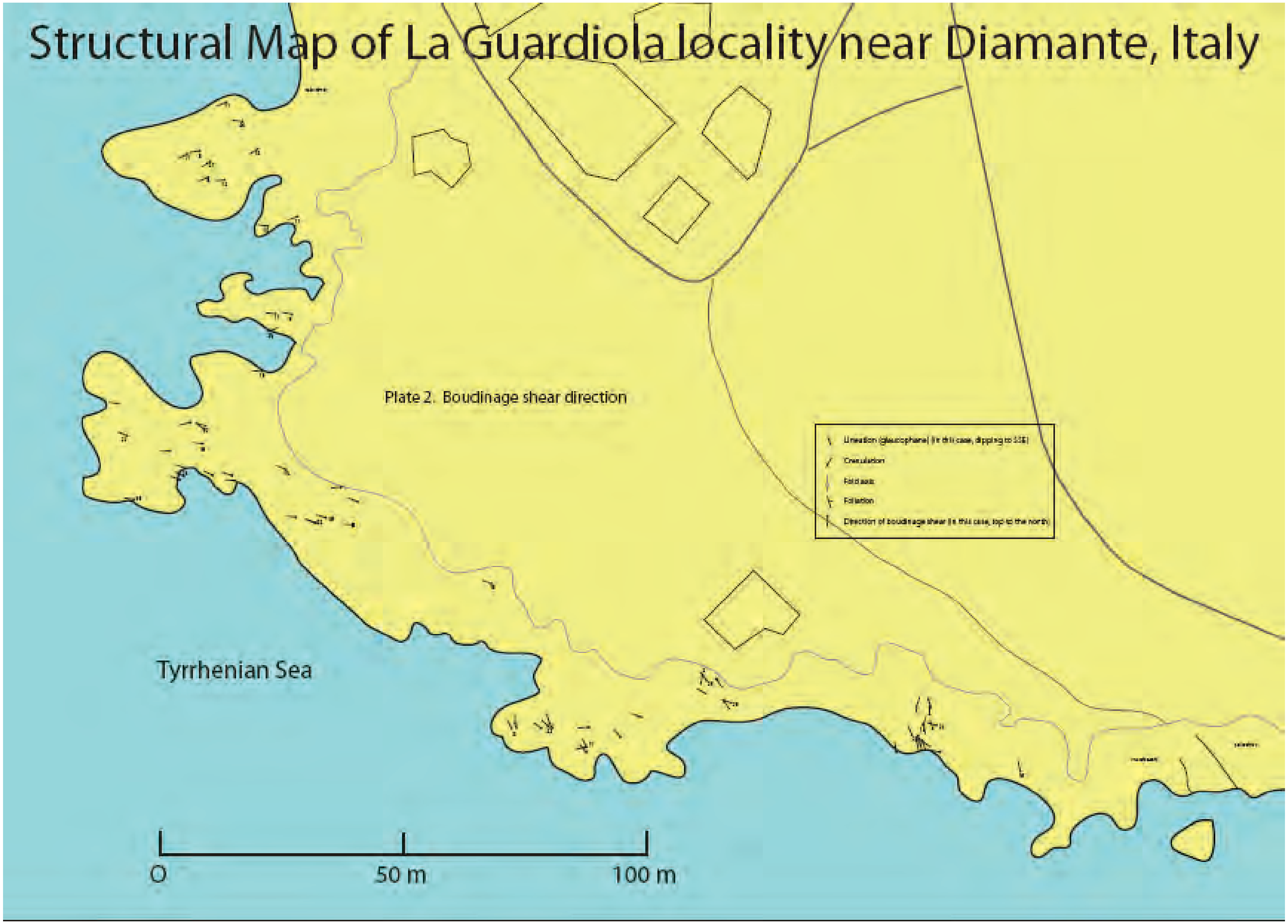


Figure 5b. Boudinage shear direction. See Plate 2 for full-sized version.

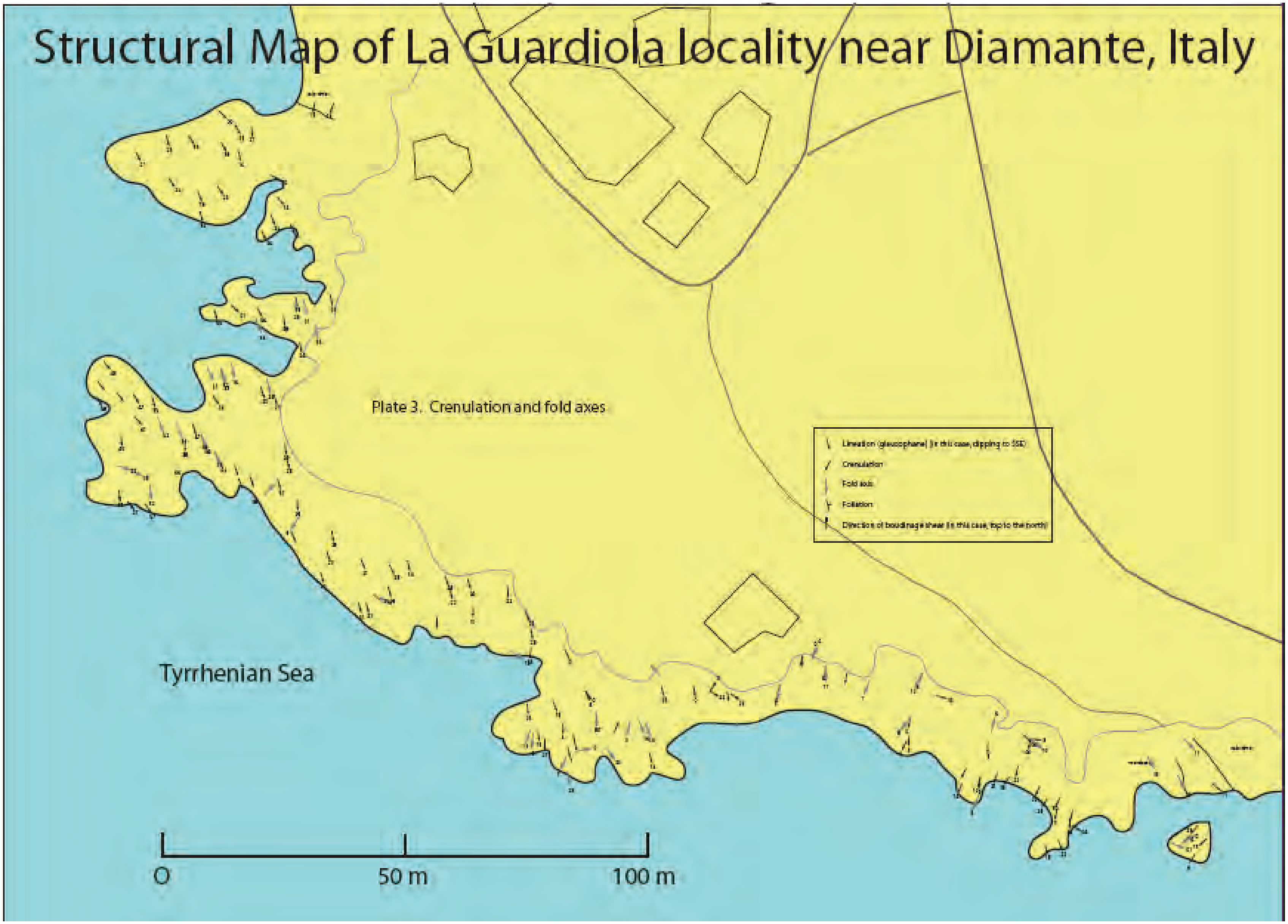
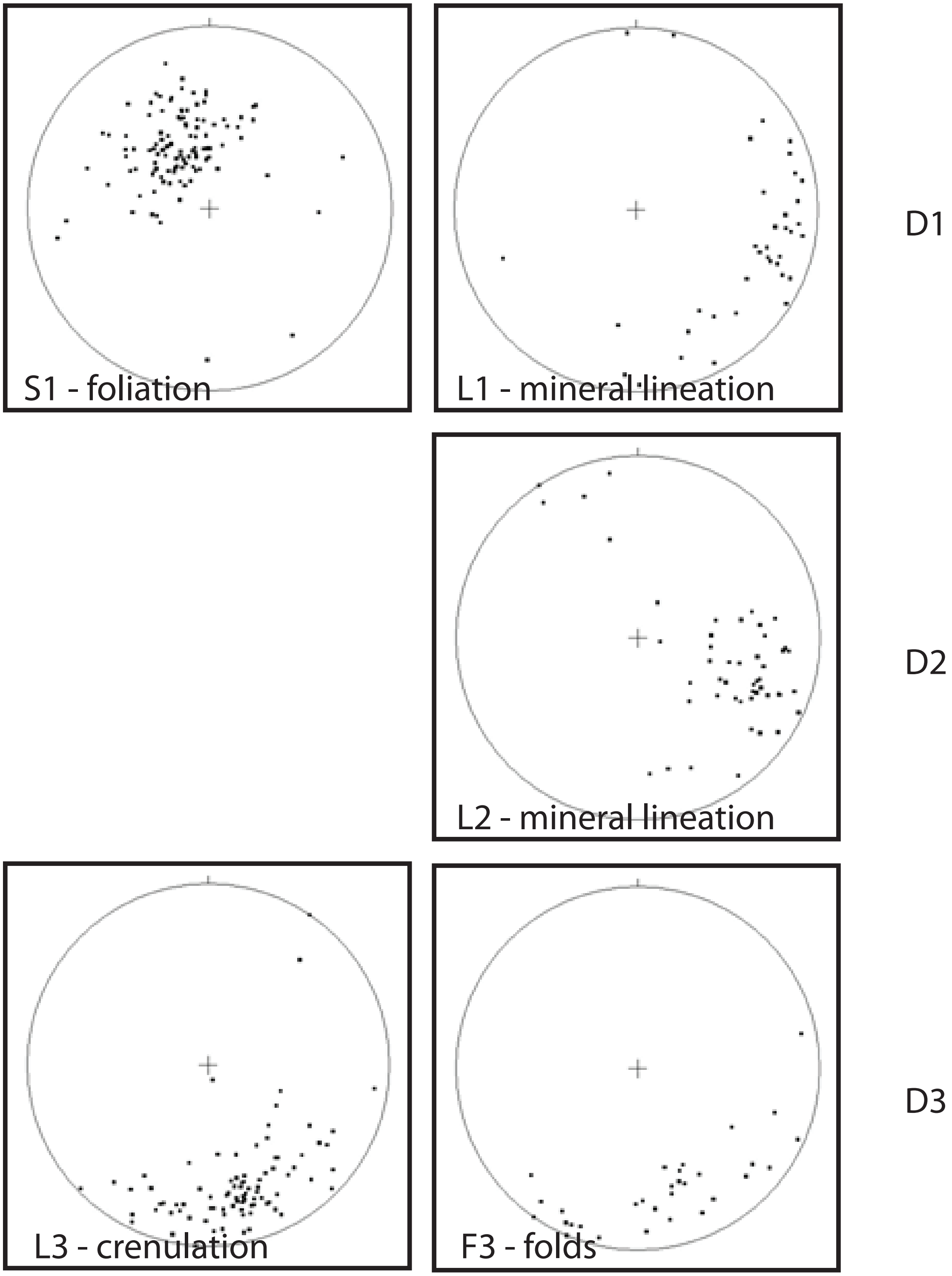


Figure 5c. Crenulation and fold axes. See Plate 3 for full-sized version.



S1 - foliation

L1 - mineral lineation

L2 - mineral lineation

L3 - crenulation

F3 - folds

Figure 6. Lower hemisphere equal-area stereoplots of structural data from Diamante. S1 are foliation poles-to-planes, L1 are glaucophane mineral lineations, L2 are vein mineral lineations, L3 are crenulation axes, F3 are fold axes.

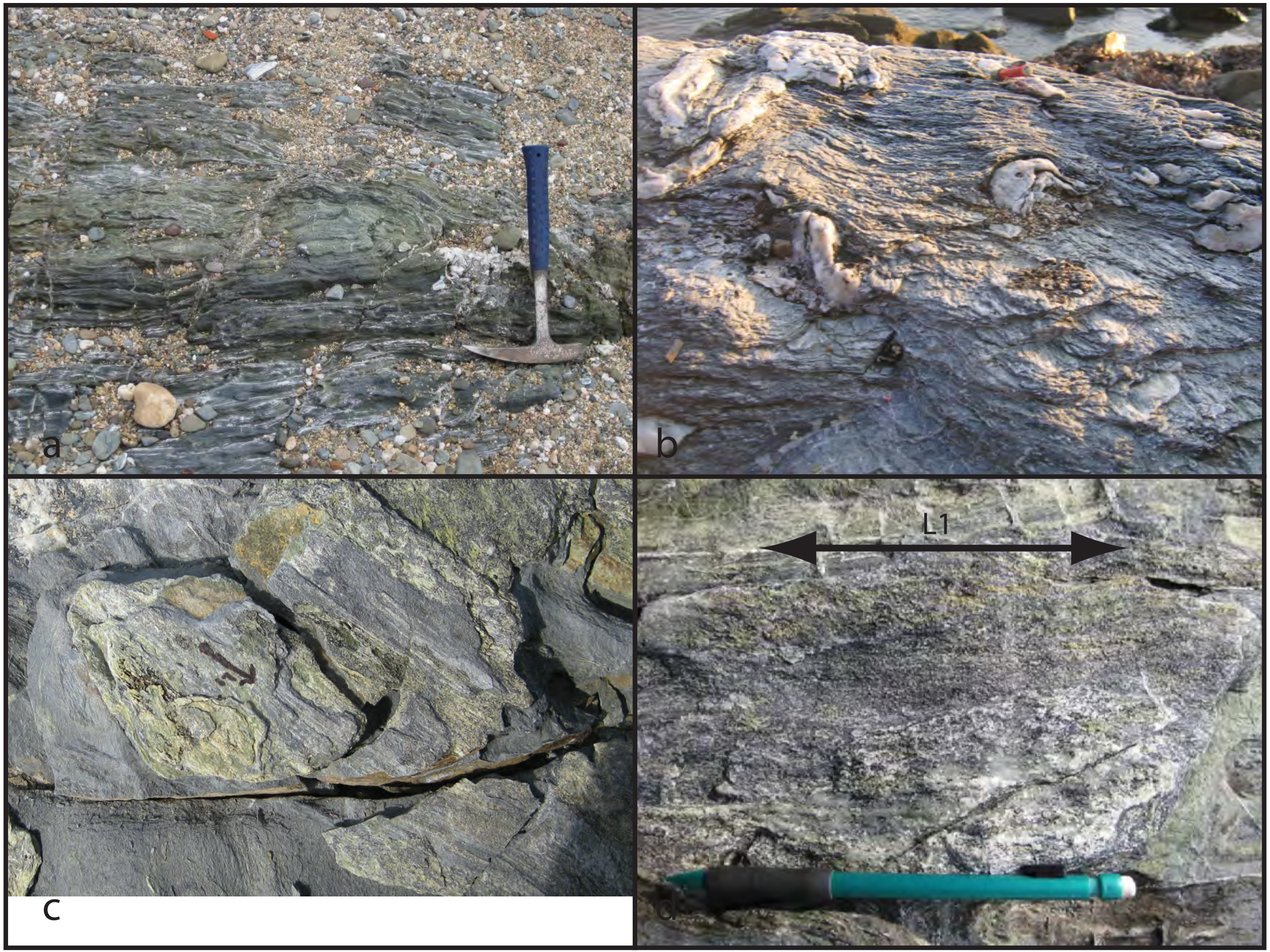


Figure 7. a) Intrafolial fold hinge, made up of epidote blueschist, in S1 foliation of the lawsonite-blueschist metabasalt. b) Apressed fold hinges developed in marbles in the calcschist cover indicating that D1 transposed the original sedimentary bedding. Photo is approximately 50 cm across. c) L1 mineral lineation on S1 foliation in the metabasalt. Arrow is appoximately 5 cm long. d) The L1 mineral lineation is defined by aligned glaucophane crystals.

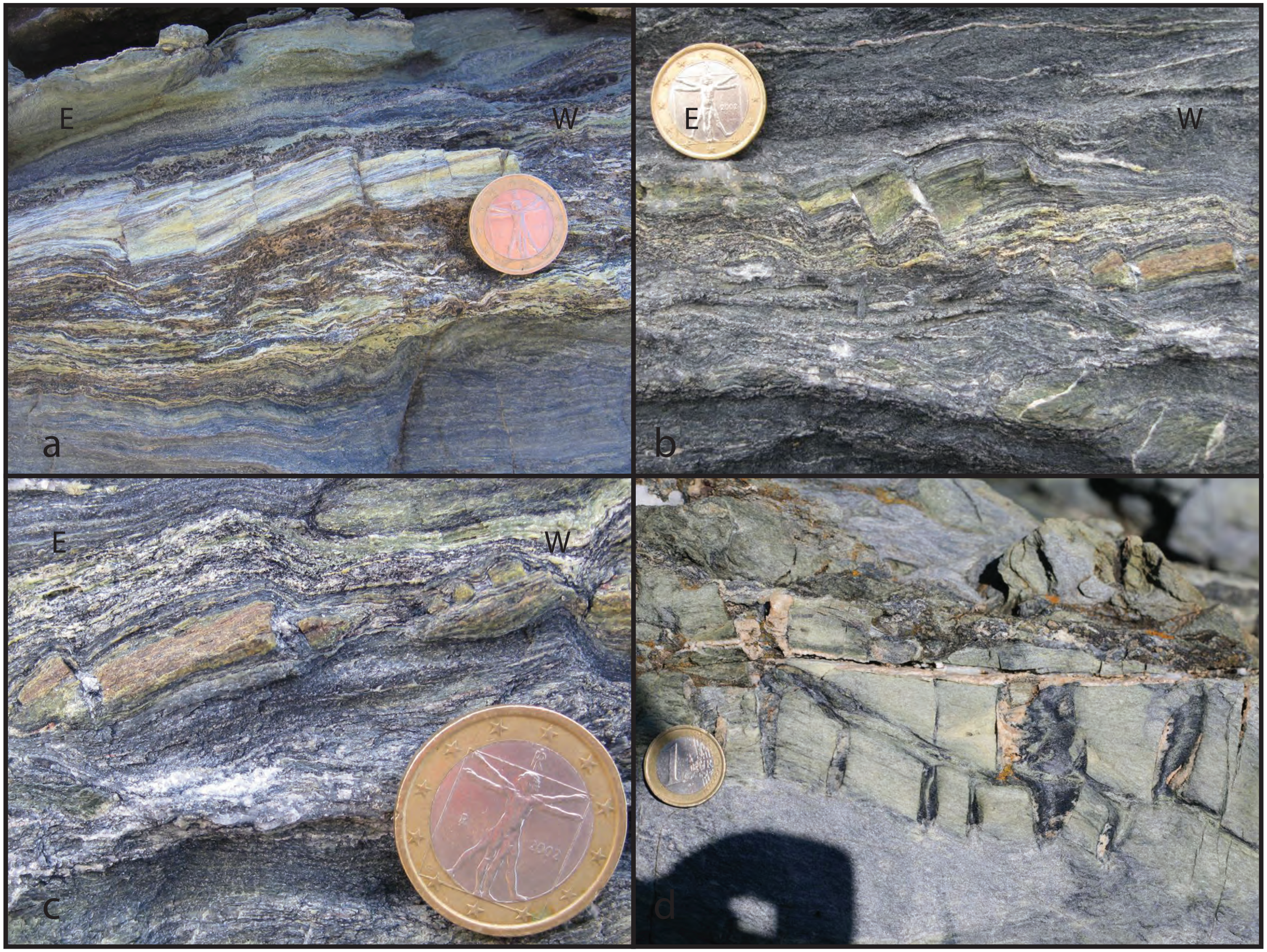


Figure 8. a) Domino boudins, consisting of epidote blueschist sitting in a lawsonite-blueschist matrix. These are deformed with a top-to-the-east sense of shear. b) In some cases the space between boudins is filled with calcite, glaucophane, or lawsonite. c) The growth of glaucophane and lawsonite in the calcite filling between these boudins indicates that deformation took place in the lawsonite-blueschist facies. d) A view of the foliation plane of shear-band boudins.

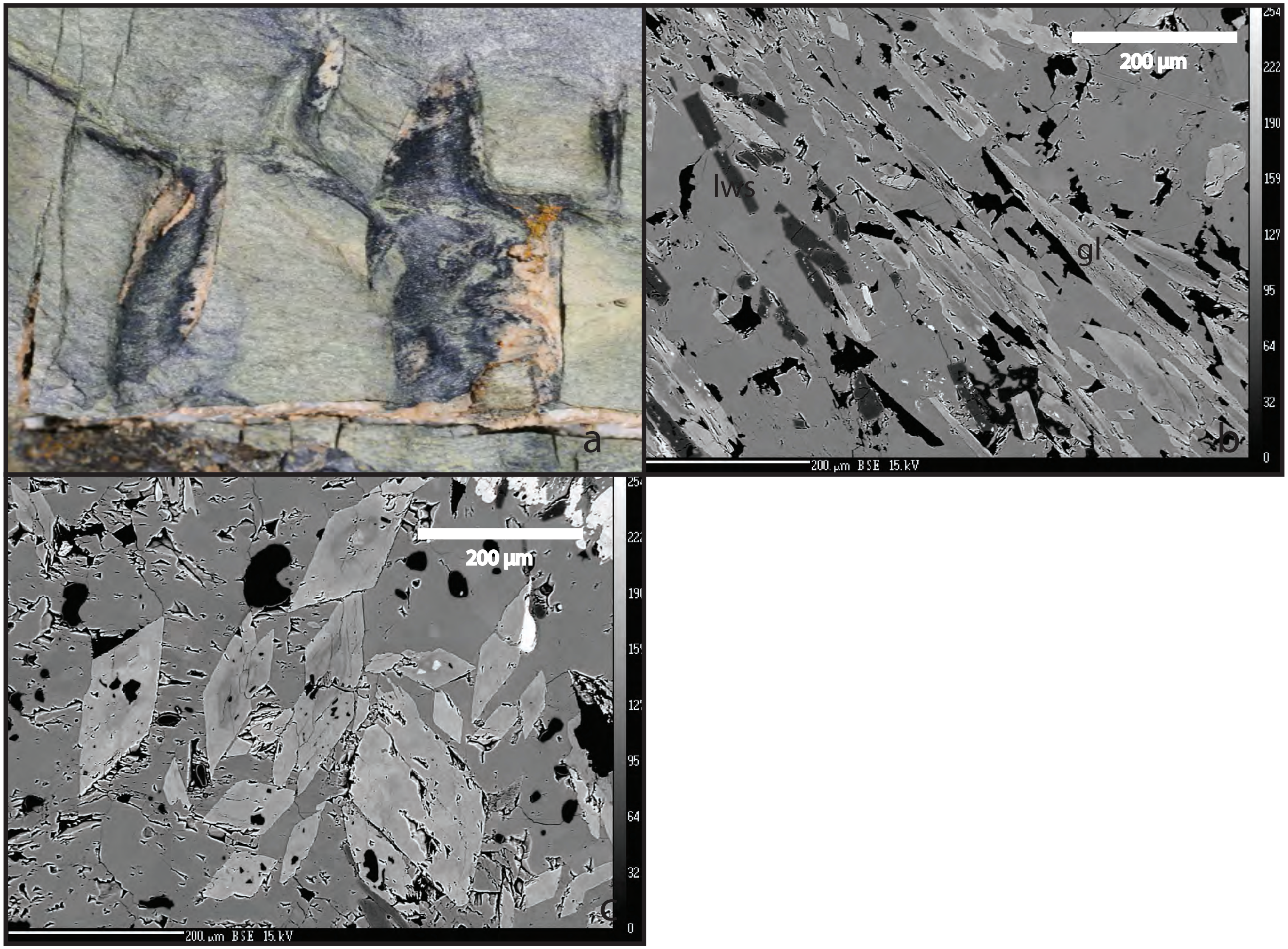


Figure 9. a) Close-up view of the shear-band boudins seen in Figure 8d. Growth of glaucophane in the inter-boudin space indicates that the shear took place in the blueschist facies. Image is 10 cm across. b) Backscatter image of lawsonite (lws) and glaucophane (gl) within domino boudin veins indicate lawsonite-blueschist facies conditions during deformation. c) Na-amphibole is zoned, from a darker, glaucophane-rich region, toward a lighter, riebeckite-rich region. This is consistent with deformation in decreasing pressure conditions.

Figure 10. a) Crenulation due to D4 deformation in metabasalts at Diamante. b) Top-to-the-east sense of vergence in crenulated fold trains in the metabasalt. c) Phengite-rich intrafolial layer where white micas where collected for Ar/Ar dating.

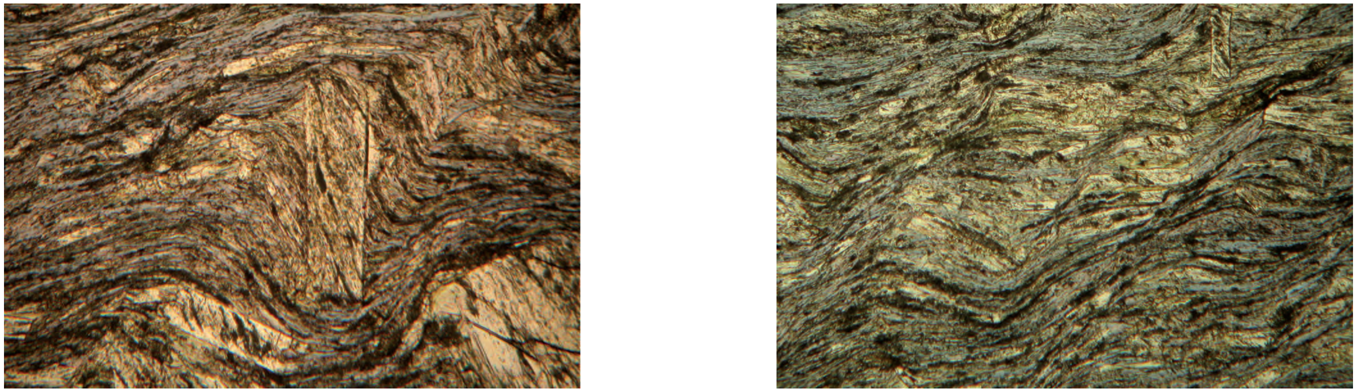


Figure 11. Photomicrographs from the same thin section of lawsonite-blueschist metabasalt at Diamante. In the image on the left, a top-to-the-right shear direction is visible. In the image on the right, top-to-the-left CS' shears can be seen. Both images are roughly 200 μm across. Images were taken by Francesca Liberi.

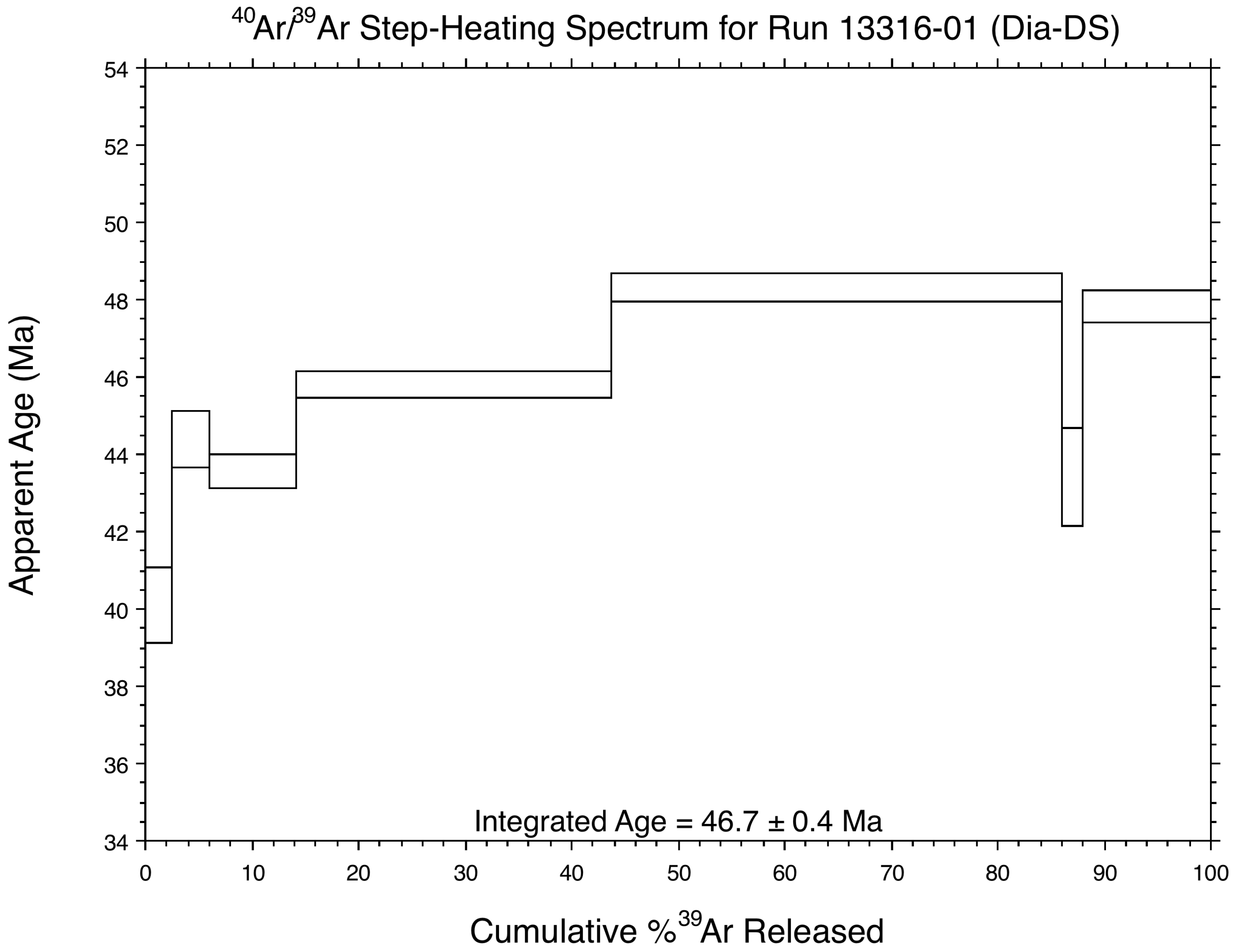


Figure 12a. Ar/Ar age spectrum for the first aliquot, a single phengite flake.

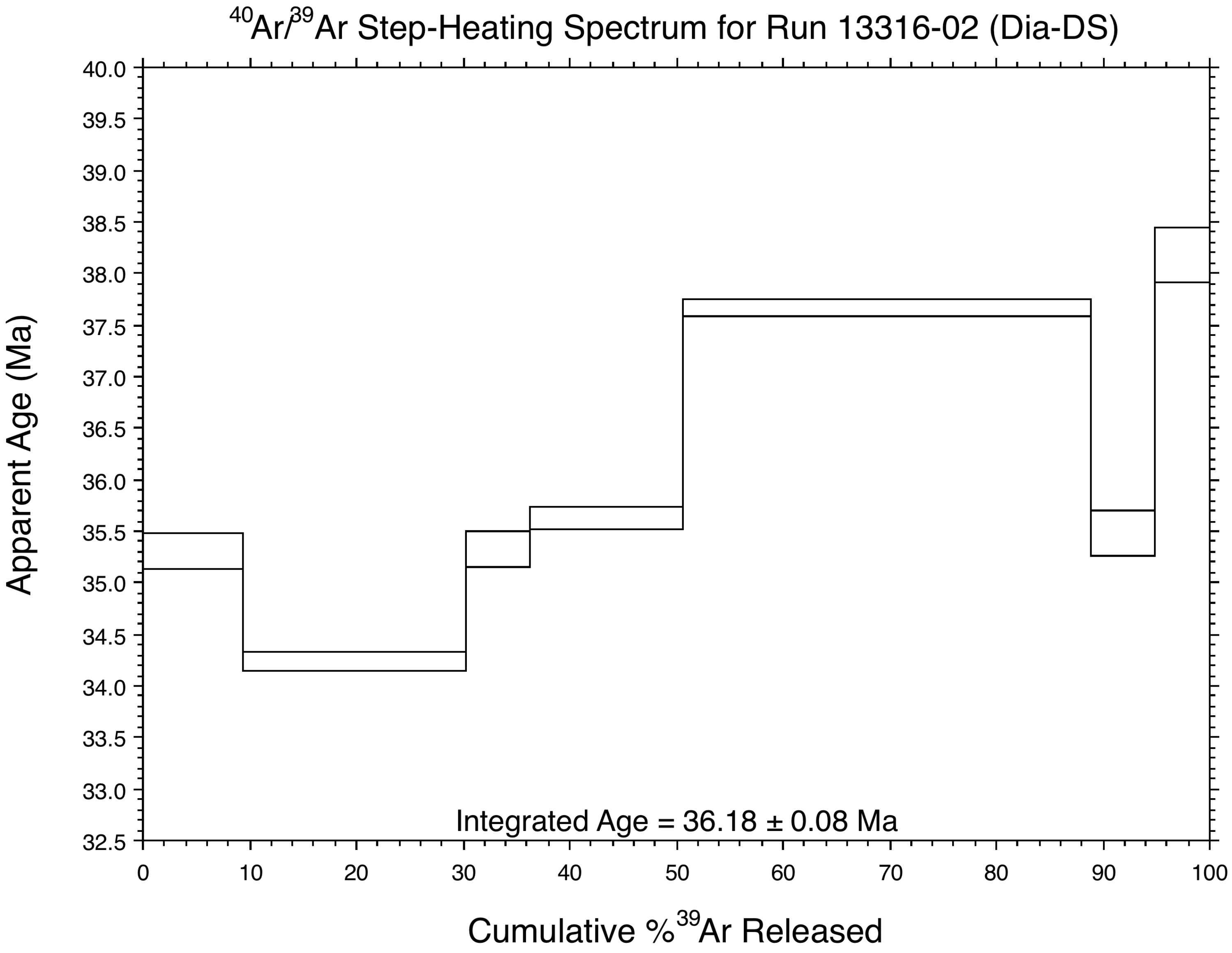


Figure 12b. Ar/Ar age spectrum for the second aliquot, five small phengites.

Figure 13. a) Crenulation in the calcschist from Vallone Bastardo, Calabria. b) Na-amphibole filled extensional veins from lawsonite-blueschist metabasalt at Terranova da Sibari. 50 euro cent coin is 24.25 mm.

a

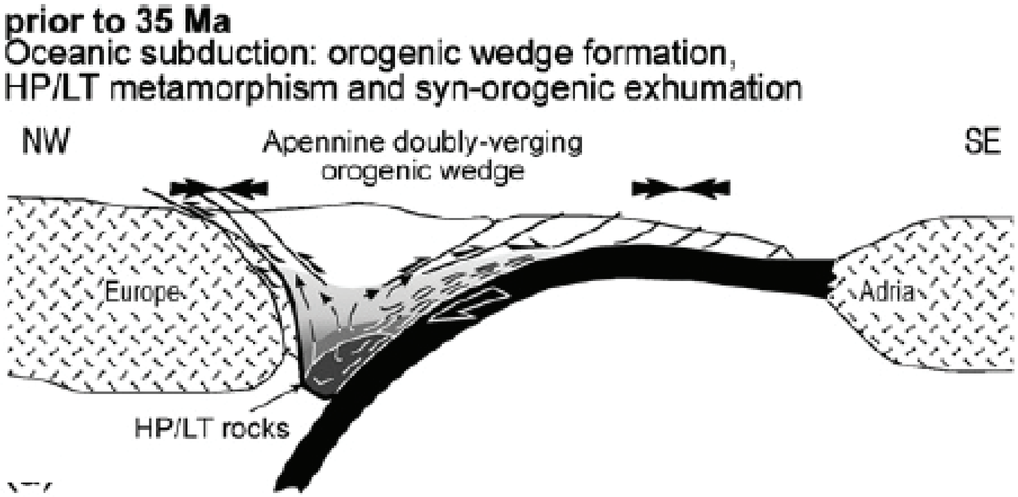
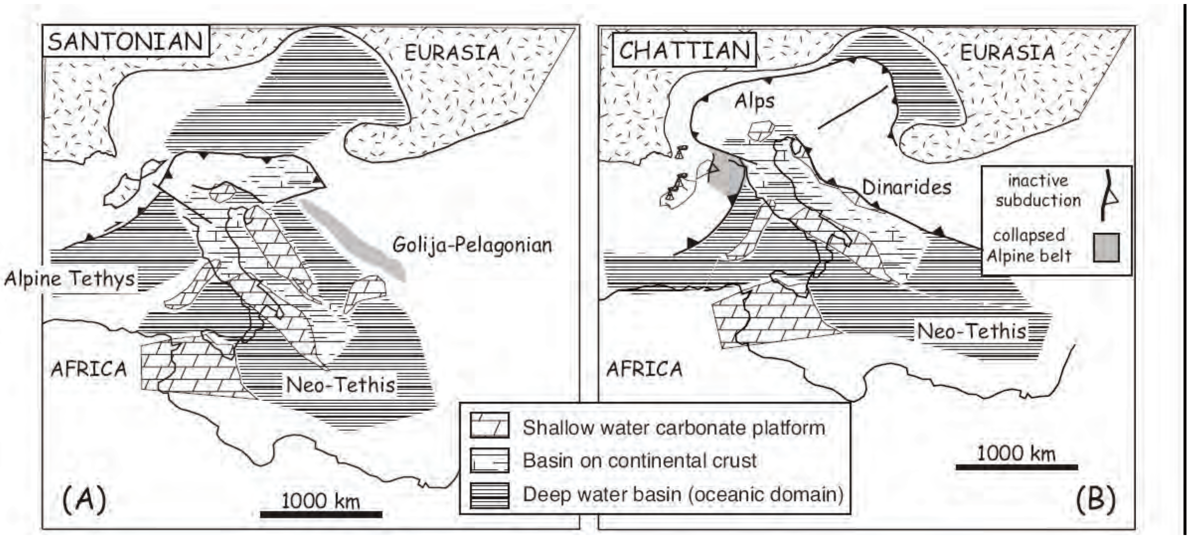


Figure 14. a) Cross-sectional sketch of a bivergent orogenic belt in the Calabria-Corsica orogen (Figure 14 from Rossetti et al., 2004). b) Illustration of west-vergent Corsican belt separated from an east-vergent Calabrian belt (Figure 4 from Arganani, 2009). In his model, this occurs in the Cretaceous. In the model present in the present paper, all subduction in this part of the Alps is Eocene, and later, in age.

b



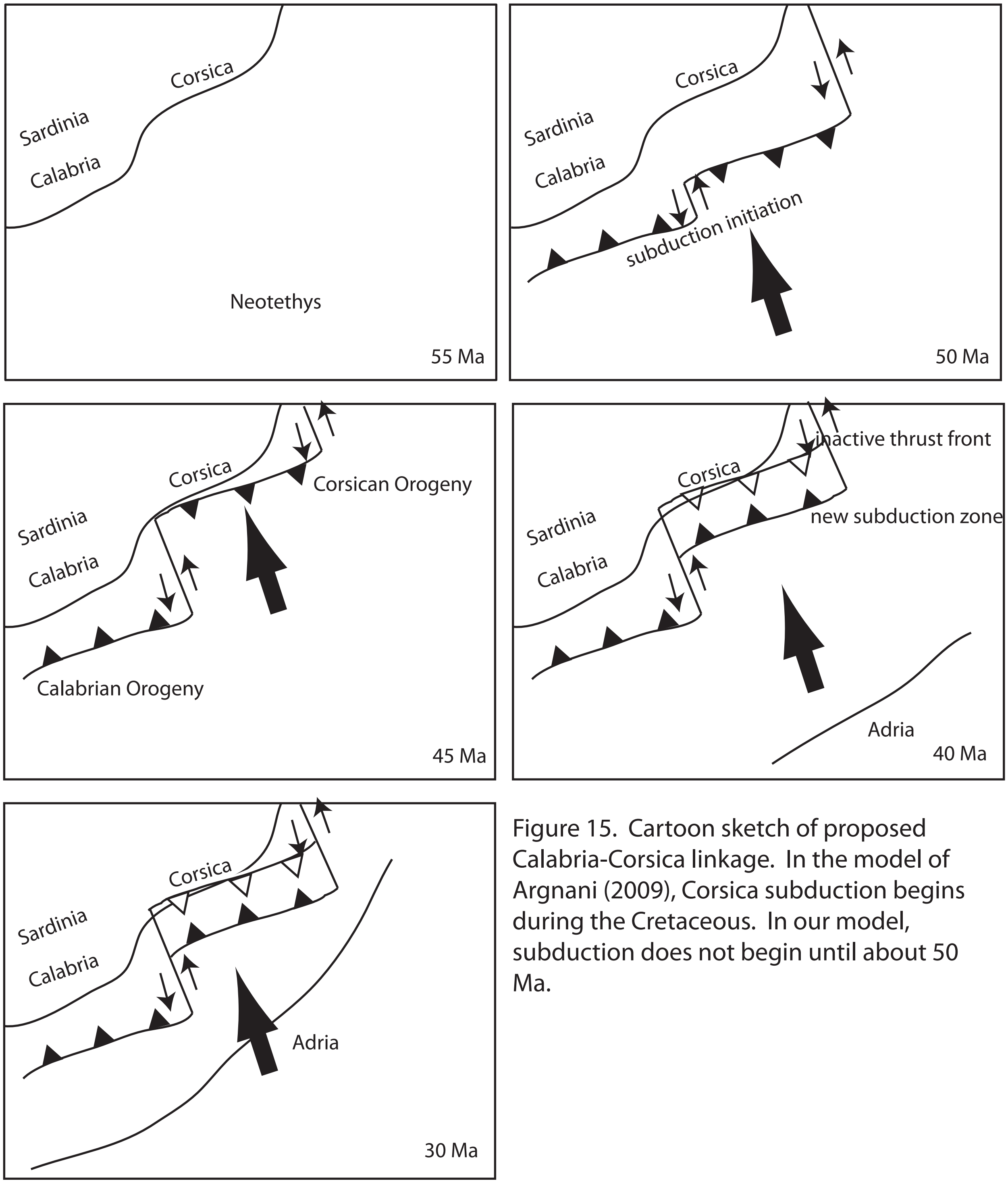


Figure 15. Cartoon sketch of proposed Calabria-Corsica linkage. In the model of Argnani (2009), Corsica subduction begins during the Cretaceous. In our model, subduction does not begin until about 50 Ma.

Introduction to Chapter 4

A mélange is a type of rock fabric in which blocks are enclosed in a fine-grained matrix. The most common types of mélange are tectonic mélanges, in which a dense network of faults juxtaposes blocks against a matrix, and sedimentary mélanges, in which blocks are deposited in a fine-grained matrix. These two types of mélanges are easily confused with each other because later tectonic deformation can obscure the original relationship of the enclosed blocks to the matrix.

The Frido Unit of Calabria is a metamorphosed shale, sandstone, and carbonate unit. In the northern part of exposure, it is considered a mélange, as there are exotic blocks of basalt and lower continental crust present in the sedimentary sequence. Previous workers have considered it to be a tectonic mélange because of the strong shear deformation of the unit. In the southern part, it is considered to be a coherent sedimentary unit, as exotic blocks are not common.

In this chapter, I present new a new structural study of the southern part o f the Frido Unit, near Monte Reventino, Calabria. In this area, the Frido has been considered to be a coherent unit, overlain by a sheet of Monte Reventino greenschist. My study of field relations indicates that the Monte Reventino rocks may instead be underwater landslide blocks (olistostromes) within the Frido sedimentary sequence, making the Frido a sedimentary mélange. This means that the metamorphic and structural history of the greenschist is not representative of the Frido Unit.

I then discuss other outcrops of the Frido Unit, located to the north, and find that they can best be understood as sedimentary mélanges. This framework help explain the diversity of lithologies (lower continental crust, granite, blueschist metabasalt, and pillow basalts) and metamorphic grades (“unmetamorphosed’ to lawsonite-blueschist) associated with the Frido Unit: each of the blocks has been deposited into a sedimentary basin.

If the entire Frido Unit is understood as a sedimentary mélange, then the variation in appearance from north to south may be due entirely to the types of sediment that reached the basin. In addition, the metamorphic and the ancient ages attributed to the Frido Unit may apply only to the blocks and not to the entire unit.

CHAPTER 4

THE FRIDO UNIT OF CALABRIA, SOUTHERN ITALY: TECTONIC IMPLICATIONS OF A SEDIMENTARY MELANGE

ABSTRACT

Sedimentary processes are an important contributor to the formation of mélanges in orogenic belts. However, they are often not recognized because later deformation can obscure original sedimentary relationships. Failure to recognize the sedimentary origin of a mélange can lead to the misinterpretation of units and their role in the tectonic history of the orogen. The age and metamorphic grade of included blocks may record events that took place earlier in the history of the orogen, or they may have a history completely unrelated to the orogen. In addition, along-strike variations may be misattributed to a change in tectonic style, or passage into a different unit.

We examine this concept within the Frido Unit of the 130-km-long Cenozoic North Calabrian Orogen of Southern Italy. The Frido Unit is phyllite, quartzite, and carbonate unit which forms the second-to-lowest unit in the tectonometamorphic stack of Calabria. The Frido Unit is considered to be a tectonic mélange in some localities, while in other localities it displays a structural coherence best likened to a thrust sheet. Each of the exposures is associated with a wide variety of oceanic and continental fragments.

We propose that the variation in styles within the Frido Unit, from mélange to coherent, is due to the sedimentary origin of the mélange. Many of the blocks, including blueschist-facies blocks, are recycled, leading to the misattribution of metamorphic events and ages to the Frido Unit. Much variation of the Frido Unit along-strike is due changes in sedimentary source and differences in the exhumation history of the orogenic belt.

INTRODUCTION

Since their recognition in the classic paper of Greenly (1919), mélanges have played an important role in the interpretation of orogenic belts, as they contain a record of structural and metamorphic events which affect an orogen. Since the term mélange is descriptive, referring only to a block-in-matrix fabric (Silver and Beutner, 1980; Festa, 2010), the genesis of mélanges has been controversial. This is because during high-strain tectonic events, the original relationship between the blocks and matrix can be obscured. In different localities, tectonic (Hsü, 1968; Cloos, 1982; Shreve and Cloos, 1986), sedimentary (Abbate et al., 1970; Cowan, 1978; Aalto, 1979; Pini, 1999), and diapiric (Westbook and Smith, 1983; Barber and Brown, 1988) processes have been cited in contributing to their formation (Raymond, 1984; Cowan, 1985; Festa, 2010).

Sedimentary mélanges are common in accretionary terranes as sediment from the oversteepened wedge front can collapse into the trench (Pini, 1999; Festa, 2010). The sediment is delivered by gravity-driven processes, such as slope failure and debris flows, and mixes with the trench fill deposits typical to subduction zones (Festa, 2010). The resultant sedimentary package is often a shale, or sandstone, matrix which encloses blocks, beds, or packages of beds (Abbate et al., 1970; Lucente and Pini, 2003; Mutti et al., 2009; Cavazza and Barone, 2010).

The failure to recognize the sedimentary origin of mélanges in orogenic belts can lead to problems in tectonic interpretation. Since blocks in mélange may be recycled, the metamorphic grade and age recorded by the blocks may not be representative of the mélange as a whole (Wakabayashi, 2011a, 2011b). This may also hold true with paleontological ages determined from the matrix, as older fossils can be reincorporated into the sandstones and shales which make up the matrix. In addition, if the block-in-matrix fabric of these units originates from sedimentary processes, then the along-strike transition between a block-in-matrix fabric and coherent nappe may not represent a transition into a new unit; instead, it may only represent a sedimentary facies change.

In the present paper, we examine the Frido Unit, a complex phyllite ± quartzite ± carbonate unit that extends over much of 130-km-long North Calabrian orogenic belt (Figure 1) (Vezzani, 1969; Amodio-Morelli et al., 1976). The Frido has long confounded workers because a variety of lithologies, metamorphic grades, and deformation styles are exposed at a single structural level, in scattered outcrops across the orogen. Near the type locality, it is considered a mélange, as blocks of dismembered ophiolite and lower continental crust are exposed in shale and serpentine matricies (Spadea, 1982; Monaco et al., 1995). This mélange is widely considered to be tectonic, as the shale and serpentinite matrices are highly sheared (Monaco et al. 1995).

However, in other localities, the Frido appears to be coherent nappe of epimetamorphic quartzite and phyllite (Piccarreta, 1973; Colonna and Piccarreta, 1975; Amodio-Morelli et al., 1976; Alvarez, 2005). Indeed, because of the lack of exotic blocks and the absence of high-pressure metamorphism, some workers exclude these outcrops from the Frido nomenclature (Bonardi et al., 1988).

The confusion as to which outcrops are actually Frido raises several questions, listed as follows:
(1) What is the metamorphic grade of the Frido Unit?
Blocks in the Frido Unit vary in metamorphic grade from epimetamorphic to lawsonite blueschist.
(2) What is the age of the Frido Unit?
The ages determined by paleontology for elements of the Frido range from the Jurassic to Oligocene.
(3) Why does the Frido Unit seem to vary between a mélange in the north and a coherent nappe unit in the south?
(4) What is the relationship of the Frido Unit with the underlying Verbicaro Unit?

Below, we describe the southernmost exposure of Frido Unit, near the city of Lamezia Terme, Calabria. This exposure of quartzite and phyllite are widely considered to be a coherent nappe, lying above a carbonate nappe and below an ophiolite nappe. However, the overlying Monte Reventino ophiolite nappe is represented by only scraps of metabasalt and serpentinite.

We propose that the discontinuous exposure of the overlying Monte Reventino ophiolite sheet is best understood as being due to sedimentary deposition—as olistostromes—into a sandstone and shale basin which is now the Frido Unit. In that case, the Frido Unit could be considered to be, in part, a sedimentary mélange.

We then apply a sedimentary mélange paradigm to other outcrops considered to be Frido. Our observations indicate that it is possible that the entire Frido Unit is a sedimentary mélange. If that is the case, the metamorphic grade and age of the blocks may not be representative of the unit as a whole. Instead, blocks may record a history of earlier events in the orogenic cycle, or they may be related to the much older Hercynian orogen. In addition, along-strike variations between exposures of mélange and coherent sheet may merely track along-strike variations in sedimentary facies.

TECTONIC SETTING

The Cenozoic fold-thrust belt involving Mesozoic carbonate and Miocene flysch exposed in much of the Italian peninsula is interrupted in Calabria, where crystalline basement representing the Hercynian and Alpine orogenic cycles is exposed (Amodio-Morelli et al., 1976; Bonardi et al., 2001) (Figure 1). Calabria records the Alpine-aged history of subduction and accretion of Tethyan ocean crust beneath a Hercynian crustal fragment (Amodio-Morelli et al., 1976). Since at least the Miocene, slab-rollback of a west-dipping subduction zone has caused back-arc extension, first allowing the drift of the Corsica-Sardinia block away from Europe, and the later separation of the Calabria microplate from that Corsica-Sardinia block during opening of the Tyrrhenian Sea (Alvarez, 1974; Malinverno and Ryan, 1986; Kastens et al., 1988).

The crystalline rocks of Calabria can be divided into a two-part tectonic stack: an upper plate and an Alpine-aged accretionary complex (Figure 2). The upper plate is comprised of a thick Hercynian crustal unit with a thin Mesozoic and Cenozoic sedimentary cover. This unit, known as the Sila Unit, preserves a complete crustal cross section, from lower crustal migmatites up through low-grade metapelites (Graessner and Schenk, 2001). Although it was deformed during the Alpine Orogen, it does not bear any evidence of Alpine-aged high-pressure metamorphism (Acquafredda et al., 1994).

The Sila is structurally above an Alpine-aged accretionary complex composed of nappes which all bear evidence of blueschist-facies metamorphism (Amodio-Morelli et al., 1976; Piccarreta, 1981). At the top, the Castagna and Bagni Units are both made of Hercynian-aged rock units which have an Alpine-aged blueschist metamorphic overprint (Colonna and Piccarreta, 1976; Piccarreta, 1981; Rossetti et al., 2001). Below these two units are dismembered Tethyan oceanic remnants, preserved as blueschist-facies metabasalts and sedimentary cover (De Roever, 1972; Lanzafame et al., 1979a; Spadea, 1994; Rossetti et al., 2001, 2004). These units have been scraped off the downgoing oceanic plate, unlike the upper-plate ophiolites common in the circum-Mediterranean region (Dilek, 2003). These fragments are closely associated with the phyllite and quartzites of the Frido Unit (Bonardi et al., 1988). The Verbicaro Unit, the lowest of the accreted units, consists of Triassic and Jurassic platform carbonates which are exposed as a large autochthonous unit north of the Sangineto Line and in several tectonic windows beneath in Northern Calabria (Ietto et al., 1995; Iannace et al., 2005a, 2007). These units with oceanic-affinity may involve one or two branches of the Tethys Ocean (Spadea et al., 1976; Spadea, 1994).

FRIDO TYPE LOCALITY AND CORRELATION TO OTHER REGIONS

This Frido Unit was defined by Vezzani (1969) along a 1,200 m section at Torrente Frido along the Calabro-Lucano border. There, it was originally recognized as a weakly-metamorphosed pelitic, calcschist unit with minor quartzite, divided into 5 members. There was a distinct stratigraphic order, as the ages of microfossils collected by Vezzani (1969) corresponded to the stratigraphic order.

However, the description at the type locality did not capture the wide variety of rocks associated with the Frido Unit. The original study only mentioned in passing the serpentinite and lower continental crust blocks associated with the Frido. These exotic blocks hinted at a mélange fabric that is one of the defining features of the Frido Unit.

The Frido Unit was considered to be high-P/T due to the presence of aragonite in the calcschist unit (Vezzani, 1969), a blueschist-facies indicative mineral (Johannes and Puhan, 1971). Later workers supported this conclusion, based on the presence of lawsonite and glaucophane in metabasalt blocks associated with the formation (Lanzafame et al., 1979b; Monaco et al., 1995).

The unit name was extended orogen-wide in the synthesis of Amodio-Morelli et al. (1976) (Figure 3). They defined it based on sedimentary and structural characteristics: it was a quartzite-phyllite-carbonate unit, structurally above the carbonates and below the ophiolites. This broad definition led to the inclusion of nearly any unit at the same structural position, including:

(1) the type locality around San Severino Lucano (Vezzani, 1969)
(2) the“flysch à quarzites” of Northern Calabria in the Fiume Lao vicinity (Grandjacquet, 1961) and the west side of the lower Crati Valley (Bousquet, 1971)
(3) quartzites and phyllites exposed in the tectonic window of Cetraro (Dietrich, 1976)
(4) phyllites exposed at Monte Cocuzzo
(5) quartzites and phyllite exposed along the north edge of the Catanzaro graben (Colonna and Zanettin Lorenzoni, 1973; Piccarreta, 1973; Colonna and Piccarreta, 1975).

These localities were included in the regional map and this framework was broadly followed by most later workers (Bonardi et al., 1988, 1994, 2001; Cello et al., 1994).

NEW OBSERVATIONS FROM MONTE REVENTINO, SILA PICCOLA

In the Sila Piccola, north of the city of Lamezia Terme, are large exposures of epimetamorphic phyllite, quartzite, and minor carbonate (Figure 1). Even though graded bedding is not apparent, the alternation between quartzite beds and thin phyllite units suggest that the unit may represent a sequence of turbidites.

These sediments are structurally superposed on carbonates at Terme Caronte, which are considered to be the southernmost exposures of the carbonate units to the north (Dietrich and Scandone, 1972. The phyllites are structurally overlain by the Monte Reventino Unit, which consists of blueschist-facies metabasalt and serpentinite overprinted in the greenschist facies (Piccarreta, 1973; Liberi et al., 2006).

Because of the basic sedimentary character of this unit and its structural position, these rocks, along with those at Gimigliano, are considered to be the southernmost exposures of the Frido Unit (Piccarreta, 1973; Colonna and Piccarreta, 1975; Amodio-Morelli et al., 1976; Alvarez, 2005).

However, there is a major difference between these rocks and the Frido Unit at the type locality. Unlike the blueschist-facies Frido Unit in the north, the Frido Unit of the Sila Piccola is reported to be non-metamorphic, leading some authors to consider it a distinct unit (Bonardi et al., 1988). We have conducted a thorough search of Frido outcrops on Monte Reventino and Monte Mancuso, searching specifically for Mg-carpholite, the mineral which indicates high-pressure conditions in phyllite-rich units (See Appendix) (Iannace et al., 2005). None was found.

Only at Monte San Giovanni, 11 km to the north, have we discovered a new occurrence of carpholite in the Frido Unit (Figure 4a). It occurs in a pelite and quartz boulder, in float, in a phyllite unit on the contact between the carbonates and the overlying units (Figure 4b). The carpholite here indicates that the boulder was metamorphosed in the blueschist facies, at pressures of > 10 kbar (Bousquet et al., 2002).

Although most workers consider the juxtaposition between the Frido and surrounding units to be due to thrusting (Amodio-Morelli et al., 1976; Piccarreta, 1973; Piccarreta, 1981; Alvarez, 2005), there has been a recent proposal that extensional faulting was the main factor in determining the present-day structural architecture of the rocks in the Sila Piccola (Rossetti et al., 2001). These workers presented a new structural classification, dividing the units into an upper, low-pressure, ophiolite unit, juxtaposed against a lower, high-pressure, Monte Reventino unit (Figure 5a).

An important part of their argument is the reclassification of Frido units, previously considered to be structurally below the ophiolite, to a position above the ophiolite (Rossetti et al., 2001). Since the Frido does not contain any HP minerals, this created a metamorphic pressure discontinuity between a low-pressure upper plate and high-pressure lower plate, implying the existence of a regional-scale normal fault between the two units. This view is illustrated in a geologic cross-section near Monte Reventino, where phyllites, previously of the Frido Unit, are structurally superposed on the Monte Reventino ophiolite (Figure 5a).

In order to test whether the Frido Unit is above, or below, the ophiolite at Monte Reventino, we revisited the area and made observations of structural relationships between the two units (Figure 6). We believe that a bulk of these observations places the Frido Unit below the Monte Reventino ophiolite:

> (a) On the south face of Monte Reventino, Rosseti et al. (2001) indicate that the Frido Unit (upper ophiolite unit, or UOU) has been dropped down along a steeply-dipping normal fault to a position below the Monte Reventino Unit (Figure 5a). This area was mapped in detail by Alvarez (2005). Although he localized the contact to within a 5 m area, it was never observed. In the present study, we have located a contact on the south face of Monte

Reventino (Figure 5b), where ophiolite is exposed above a calcschist horizon (Figure 6) (39° 2'14.93" N, 16°18'24.96" E). The foliation in the underlying calcschist is sub-horizontal and parallel to this contact. The same contact is inferred on the north side of Monte Reventino, where Frido quartzite beds are exposed at about the same elevation, indicating that a sub-horizon contact continues for at least 1 km—topographically beneath the ophiolite.

(b) On the north side of the Monte Mancuso–Monte Reventino massif, outcrops of greenschist are exposed in the bottom of north-flowing drainages at Fosso Petrullo and Fosso Magalda (Piccarreta and Zirpoli, 1970; Piccarreta, 1973). At Fosso Petrullo, the distinctive phyllite and quartzite of the Frido Unit outcrops below greenschist and serpentine units which are associated with the ophiolite (Piccarreta, 1973).

(c) At the mouth of the Savuto River, quartzites of the Frido Unit underlie rocks that have been mapped as the sedimentary cover of the ophiolite (Figure 5c) (Piccarreta and Zirpoli, 1970).

(d) At the switchbacks on the road just east of the town of San Mango, Frido Unit quartzites and phyllites lie structurally beneath metabasalts and serpentines of the ophiolite unit (Figure 5d).

These observations indicate that, in general, a vast majority of the Frido quartzites and phyllites structurally underlie the ophiolite in the Sila Piccola, consistent with the observation of most authors.

However, there are a few exceptions that have been described in the literature. Piccarreta (1975) notes three localities (Falerna Cemetery, the Capuchin Monastery at Nocera Terinese, and the upper part of Fosso della Manca) where rocks of the Frido Unit are positioned within the Monte Reventino Unit. Indeed, there are several places (Trappeto Mauri, I Cappuccini) where the “sedimentary cover” of the ophiolite lies below it and where the Frido Unit lies above the greenschist (Piccarreta and Zirpoli, 1970; Piccarreta, 1973).

These exceptions hint at the unusual relationship between the Frido Unit and the Monte Revetino Unit. In our reconnaissance geologic map, it is clear that the Monte Reventino unit does not represent a complete nappe (Figure 6). It exists discontinuously, generally along the contact between the Frido Unit and the Zangarona Schist. These blocks, sometimes less than 100 m in extent, are very similar to the main Monte Reventino outcrop, mapped by Alvarez (2005), with serpentinites and metabasalts.

This type of pattern, with discontinuous rock bodies, invokes extensional attenuation as an explanation; however, since both the Zangarona Schist and the ophiolite units are HP (Chapter 1 of this thesis; Colonna and Piccarreta, 1975), there is no metamorphic pressure discontinuity that would suggest a major normal fault.

Instead, we suggest that the Monte Reventino greenschist and serpentine blocks are olistostromal blocks which were deposited near the top of the Frido sedimentary unit. These blocks were involved in an earlier phase of subduction, exhumed, and redeposited in the Frido sedimentary basin. In this case, many of the structural, and metamorphic, features of these metabasalts may not be representative of the unit and may instead record pieces of the earlier history of the orogen.

This idea immediately explains several observations:
(1) On the south face of Monte Reventino, we have identified detrital serpentine in the uppermost calcschist of the Frido Unit. This indicates that serpentinite bodies were in the catchment of the Frido depositional basin. In addition, what appear to be serpentinite turbidites are present in the Monte Reventino ophiolite body (Alvarez, 2005).

(2) The Monte Reventino mapped by Alvarez (2005) may itself be a large block of serpentine and metabasalt that continues along strike to the northwest. It is a thin slice, about 100 m thick, that pinches out just SE of the Monte Reventino summit (Figure 7a). The upper contact is a later, brittle contact (Alvarez, 2005), but the lower contact is flat—consistent with a depositional contact. This is consistent with the size of previous reported serpentinite olistolith blocks (Lockwood, 1971).

(3) Alvarez (2005) demonstrated that D2 folds axes in the Monte Reventino Unit were twisted during a later shear event, D3. The cause of this structural event was indeterminate; both shortening and extension were considered to be possible mechanisms in twisting the folds.

Alvarez (2005) noted that the deformation in the Frido Unit had no correspondence to folds recorded in the Monte Reventino Unit. If the Monte Reventino block is an olistostrome, D1 and D2 may have taken place earlier in subduction, with only D3 taking place with the Frido Unit.

(4) There appear to be other exotic blocks, such as the granite block just above Nocera Terinese (Figure 7b), the greenschist at the mouth of the Savuto River, and a block of sheared granite on the road between San Mango and Nocera Terinese. There are also blocks which appear to be recycled sandstone (7c).

(5) Some of the scattered blocks of metabasalt preserve a different metamorphic history from the main block exposed at Monte Reventino, where there is a thorough greenschist-facies overprint. At Trappeto Mauro, just west of San Mango, there is a metabasalt which has distinct blue layers containing Na-amphibole (Piccarreta, 1973). Outside of the map area, at Coreca, a similar glaucophane-bearing metabasalt associated with serpentinite is exposed at the contact between Zangarona Schist and carbonate.

(5) The carpholite-bearing block at Monte San Giovanni may simply be a block in a sedimentary matrix. This would explain difference in metamorphic grade between the high-pressure block and the seemingly low-pressure matrix surrounding it.

HOW DOES INTERPRETING THE FRIDO AS A SEDIMENARY MELANGE AFFECT THE INTERPRETATION OF OUTCROPS CONSIDERED TO BE FRIDO UNIT?

If the Frido Unit near Monte Reventino is a sedimentary mélange, could this change our understanding of other outcrops in Calabria?

Near San Severino Lucano

Large exposures of the Frido Unit, including the type locality described by Vezzani (1969), exist around the town of San Severino Lucano (Lanzafame et al., 1979a; Monaco et al., 1995) (location Figure 3). This area has been mapped as a two-part formation with an upper calcschist subunit and lower pelitic schist subunit (Monaco et al., 1995). The lower unit contains blocks of serpentinite, metabasalt, and lower continental crust, up to 10 km in size, enclosed in a pelitic matrix (Monaco et al., 1995). Some exposures of serpentine are themselves mélange, as they contain garnetiferous gneiss and amphibolite schists in a sheared serpentinite matrix (Spadea, 1982; Monaco et al., 1995). In general, the block-in-matrix fabric is localized to the upper and lower contacts of the subunits (Monaco et al., 1995; Monaco and Tortorici, 1995).

The blocks in the shale-matrix mélange vary in metamorphic grade. Some metabasalt blocks contain glaucophane and lawsonite, indicating high-P/T conditions (Lanzafame et al., 1979a; Spadea, 1982; Monaco et al., 1991; 1995; Knott, 1994; Monaco and Tortorici, 1995). This assemblage has been used to estimate pressures of 8-10 kbar at temperatures of 450 °C (Monaco, 1993). In the recycled Hercynian continental blocks, lawsonite develops in the gneiss and a blue-green amphibole grows in amphibolites, indicating HP conditions affected the blocks (Spadea, 1982).

The matrix of both subunits has experienced high-P/T conditions. Aragonite, an indicator of HP conditions (Johannes and Puhan, 1971), has been reported from the calcschist member of the Frido Unit (Spadea, 1976). In the Frido mapped as shale-matrix mélange, we have located a new outcrop of sandstone containing Mg-carpholite (Figure 8a, 8b). Mg-carpholite is a blueschist facies indicator in metapelites, indicating pressures of at least 1.0 GPa (Bousquet et al., 2002).

Since both the matrix and enclosed blocks have evidence of blueschist-facies metamorphism, it is likely that the entire mélange unit was metamorphosed at high-P/T conditions.

For some time, the Frido Unit was considered to be Cretaceous, based on a paleontological study of the type section (Vezzani, 1969). This age was replaced by the discovery of Chattian (Upper Oligocene) fossils in the calcschist unit, limiting the age to 28.4 – 23.03 Ma (Bonardi et al., 1993). The diversity of paleontological ages present in the formation could indicate that the formation spans a long time range, or, it could indicate that there has been reworking of bioclasts.

This mélange has generally been considered to be of tectonic origin (Vezzani, 1969; Ogniben, 1969; Knott, 1987; Monaco, 1993; Monaco and Tortorici, 1995; Tortorici et al., 2009). This characterization is based on the sheared appearance of the Frido Unit and the presence of internal thrust duplexes within the formation (Monaco, 1993; Monaco and Tortorici, 1995; Tortorici et al., 2009). In addition, granitic blocks enclosed in the serpentine-matrix mélange have a mylonitic texture near the rims (Knott, 1987; Monaco and Tortorici, 1995;).

However, there are features which are suggestive of a sedimentary mélange. Some metabasalt blocks are exposed with depositional contacts with their sedimentary cover, such as at Monte

Tumbarino (Lanzafame et al., 1979b). Although this block has been mapped as part of the unmetamorphosed Calabro-Lucano flysch (Monaco et al., 1995), the presence of HP indicative minerals suggest that it is part of the Frido Unit. Continuity between a block and the surrounding matrix would only be expected in the case of sedimentary mélanges, not in the case of tectonic mélanges.

Furthermore, the continentally-derived blocks are often part of a serpentine-matrix mélange. These blocks are likely to have been emplaced as olistostrome slides in the sedimentary basin (Spadea, 1982). This indicates that the serpentinites have been through at least two subduction cycles: one in which granite was tectonically incorporated into a serpentine, creating the mylonitic shear fabric, and a second which involved the subduction of serpentinite blocks which had been deposited in the Frido basin.

It is interesting to note that several other units in this region of Calabria are considered to be sedimentary mélanges. The adjacent Calabro-Lucano mélange is considered to have olistostromal deposition as the main cause of the block-in-matrix fabric (Spadea, 1982; Monaco and Tortorici, 1995; Tortorici et al., 2009). In addition, the Bifurto Unit (Selli, 1957), considered to be the stratigraphic top of the Pollino carbonate unit, appears to be a sedimentary mélange (D'Errico and Staso, 2010). Recycling of sedimentary blocks has recently been noted by Cavazza and Barone (2010) in the Varicolored Clays of Calabria. Although these units are younger and have been metamorphosed at a lower grade than the Frido, the chaotic nature of these formations indicates the unstable nature of the Calabria orogenic wedge front.

TIMPA SAN ANGELO

Frido mélange is exposed at Timpa San Angelo, near the town of Castrovillari (Grandjacquet, 1961; Iannace et al., 2005) (location Figure 3, Figure 8a). At this locality, blocks of carbonate, peridotite, and metabasalt are enclosed in a shale matrix, superposed on the Verbicaro carbonates. Although most of the exposure is in a field, with scattered exotic blocks, in places the relationship between the blocks and matrix is visible (Figure 8d). It appears that the blocks share the same deformation history as the matrix, indicating incorporation previous to the first episode of deformation.

The blocks have been metamorphosed in the blueschist facies. Green carpholite—some of the most pristine in Calabria—is present in carbonates and the metabasalt contains blue amphibole. Although there are no mineralogical indicators of the metamorphic grade of the shale matrix, the fact that the underlying Verbicaro Unit is metamorphosed in the blueschist facies suggests that the entire mélange unit has been metamorphosed.

TERRANOVA DA SIBARI

The exposures of carbonate, phyllite, quartzite, and metabasalt near the town of Terranova da Sibari bear strong similarities to the Frido Unit (Spadea et al., 1976) (location Figure 3). Because of similarities, these outcrops have been considered to be related to the Frido Unit (Spadea et al., 1976; Lanzafame et al., 1979a; Bonardi et al., 1988).

This area was mapped by Spadea et al. (1976), who divided the rocks into two units: a lower nappe containing metabasalts and a sedimentary cover and an upper nappe comprised of pillow basalts and a calcschist cover (Spadea et al. 1976; Lanzafame et al., 1979; Tortorici et al., 2009).

The lower nappe is dominantly calcschist, phyllite, and quartzite with lenses of metabasalt metamorphosed in the lawsonite-blueschist facies. Pressures of 9-11 kbar at a temperature of 350 °C have been estimated from the metabasalts (Liberi et al., 2006). In the present study, we have discovered new exposures of carpholite-bearing phyllite, quartzite, and carbonate at the Vallone Bastardo locality of Spadea et al. (1976). This indicates that both the metabasalts and the sediments associated with lower nappe were metamorphosed in similar high-pressure conditions.

The upper nappe consists of a Calpionella-bearing calcschist with lenses of pillow basalt and its chert cover. The sequence was considered by previous workers to be unmetamorphosed (Spadea et al., 1976); however, these rocks are identical to the pillow basalts exposed at Malvito, which are contain high-Si^{4+} phengite and lawsonite (Liberi et al., 2006). Thus, it is likely that they too are high pressure.

We examined field relationships at three outcrops at Terranova da Sibari (39°39'37.34"N, 16°20'17.44"E), Vallone Bastardo (39°37'46.77"N, 16°17'51.15"E), and Fonte Pippana, each of which were mapped by Spadea et al., (1976).

The unit considered to be the lower nappe is comprised of a lawsonite-blueschist metabasalt overlain by a calcschist and metapelite sedimentary cover; this sedimentary sequence is intercalated with lenses of metabasalt. Good exposures of this nappe can be seen in a gully on the northeast side of Terranova da Sibari. The relationship between the basalt and sediments appears to be primary based on close interfingering between the metabasalt and calcschist. These relationships are illustrated in the tectonostratigraphic column and related description in Figure 10 of Spadea et al. (1976).

The coherent nature of the lower nappe can be seen at also be seen at the Vallone Bastardo exposure, near Terranova da Sibari, where beds of quartzite, carbonate, and phyllite have the character of a broken formation (Hsü, 1977; Festa et al., 2010). Here, carpholite-bearing sandstones appear to be disrupted beds, never forming complete layers, and are surrounded by bedded shale. Nearby, coherent bedded carbonates are metamorphosed in the blueschist-facies, indicated by carpholite growing in calcite veins.

The upper, low-pressure nappe consists of limestone with lenses of reddish-brown pillow basalt. In places a depositional contact of radiolarian chert on basalt is visible. The limestones contain breccia beds which bear nummulites fossils Lutetian (Eocene) age (48.6-40.4 Ma) (Bouillin, 1984; Wallis et al., 1998). In places, there are slices of granite (Spadea et al., 1976; Bouillin; 1984; Wallis et al., 1998) which likely were deposited as olistostromes (Tortorici et al., 2009).

The relationship between the two nappes has been controversial. We will consider three possibilities, as follows:

(1) Most workers consider that the juxtaposition between the two nappes to be due to a thrust fault (Spadea et al., 1976). This thrust arrangement has been extended to other regions in Calabria (Lanzafame et al., 1979a). However, near Terranova da Sibari, there is an unmetamorphosed calcturbidite unit that contains Eocene fossils located between the two units (Bouillin, 1984) (Figure 9a).

The only way this tectonic relationship could be produced with thrusting is by having the upper nappe overthrust a lower nappe, which had already been exhumed and covered with sediment. We considered this to be unlikely as it involved thrusting, then extension, then thrusting; also, this scenario does not explain the lawsonite found in the upper nappe.

(2) Some workers have considered the juxtaposition of a high-pressure metabasalt unit above a low-pressure metabasalt unit to be due to a normal fault (Wallis et al., 1998) (Figure 9a). However, since both nappes contain lawsonite, there may not be the metamorphic pressure discontinuity recognized in previous studies. In addition, a normal fault model does not explain the presence of a thin slice of granite between the low-pressure nappe and high-pressure nappe.

(3) A third possibility, suggested by the present paper, is that the entire unit is a sedimentary mélange, deposited in the Eocene, and metamorphosed in a low-level blueschist facies. In this possibility, there are three types of blocks in a limestone and phyllite matrix: pillow basalts, granites, and lawsonite blueschist facies metabasalt and its cover sequence.

This idea would explain several observations:

> (a) The diversity of metamorphic grades associated with the unit could be due to blocks with different histories being incorporated into a sedimentary matrix. In the original sedimentary sequence both pillow basalts and lawsonite-blueschist metabasalt were incorporated into a calcareous and phyllite matrix.
> (b) There is a hiatus between the age of the upper nappe cover units and the surrounding calcschists. The radiolarian cherts are considered to be Tithonian-Berriasian (Late Jurassic to Early Cretaceous) in age, while the limestones are considered to be Tithonian-Neocomian (also Late Jurassic to Early Cretaceous) in age (Lanzafame et al., 1979a). The matrix has fossils which are Eocene in age. This could be explained if the older units are blocks in a younger matrix.
> (c) The granites could be olistostromal blocks in the calcschist, a possibility suggested by Tortorici et al. (2009).

In addition, this would explain the strange regional relationship between the “upper” nappe and lower “nappe”. The Malvito Unit, an upper-nappe equivalent, is thought to exist throughout Northern Calabria (Dietrich and Scandone, 1972; Lanzafame et al., 1979a; Cello et al. 1996; Liberi et al., 1979). However, the relationship between the Malvito and “lower” nape is not clear. In many places, the Malvito overlies a lower unit (Cello et al., 1996). However, in some places, the pillow basalts appear to be structurally beneath the blueschist metabasalt (Spadea et al., 1979). If all of these blocks are part of a Frido-style mélange, juxtaposition between blocks of different metamorphic grades would be expected.

This raises an important question—if these are merely blocks in mélange, then how did the metamorphic event produce carpholite in the phyllite, carbonate, and quartzites, but only lawsonite and albite in the pillow basalts? Perhaps the oxidation state of basalts is playing a role in metamorphic grade (as in Chapter 2), or the pressures estimated by carpholite are too high. In addition, there are no metamorphic indicators in the Eocene calcturbidite unit. However, oftentimes the calcareous units do not retain evidence of metamorphism, even when they have been to blueschist-facies conditions (Iannace et al., 2005).

Understanding the Frido Unit as a sedimentary mélange is consistent with observations at Monte Reventino, San Severino Lucano, Timpa San Angelo, and Terranova da Sibari. In the following discussion, we will investigate whether this new framework can help us understand the tectonic history of the Frido Unit.

DISCUSSION

(1) What is the metamorphic grade of the Frido Unit?

If blocks in a sedimentary mélange are olistolithic deposits, they may preserve a previous metamorphic history unrelated to the mélange (Wakabayashi, 2011a, 2011b). In this case, the metamorphic grade of the blocks cannot be used to indicate the grade of the unit as a whole. Instead, the metamorphic grade of the sedimentary matrix is more appropriate in determining the grade of the unit

The various lithologies associated with the Frido unit vary from nearly unmetamorphosed to lawsonite-blueschist facies. Many of these observations are of blocks in a matrix, which are likely of sedimentary origin and thus inappropriate for determining the metamorphic grade of the unit. Instead, the metamorphic grade of the Frido must be determined from minerals which grow in the matrix are coincident the main structural phase of deformation.

For the Frido, the blocks in the northern outcrops near San Severino Lucano have been considered to be HP, based on the presence of lawsonite and blueschist in metabasalt blocks (Monaco et al., 1995). The presence of aragonite, in the calcschist subunit, and carpholite, in the sandstone and phyllite subunit, indicate that the matrix in subunits is HP. This indicates that the matrix is isofacial with the blocks: both were metamorphosed in blueschist-facies conditions.

A similar situation exists to the south. Near Terranova da Sibari, there are blocks of pillow basalt and metabasalt in a calcschist and phyllite matrix. The blocks are radically different in appearance in hand sample, with the pillow basalts appearing unmetamorphosed, and the metabasalts clearly lawsonite blueschist. However, petrographic observations indicate that the pillow basalts contain lawsonite (Liberi et al., 2006). Thus it is likely that the entire unit was metamorphosed in a low-level blueschist-facies, with new crystallization of carpholite in matrix phyllite, sandstones, and carbonates, and crystallization of lawsonite in the basaltic blocks.

In the southern part of Frido exposure, map relations indicate that the Monte Reventino unit may be olistostromal blocks near the top of the Frido Unit. In that case, the blueschist-facies metamorphic event recorded in these rocks is not indicative of the mélange as a whole. Instead, the blueschist may have formed earlier in the history of the orogen, perhaps at the same time as the Na-amphibole and lawsonite in the Zangarona Schist (Colonna and Piccarreta, 1975). The blueschist was then exhumed and redeposited in the Frido sedimentary basin.

The Monte Reventino blocks underwent a late greenschist-facies overprint. If this also affected the Frido Unit, then the metamorphic grade of the Frido may be a product of exhumation and not peak metamorphic grade (Chapter 2 of this thesis). In that case, the high-pressure indicators within the Frido Unit may have been destroyed by a greenschist overprint.

In summary, the Frido Unit appears to be a blueschist-facies mélange in the north, as the matrix appears to have HP-indicative minerals, such as aragonite and carpholite (Figure 3). In the southern part of the range, the only indicators of blueschist are in olistostromal blocks, suggesting that the unit may not have undergone a high-pressure event. However, it is also possible that the Frido in the south was a HP unit, but the mineralogical indicators of high pressure were destroyed during exhumation.

(2) What is the age of the Frido Unit?

In Calabria there has been lack of precision with the use of the word “age”. As an accretionary orogen, sedimentary units exposed in Calabria have two distinct ages: the age of deposition and the age of accretion. The age of deposition can be determined paleontologically, or through detrital zircons (Snow et al., 2010). The age of accretion can be determined from the age of metamorphic minerals which crystallize during subduction.

There has been much disagreement about the depositional age of the Frido Unit, mainly because dates from the northern region were used to establish the original age of all Frido-like formations in the entire unit, from north to south. Vezzani (1969) considered the Frido to be lower Cretaceous, based on planktonic foraminifera found in the calcschist subunit of the type locality. Since fossils were rare, or non-existent, in other exposures of the Frido to the south, the type locality date was applied across the orogen (Piccarreta, 1973; Amodio-Morelli et al., 1976; Spadea et al., 1976; Dietrich, 1976; Lanzafame et al., 1979). This date was used to develop a tectonic framework for the Frido Unit, associating it with an early, west-vergent orogen (Amodio-Morelli et al., 1976).

This Cretaceous age was updated by the discovery of Chattian (Chattian = 28.4 – 23.03 Ma) microfossils near the Frido type locality (Bonardi et al., 1993). Even with this new date, most authors continued to consider the Frido in the southern zone to be Cretaceous in age—even though no fossils had been discovered in the southern area—based on the now outdated dates from the type locality (Spadea,1994; Cello et al., 1996; Bonardi et al., 2000). These studies also ignored the Eocene fossils found at Terranova da Sibari by Bouillin (1984).

Thus, the depositional age for the Frido is Oligocene in the north, near the type area, and Eocene, the central part, near Terranova da Sibari. There are no age constraints near Monte Reventino.

Accretionary ages are difficult to determine for much of the unit, since there are few radiometric studies of metamorphic ages. In chapter 3 of this thesis we determined that the blueschist-facies rocks at Diamante, considered to be equivalent to the rocks at Terranova da Sibari, have a phengite Ar/Ar age of 48 Ma. At first, this appears to indicate an accretionary age. However, if this date is extended to similar rocks at Terranova da Sibari it creates a timing problem. Since the rocks at Terranova da Sibari are in contact with an Eocene-aged (48.6-40.4 Ma) sedimentary formation (Figure 9a), then it implies that the Diamante block is a recycled block. The 48 Ma age dates the first episode of subduction that the block underwent.

(3) What is the tectonic style of the Frido Unit?

The Frido is a shale- and serpentinite-matrix mélange, with blocks of ophiolite and continental crust, near its type area (Monaco et al., 1995). Most workers consider it to be a tectonic mélange, with blocks emplaced during a high-strain event (Knott, 1987; Tortorici et al., 2009). In the present chapter, we suggest that the Frido Unit is of sedimentary origin, with the block-in-matrix appearance due to the deposition of olistostromes in a shale matrix.

If most included blocks are olistostromes (Aalto, 1989; Wakabayashi, 2011), then passage between areas that do not involve mélange may not involve a change in tectonometamorphic unit, or in structural style. Instead, the change in character may be due to a facies change between units, from a depositional setting which involves much extrabasinal input, into areas which have dominantly siliciclastic sedimentation.

In places where olistolithic deposition was concentrated, such as near the type area, the Frido appears to have a mélange aspect. Where olistoliths were less common or much larger, for example at Monte Reventino, a stratigraphic appearance dominates, and the unit may resemble a coherent sedimentary unit instead of a mélange.

Indeed, variations through time at single localities are evident. At Monte Reventino, most of the Frido Unit consists of ordered quartzite and phyllite. Only near the top of the unit does a mélange texture begin to develop. This is probably due to the arrival of the unit at the subduction trench and the beginning of the accumulation of submarine landslide material.

Sedimentary mélanges have been increasingly recognized in the Franciscan Complex, where evidence is increasingly showing that mélange are sedimentary, as opposed to tectonic (Wakabayashi, 2011a, 2011b). Serpentine-matrix-mélanges are showing depositional contacts with surrounding units, indicating that the incorporation of exotic blocks took place via landsliding mechanisms on the ocean floor.

(4) Could the Frido Unit represent the sedimentary cover of the Verbicaro carbonate unit?

One question that should be briefly addressed is whether the Frido Unit could be the sedimentary cover of the underlying carbonate unit. The sedimentary cover of the Verbicaro Unit is seen at the Alberosa locality just north of the town of Verbicaro (Iannace et al., 2007). At this locality, the metamorphosed platform carbonates consist of Jurassic cherty metalimestone, covered discomformably by the calcareous metaconglomerates of the Colle Trodo Formation. An intermediate marly sequence, dated to Eocene to early Miocene by Grandjacquet and Grandjacquet (1962) leads upward into the phyllites and calcschists of the Fiume Lao Schist

(Iannace et al., 2007). The presence of carpholite in the Fiume Lao Schist indicates that the entire unit was metamorphosed in blueschist-facies conditions (Iannace et al., 2007). The continuity between the Verbicaro Unit and the Fiume Lao Schist, both in sedimentary age and metamorphic grade, indicates that they should considered to be one unit (D'Errico and Di Staso, 2010).

The Verbicaro Unit is structurally overlain by the Diamante ophiolite unit, which we argue in the present paper is equivalent to the Frido Unit exposures at Terranova da Sibari (Cello et al., 1994; Iannace et al., 2005, 2007; D'Errico and Di Staso, 2010). If we take these rocks to be Eocene in age, as indicated by fossils from Terranova da Sibari (Bouillin, 1984), they are a separate nappe which was accreted earlier than the Aquitanian sedimentary rocks of the upper Verbicaro Unit.

Thus, it is unlikely that the Verbicaro Unit and the Frido Unit are lateral equivalents. Instead, the older Frido Unit is structurally above the Verbicaro Unit, having been accreted earlier, in agreement with all published literature.

However, it is important to note that the Frido Unit does not always overlie the HP Verbicaro Unit. At the type area of the Frido Unit most authors consider the Frido to be distinct from the underlying Pollino Unit (Bonardi et al., 1988, 2001; Monaco et al., 1995). This is because the underlying unit is low-pressure, implying a metamorphic pressure discontinuity between the two units (Iannace et al., 2005).

ALONG-STRIKE VARIATION IN MELANGE

Do units associated with the Frido represent one unit? Why do its characteristics change along strike?

Our observations indicate that the Frido Unit is a sedimentary mélange, deposited at the toe of the orogenic wedge as it approached the trench. The mélange blocks appear to be concentrated at the top of the formation, as would be expected if olisotromes were derived from the front of the wedge and were deposited on an existing sedimentary sequence (Festa, 2010).

The blocks in the Frido Unit are represented by various blocks, as follows:
northern (San Severino): serpentinite, lower continental crust, metabasalt and cover
central (Diamante-Terranova): metabasalt and calcschist, pillow basalts and radiolarian chert
southern (Monte Reventino): metabasalt, serpentinite

The blueschist and serpentinite blocks are multi-cycle, having been involved in a previous cycle of subduction. The blueschist-facies metabasalts, possibly derived from an extruded nappe associated with the high-pressure Zangarona Schist, were deposited in the Frido basin and subducted for a second time after the Eocene. Serpentinite blocks, which served as a matrix tectonically enclosing blocks of lower continental crust were also redeposited in the sedimentary basin. Similar multi-cycle blocks have been recognized in other orogens, such as the Franciscan Complex of California (Wakabayashi, 2011a, 2011b) and the Sanbagawa of Japan (Osozawa et al., 2009).

The entire unit appears to have been metamorphosed at low temperature with a moderate pressure, forming carpholite in carbonates and quartzites, and lawsonite in the pillow basalts. The peak metamorphic pressures may have been similar along the length of the unit; however, along the southern edge of the orogen exhumation took place in the greenschist facies.

The lithological and metamorphic characteristics of the Frido Unit appears to be relatively continuous along the 130 km length of the orogen; however, to show that it was accreted as one body the accretion age at different exposures needs to be determined. A continuous unit should have the same accretion age along the entire length of the orogen. For the Frido, we do not have a direct record of the accretionary age through radiometric dates. However, we can estimate it indirectly by determining the youngest sedimentary deposit in each exposure. The youngest sedimentary ages provide an upper limit to the accretionary age of a formation.

In the northern outcrops around San Severino Lucano the Frido Unit is Upper Oligocene in age. In the south, nummulites indicate that the Frido Unit is Eocene in age. These two data points imply that the Frido Unit in the south is older than the Frido Unit in the north. However, these are only estimates of accretionary age and more detailed stratigraphic work is necessary to show that the accretionary age of the unit is similar along the length of the orogen.

CONCLUSION

The determination of along-strike continuity of units can be a difficult task in orogenic belts. Units often vary in protolith composition, peak metamorphic grade, age of metamorphism, degree of retrograde metamorphism, age of retrograde metamorphism, and tectonic style. In sedimentary mélanges, along-strike correlations can be especially difficult because of the distinct history recorded by included blocks and because of sedimentary facies changes along strike.

This has certainly been the case with the Frido Unit of Calabria, which varies in appearance between mélange and coherent nappe. In the northern half of Calabria, the Frido Unit is often a shale-matrix mélange which often encloses or supports scraps of exotic material, including peridotite and metabasalt. In the southern half, the Frido Unit is considered to be a strong, quartzite rich unit, with thrust-sheet scale continuity. The concept of a type locality, located in a single place in the northern part of Calabria, has been unsuccessful in capturing the variety of tectonic styles exposed along the length of the orogen.

If the Frido Unit is understood as a sedimentary mélange, a consistent character emerges. It is a blueschist facies unit, with a shale, sandstone, and carbonate protolith, which includes three types of olistostromal blocks: blueschist-facies metabasalt recycled from an earlier stage of the orogen, blocks from the much older Hercynian Unit, and fragments of Tethyan crust. This unit was likely metamorphosed in the Oligocene, based on the youngest fossils preserved in the sedimentary matrix. Lower stratigraphic levels appear to be coherent, while the upper levels contain a majority of the mélange. The along-strike difference, with alternation between mélange and thrust sheet, can be explained with sedimentation coming from different sources. Recognizing that a mélange unit has a sedimentary origin is a key component in understanding the metamorphic history of the Calabrian Orogen and is relevant to other orogens.

ACKNOWLEDGEMENTS

I would like to thank John Wakabayashi and Walter Alvarez for reviewing several drafts of this chapter. Francesca Liberi and Eugenio Piluso of the University of Calabria are thanked for helpful discussions and hospitality. I would also like to thank the Alessio and Locher families of Cosenza for support during field research, and Sylvia Moses for help in field work.

REFERENCES

Aalto, K.R., 1989, Franciscan Complex olistostrome at Crescent City, northern California: Sedimentology, v. 36, p. 471-495.

Abbate, E., Bortolotti, V., and Passerini, P., 1970, Olistostromes and olistoliths, in, Sestini, G., ed., Development of the Northern Apennines Geosyncline: Sedimentary Geolology, v. 4, no. 3–4, p. 521–557.

Alvarez, W., Cocozza, T., and Wezel, F.C., 1974, Fragmentation of the Alpine orogenic belt by microplate dispersal: Nature, v. 248, p. 309-314.

Alvarez, W., 2005, Structure of the Monte Reventino greenschist folds: a contribution to untangling the tectonic-transport history of Calabria, a key element in Italian tectonics: Journal of Structural Geology, v. 27, p. 1355-1378.

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., and Zuppetta, A.,1976, L’arco Calabro-Peloritano nella’orogene Appenninico-Maghrebide: Memorie della Società Geologica Italiana, v. 17, p. 1-60.

Acquafredda, P., Lorenzoni, S., Lorenzoni, E.Z., 1994, The Bocchigliero Paleozoic sequence in the context of the Calabrian-Peloritan Herycnian Range (Italy): Geological Journal, v. 29, p. 45-58.

Barber, T., and Brown, K., 1988, Mud diapirism: The origin of melanges in accretionary complexes?: Geology Today, v. 4, p. 89–94.

Bonardi, G., Amore, F.O., Ciampo, G., de Capoa, P., Miconnet, P., and Perrone, V., 1988, Il complesso Liguride Auct.: Stato delle conoscenze e problemi aperti sulla evoluzione Pre-Apenninica ed I suoi rapporti con l’arco Calabro: Memorie della Società Geologica Italiana, v. 41, p. 17-35.

Bonardi, G., de Capoa, P., Fioretti, B., and Perrone, V., 1993, L’age des metacalcaires de l’Unite du Frido, (region calabro-lucanienne, Italie) et ses implications geodynamique: C. R. Acad. Sci. Paris, v. 317, p. 955-962.

Bonardi, G., Cavazza, W., Perrone, V., and Rossi, S., 2001, Calabria-Peloritani Terrane and northern Ionian Sea, in, Anatomy of an Orogen, Vai, G.B., and Martini, J.P., eds., p. 287-306: Kluwer Academic, Norwell MA.

Bouillin, J.-P., 1984, Nouvelle interprétation de la liaison Apennin-Maghrébides en Calabre; conséquences sur la paléogéographie téthysienne entre Gibraltar et les Alpes: Revue de Géologie Dynamique et de Géographie Physique, v. 25, p. 321-338.

Bousquet, J.-C., 1971, La tectonique tangentielle des series calcareo-dolomitiques du nord est de l’apennin Calabro-Lucanien (Italie Meriodionale): Geologica Romana, v. 10, p. 23-52.

Bousquet, R., Goffé, B., Vidal, O., Oberhänsli, and Patriat, M., 2002, The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: New constraints on the evolution of the Alps: Geological Society of America Bulletin, v. 114, p. 207-225.

Busato, S., and Giampaolo, C., 1983, Ferrocarpholite from Mormanno (Northern Calabria, Italy): Periodico di Mineralogia, v. 52, p. 403-426.

Caire, A., Glangeaud, L., and Grandjacquet, C., 1960, Les grands traits etructuraux et l’évolution du territoire calabro-sicilien (Italie méridionale): Bulletin de la Société Géologique de France, v. 72, p. 915-938.

Cavazza, W., and Barone, M, 2010, Large-scale sedimentary recycling of tectonic melange in a forearc setting: The Ionian basin (Oligocene-Quaternary, southern Italy): Geological Society of America Bulletin, v. 122, p. 1932-1949.

Cello, G., Invernizzi, C., and Mazzoli, S., 1996, Structural signature of tectonic processes in the Calabrian Arc, southern Italy: Evidence from the oceanic-derived Diamante-Terrnova unit: Tectonics, v. 15, p.187-200.

Cloos, M., 1982, Flow melanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California: Geological Society of America Bulletin, v. 93, p. 330–345.

Colonna, V., and Piccarreta, G., 1975, Schema strutturale della Sila Piccola Meridionale: Bolletino della Società Geologica Italiana, v. 94, p. 3-16.

Colonna, V., and Piccarreta, G., 1976, Contributo alla conoscenza dell’unita di Castagna in Sila Piccola: Rapporti tra micascisti, paragneiss e gneiss occhiadini: Bollettino della Società Geologica Italiana, v. 95, p. 1-10.

Colonna, V., and Zanettin Lorenzoni, E., 1973, Sulla presenza di un complesso equiparabile alla Formazione del Frido” nella zona di Gimigliano (Catanzaro): Atti Acc. Pont. Napoli, n.s., v. 22, 11 p.

Cowan, D.S., 1978, Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San Simeon, California: Geological Society of America Bulletin, v. 89, p. 1415–1423.

Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451-462.

De Roever, E.W.F., 1972, Lawsonite-albite facies metamorphism near Fuscaldo, Calabria (Southern Italy), its geological significance and petrological aspects: GUA Papers in Geology, ser. 1, v. 3, 171 p.

D'Errico, M., and Di Staso, A., 2010, Stratigraphic revision of the Cenozoic deposits of the Lungro-Verbicaro Unit (Northern Calabria): new data for the reconstruction of tectonic evolution of the southern Apennines: Italian Journal of Geoscience, v. 129, p. 450-456.

Dietrich, D., 1976, La geologia della Catena Costiera Calabra tra Cetraro e Guardia Piemontese: Memorie della Società Geologica Italiana, v. 17, p. 61-121.

Deitrich, D., and Scandone, P., 1972, The position of the basic and ultrabasic rocks in the tectonic units of the Southern Apennines: Atti della Accademia pontaniana, v. 21, p. 61-75.

Dilek, Y., 2003, Ophiolite pulses, mantle plumes, and orogeny, in, Dilek, Y.,and Robinson, P.T., eds., Ophiolites in Earth History: Geological Society Special Publication, v. 218, p. 9-19.

El-Shazly, A.K., 1995, Petrology of Fe-Mg-carpholite-bearing metasediments from NE Oman: Journal of Metamorphic Geology, v. 13, p. 379-396.

Festa, A., Pini, G.A., Dilek, Y., and Codegone, G., 2010, Mélanges and mélange-forming processes: a historical overview and new concepts: International Geology Review, v. 52, p. 1040-1105.

Grandjacquet, C., 1961, Le «flysch à quartzites» des territoires calabro-lucaniens (Italie méridionale): Bulletin de la Société Géologique de France, ser. 7, v. 3, p. 115-120.

Grandjacquet, C., and Gradjacquet, M.J., 1962, Geologie de la zone de Diamante-Verbicaro (Calabre): Geologica Romana, v. 1, p. 297-312.

Graessner, T., and 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, v. 42, p. 931-961.

Greenly, E., 1919, The Geology of Anglesey, Vols I and II: Memoirs of Geological Survey: London, HM Stationary Office, p. 1–388, 390–980.

Guerrera, F., Martín-Martín, M., Perrone, V., and Tramontana, M., 2005, Tectono-sedimentary evolution of the southern branch of the Western Tethys (Maghrebian Flysch Basin and Lucanian Ocean): consequences for Western Mediterranean geodynamics: Terra Nova, v. 17, p. 358-367.

Hsü, K.J., 1968, Principles of mélanges and their bearing on the Franciscan-Knoxville Paradox: Geological Society of America Bulletin, v. 79, p. 1063–1074.

Iannace, A., Bonardi, G., D’Errico, M., Mazzoli, S., Perrone, V., and Vitale, S., 2005a, Structural setting and tectonic evolution of the Apennine Units of northern Calabria: Comptes Rendus Geoscience, v. 337, p. 1541-1550.

Iannace, A., Garcia-Tortosa, F.J., and Vitale, S., 2005b, Triassic metasedimentary successions across the boundary between the southern Apennines and the Calabria Arc (northern Calabria, Italy): Geological Journal, v. 40, p. 155-171.

Iannace, A., Vitale, S., D’Errico, M., Mazzoli, S., Di Staso, A., Macaione, E., Massina, A., Reddy, S.M., Somma, R., Zamparelli, V., Zattin, M., and Bonardi, G., 2007, The carbonate tectonic units of northern Calabria (Italy): A record of Apulian palaeomargin evolution and Miocene convergence, continental crust subduction, and exhumation of HP-LT rocks: Journal of the Geological Society, v. 164, p. 1165-1186.

Ietto, A., Perri, E., and Ietto, F., 1995, The sequence of Mount Cocuzzo (Catena Costiera, Calabria) in the dolomitic Trias of Southern Apennines: Bollettino della Società Geologica Italiana, v. 114, p. 215-244.

Johannes, W., and Puhan, D., 1971, The calcite-aragonite transition, reinvestigated: Contributions to Mineralogy and Petrology, v. 31, p. 28-38.

Kastens, K., Mascle, J., and others, 1988, ODP Leg 107 in the Tyrrhenian Sea: Insights into passive margin and back-arc basin evolution: Geological Society of America Bulletin, v. 100, p. 1140-1156.

Knott, S.D., 1987, The Liguride Complex of southern Italy—a Cretaceous to Paleogene accretionary wedge: Tectonophysics, v. 142, p. 217-226.

Knott, S.D., 1994, Structure, kinematics and metamorphism in the Liguride Complex, southern Apennines, Italy: Journal of Structural Geology, v. 16, p. 1107-1120.

Lanzafame, G., Spadea, P., and Tortorici, L., 1979a, Mesozoic ophiolites of Northern Calabria and Lucanian Apennine (Southern Italy): Ofioliti, v. 4, p. 173-182.

Lanzafame, G., Spadea, P., and Tortorici, L., 1979b, Relazioni stratigrafiche tra ofioliti e Formazione del Frido nella Calabria settentrionale e nell’Appennino lucano: Ofioliti, v. 4, p. 178-182.

Liberi, F., Morten, L., and Piluso, E., 2006, Geodynamic significance of ophiolites within the Calabrian Arc: Island Arc, v. 15, p. 26-43.

Lockwood, J., 1971, Sedimentary and gravity-slide emplacement of serpentinite: Geological Society of America Bulletin, v. 82, p. 919-936.

Lucente, C.C., and Pini, G.A., 2003, Anatomy and emplacement mechanism of a large submarine slide within the Miocene foredeep in the Northern Apennines, Italy: A field perspective: American Journal of Science, v. 303, p. 565–602.

Lustrino, M., Morra, V., Fedele, L., and Franciosi, L., 2009, Beginning of the Apennine subduction system in central western Mediterranean: Constraints from Cenozoic "orogenic" magmatic activity of Sardinia, Italy: Tectonics, v. 28, TC5016, doi:10.1029/2008TC002419.

Malinverno, A., and Ryan, W.B.F., 1986, Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking in the lithosphere: Tectonics, v. 5, p. 227-245.

Massone, H.-J., and Schreyer, W., 1987, Phengite geobarometry based on the limited assemblage with K-felspar, phlogopite and quartz: Contributions to Mineralogy and Petrology, v. 96, p. 212-224.

Monaco, C., and Tortorici, L., 1995, Tectonic role of ophiolite-bearing terranes in the development of the Southern Apennines orogenic belt: Terra Nova, v. 7, p. 153-160.

Monaco, C., Tansi, C., Tortorici, L., De Francesco, A.M., and Morten, L., 1991, Analisi geologico-strutturale dell'Unità del Frido al confine Calabro-Lucano (Apennino Meridionale): Memorie della Società Geologica Italiana, v. 47, p. 341-353.

Monaco, C., Tortorici, L., Morten, L, Criteeli, S., and Tansi, C., 1995, Geologia del versante nord-orientale del massiccio del Pollino (confine Calabro-Lucano): Nota illustrative sintetica della carta geologica alla scalla 1:50.000: Bollettino della Società Geologica Italiana, v. 114, p. 277-291.

Mutti, E., Bernoulli, D., Ricci Lucchi, F., and Tinterri, R., 2009, Turbidites and turbidity currents from Alpine 'flysch' to the exploration of continental margins: Sedimentology, v. 56, p. 267–318.

Ogniben, L., 1973, Schema geologico della Calabria in base ai dati odierni: Geologica Romana, v. 12, p. 243-585.

Osozawa, S., Morimoto, J., and Flower, M.F.J., 2009, "Block-in-matrix" fabrics that lack shearing but possess composite cleavage planes: A sedimentary melange origin for the Yuwan accretionary complex in the Ryukyu island arc, Japan: Geological Society of America Bulletin, v. 121, p. 1190-1203.

Piccarreta, G., and Zirpoli, G., 1970, Contributo alla conoscenza delle metamorfiti comprese fra Martirano e Falerna (Calabria): Bollettino della Società Geologica Italiana, v. 89, p. 113-144.

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

Piccarreta, G., 1981, Deep-rooted overthrusting and blueschist metamorphism in compressive continental margins. An example from Calabria (Southern Italy): Geological Magazine, v. 118, p. 539-544.

Pini, G.A., 1999, Tectonosomes and olistostromes in the Argille Scagliose of the Northern Apennines, Italy: Geological Society of America Special Paper 335, 73 p.

Principi, G., and Treves, B., 1984, Il sistema Corso-Appenninico come prisma d'accrezione. Riflessi sul problema generale del limite Alpi-Appennini: Memorie della Società Geologica Italiana, v. 28, p. 549-576.

Raymond, L., 1984, Classification of melanges, in, Raymond, L.A., eds., Melanges: Their nature, origin and significance: Geological Society of America Special Paper 198, p. 7-20.

Rossetti, F., Faccenna, C., Goffé, B., Monié, P., Argentier, A., Funiciello, R., and 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, v. 20, p. 112-133.

Rossetti, F., Goffé, B, Monié, P, Faccenna, C., and Vignaroli, G., 2004, Alpine orogenic P-T-t-deformation history of the Catena Costiera area and surroudnign regions (Calabrian Arc, southern Italy): The nappe edifice of north Calabria revised with insights on the Tyrrhenian-Apennine system formation: Tectonics, v. 23, TC6011, doi:10.1029/2003TC001560.

Selli, R., 1957, Sulla trasgressione del Miocene nell'Italia Meridionale: Giornale di Geologia, v. 26, p. 1-54.

Shreve, R.L., and Cloos, M., 1986, Dynamics of sediment subduction, melange formation, and prism accretion: Journal of Geophysical Research, v. 91, p. 10229-10245.

Silver, E.A., and Beutner, E.C., 1980, Melanges: Geology, v. 8, p. 32–34.

Snow, C.A., Wakabayashi, J., Ernst, W.G., and Wooden, J.L., 2010, Detrital zircon evidence for progressive underthrusting in Franciscan metagraywackes, west-central California, v. 122, p. 282-291.

Spadea, P., 1976, I carbonati nelle rocce metacalcaree della formazione del Frido della Lucania: Ofioliti, v. 1, p. 431-456.

Spadea, P., Tortorici, L., Lanzafame, G., 1976, Serie ofiolitifere nell'area fra Tarsia e Spezzano Albanese (Calabria): Stratigrapfia, petrografia, rapporti strutturali: Memorie della Società Geologica Italiana, v. 17, p. 135-174.

Spadea, P., 1982, Continental crust rocks associated with ophiolites in Lucanian Apennine (Southern Italy): Ofioliti, v. 7, p. 501-522.

Spadea, P., 1994, Calabria-Lucania ophiolites: Bollettino Geofisica Teorica Applicata, v. 36, p. 141-144.

Terabayashi, M., and Maruyama, S., 1998, Large pressure gap between the Coastal and Central Franciscan belts, northern and central California: Tectonophysics, v. 285, p. 87-101.

Theye, T., Seidel, E., and Vidal, O., 1992, Carpholite, sudoite, and chloritoid in low-grade high-pressure metapelites from Crete and Peloponnese, Greece: European Journal of Mineralogy, v. 4, p. 487-507.

Tortorici, L., Catalano, S., and Monaco, C., 2009, Ophiolite-bearing melanges in southern Italy: Geological Journal, v. 44, p. 153-166.

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

Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: v. 100, p. 19-40.

Wakabayashi, J., 2011a, Mélanges of the Franciscan Complex, California: Diverse structural setting, evidence for sedimentary mixing, and their connection to subduction processes, in, Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of Formation and Societal Significance: Geological Society of America Special Paper.

Wakabayashi, J., 2011b, Subducted sedimentary serpentinite mélanges: Record of multiple burial exhumation cycles and subduction erosion: submitted to Tectonophysics.

Wallis, S.R., Platt, J.P., and Knott, S.D., 1993, Recognition of syn-convergent extension in accretionary wedges with examples from the Calabrian Arc and the Eastern Alps: American Journal of Science, v. 293, p. 463-495.

Westbrook, G.K., and Smith, M.J., 1983, Long decollements and mud volcanoes: Evidence from the Barbados Ridge Complex for the role of high pore-fluid pressure in the development of an accretionary complex: Geology, v. 11, p. 279–283.

APPENDIX

USING MG-CARPHOLITE TO DETERMINE ALONG-STRIKE VARIATION IN METAMORPHIC GRADE

In this chapter, we report the occurrence of Mg-carpholite in several new localities in Calabria. Mg-carpholite is important in determining the HP conditions experienced in pelitic compositions (Theye et al., 1992; Bousquet et al., 2002).

Since differences in metamorphic grade are an important basis in distinguishing two different tectonometamorphic units, it is important to discuss the previously reported differences in metamorphic grade at different localities of the Frido Unit (Figure 3). The recognition of Mg-carpholite as a blueschist-facies indicator in metapelites has allowed the Frido Unit, previously considered to be epimetamorphic, to be thought of as a high-pressure blueschist-facies unit in places (Iannacet et al., 2005a, 2007). As part of this study, several new localities containing Mg-carpholite were found.

Both Mg- and Fe- carpholite ($(Mg, Fe)Al_2Si_2O_6(OH)_4$) are considered to be indicators of high pressure metamorphic conditions in metapelites (Theye et al., 1992; El-Shazly, 1995; Rossetti et al., 2001, 2004). Furthermore, the equilibrium,

3 Car + 2 Phe = 2 W + 5 Qtz + Chl + 2 Ms

can be used to established pressure based on the Si^{4+} content of phengite, with higher Si^{4+} indicating high crystallization pressures (Bousquet et al., 2002).

In separate reaction,

Car = Cld + Qtz + W

X_{Mg} of carpholite can be used to established temperature, with higher X_{Mg} indicating higher temperatures (Bousquet et al., 2002). This pair of equations was used by Rossetti et al. (2001, 2004) to determine metamorphic conditions in the sedimentary cover related to the blueschist-facies Calabrian ophiolite unit.

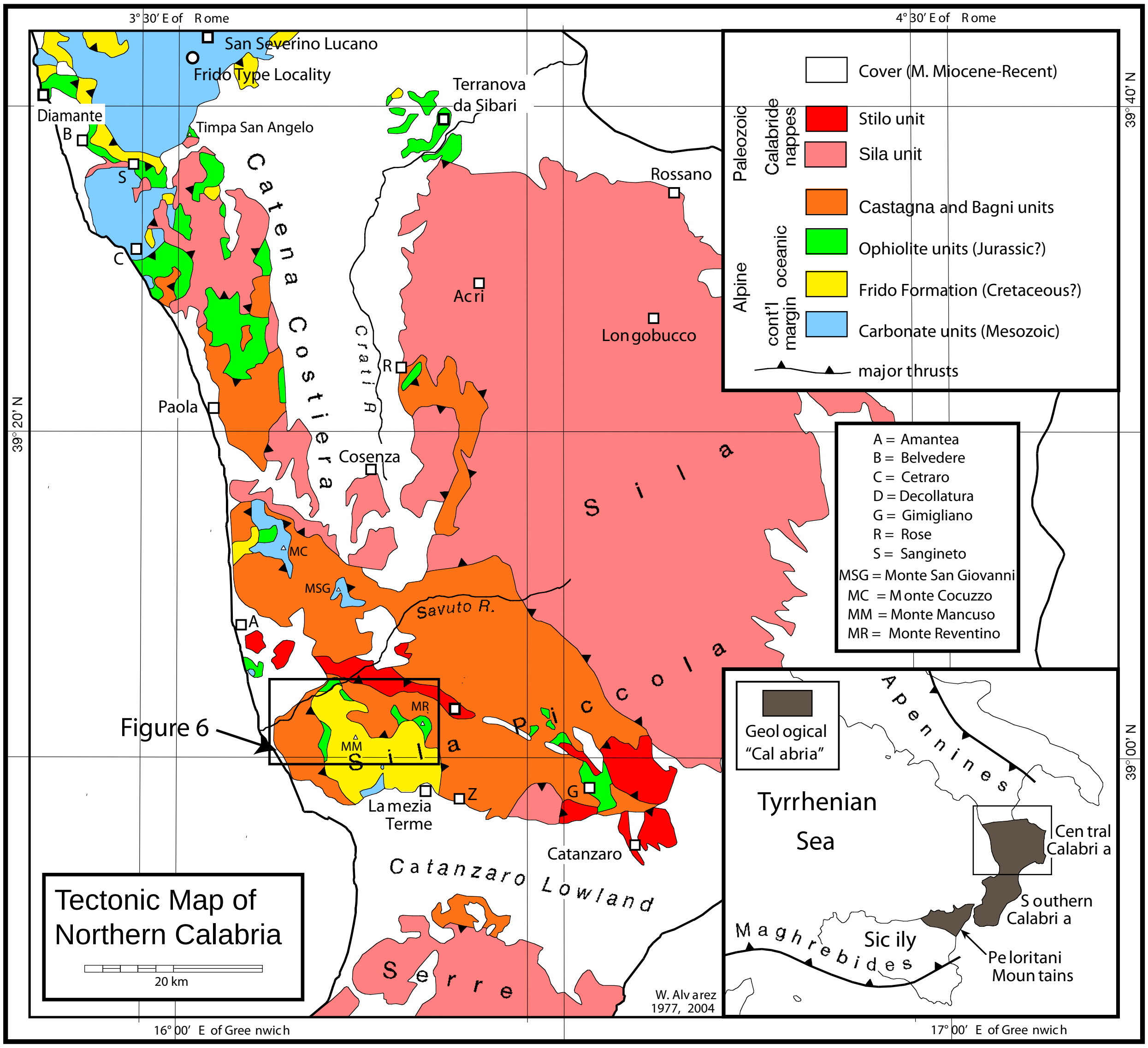


Figure 1. Tectonic map of Northern Calabria. The Frido Unit is closely associated with the ophiolite units of Calabria.

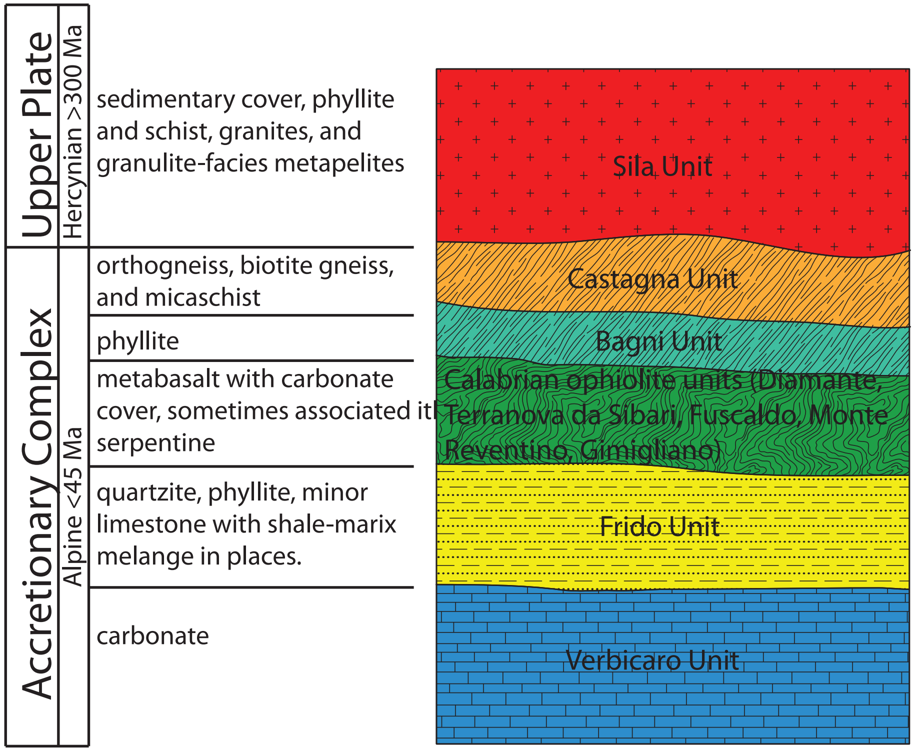


Figure 2. The tectonic units of Calabria. The Sila Unit represents the upper plate of an Alpine-aged subduction system. All units of the accretionary complex bear evidence of blueschist-facies metamorphism.

Correlation of lowest phyllite unit across Northern Calabria

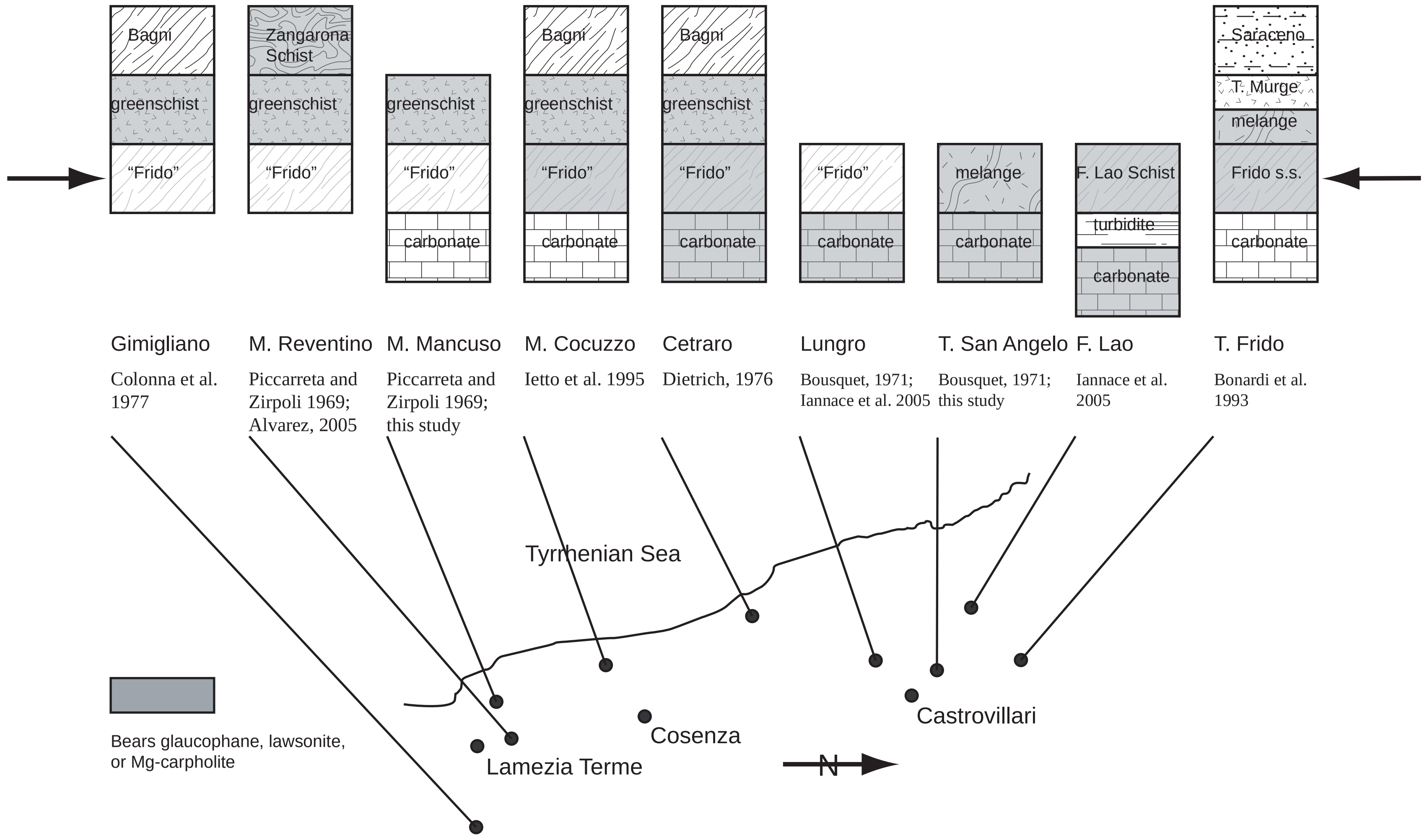


Figure 3. Correlation of exposures considered to be part of the Frido Unit in Amodio-Morelli et al. (1976).

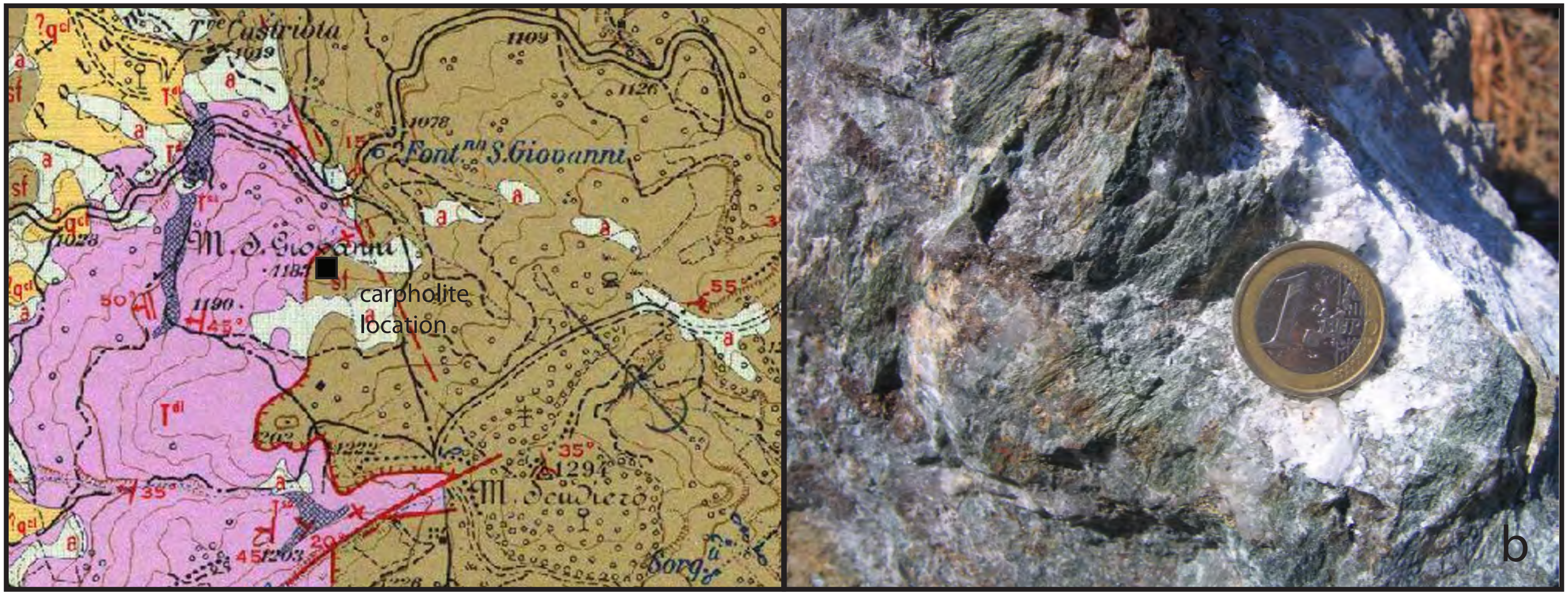


Figure 4. a) Location of carpholite locality. b) Carpholite in a phyllite and quartzite boulder at Monte San Giovanni, just southeast of Monte Cocuzzo.

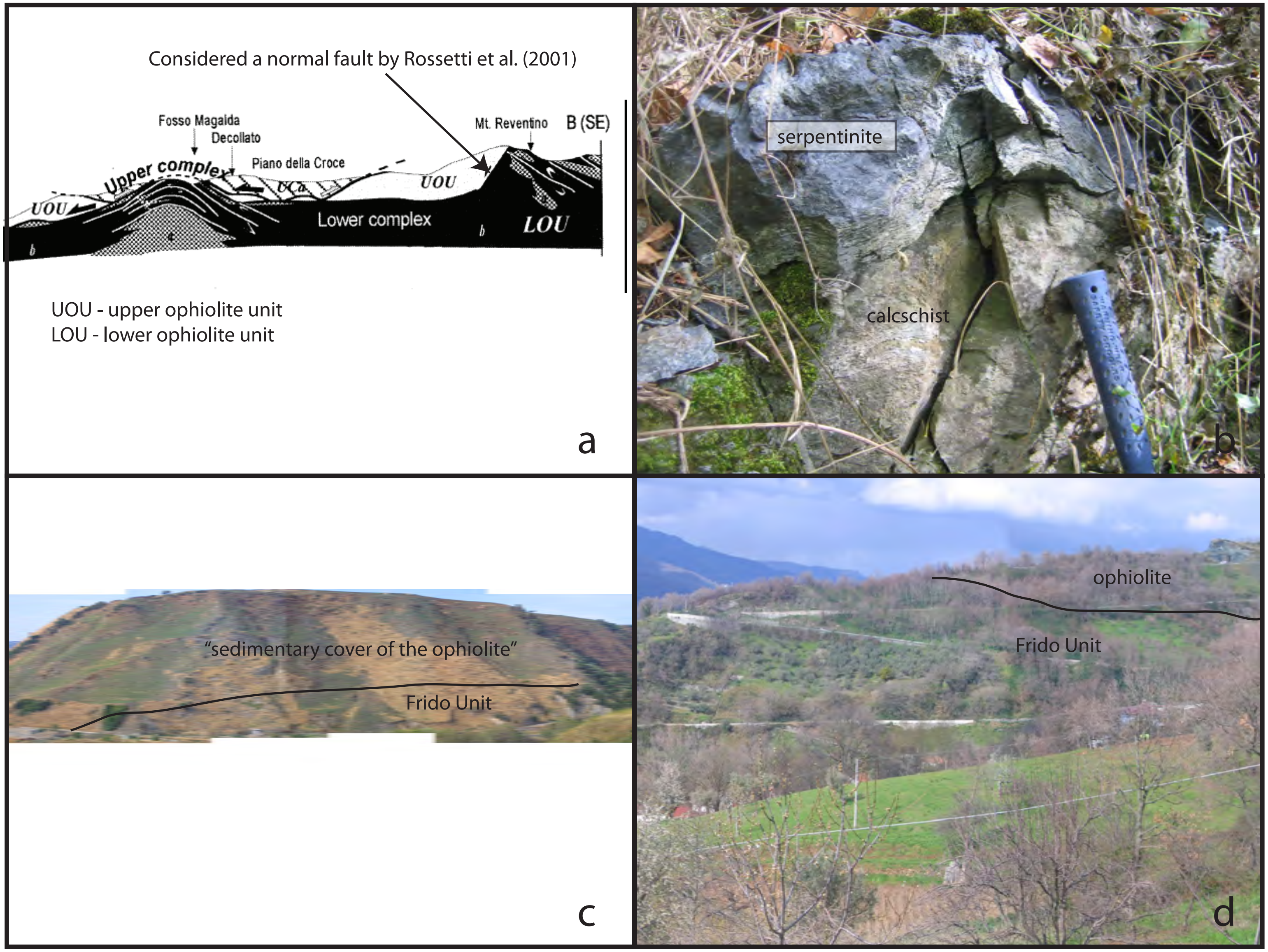


Figure 5. a) Cross section of upper ophiolite-lower ophiolite complex from Rossetti et al. (2001). b) Contact between serpentinite, above, and calcschists of the Frido Unit, below. c) Near the mouth of the Savuto River, the Frido lies beneath the ophiolite unit. d) Contact between the ophiolite unit and the Frido Unit just east of San Mango.

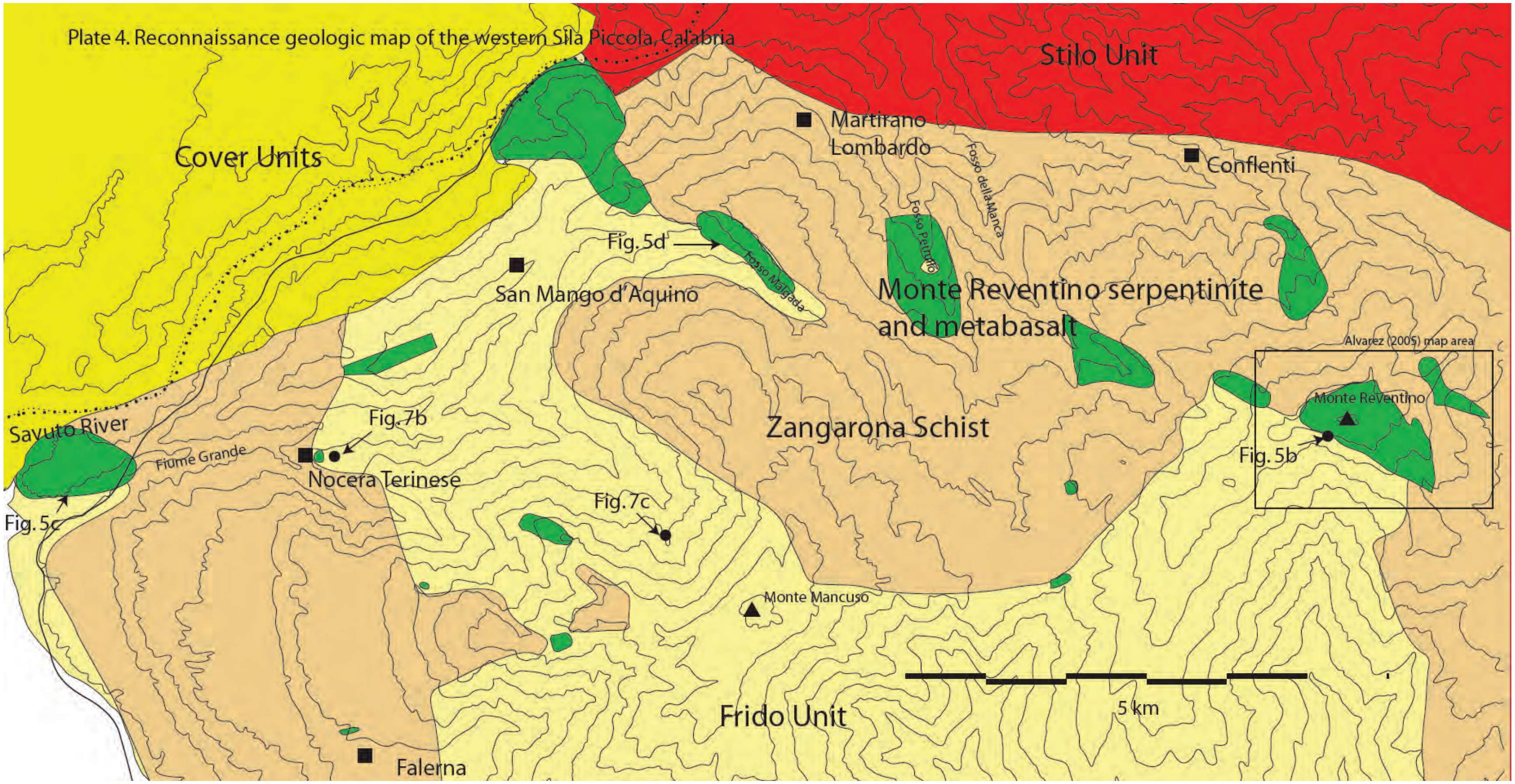


Figure 6. Reconnaissance geologic map of the western Sila Piccola, Calabria. See Plate 4 for full-sized version.

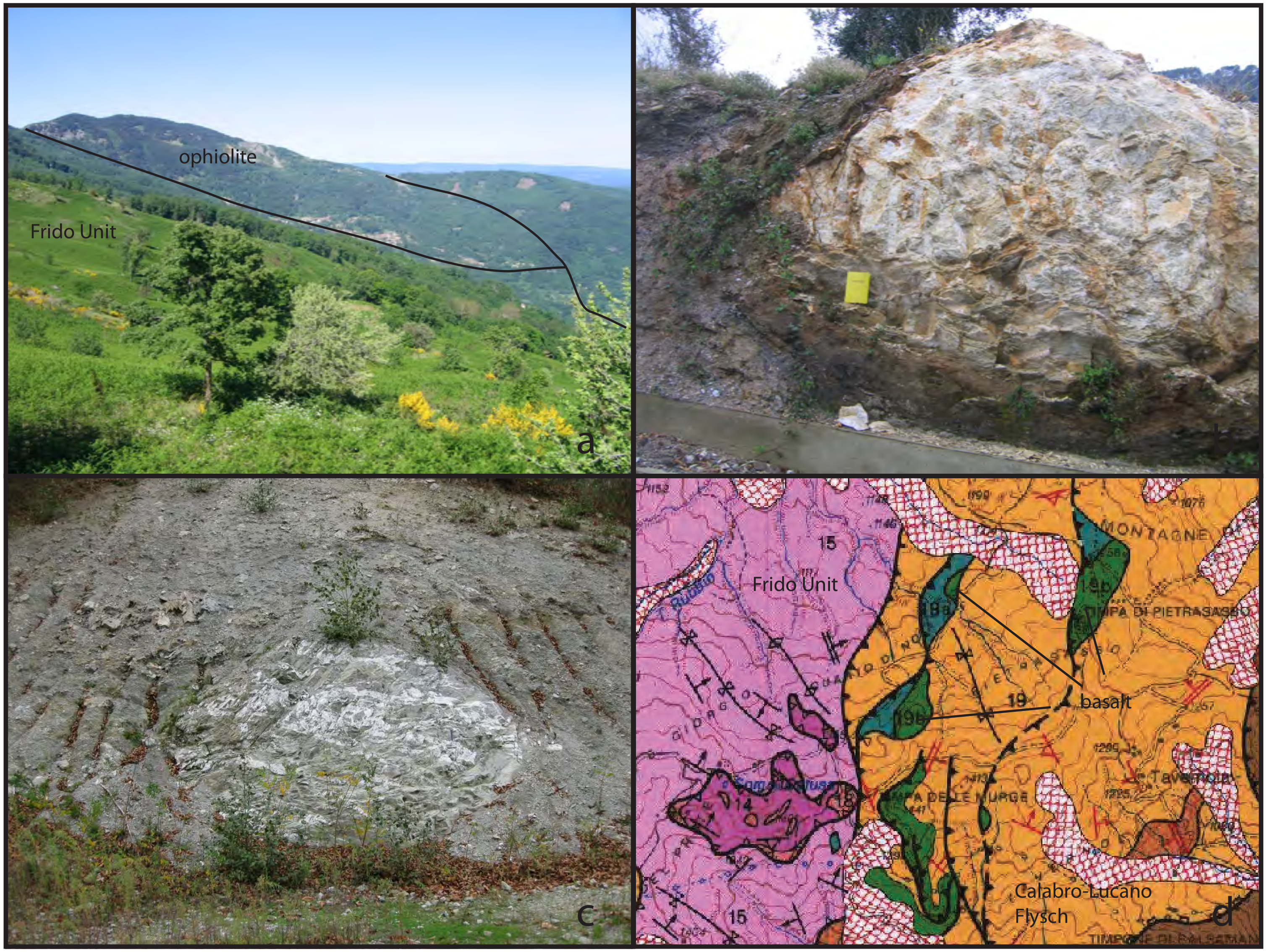


Figure 7. a) View of south face of Monte Reventino showing the thin sliver of metabasalt and serpentine between the Zangarona Schist and Frido Unit. b) Block of granite in Frido Unit just east ofFalerna. c) Block of sandstone in Frido Unit shale matrix. d) Map of the San Severino are showing the location of serpentine-matrix melange (unit 19a), from Monaco et al. (1995).

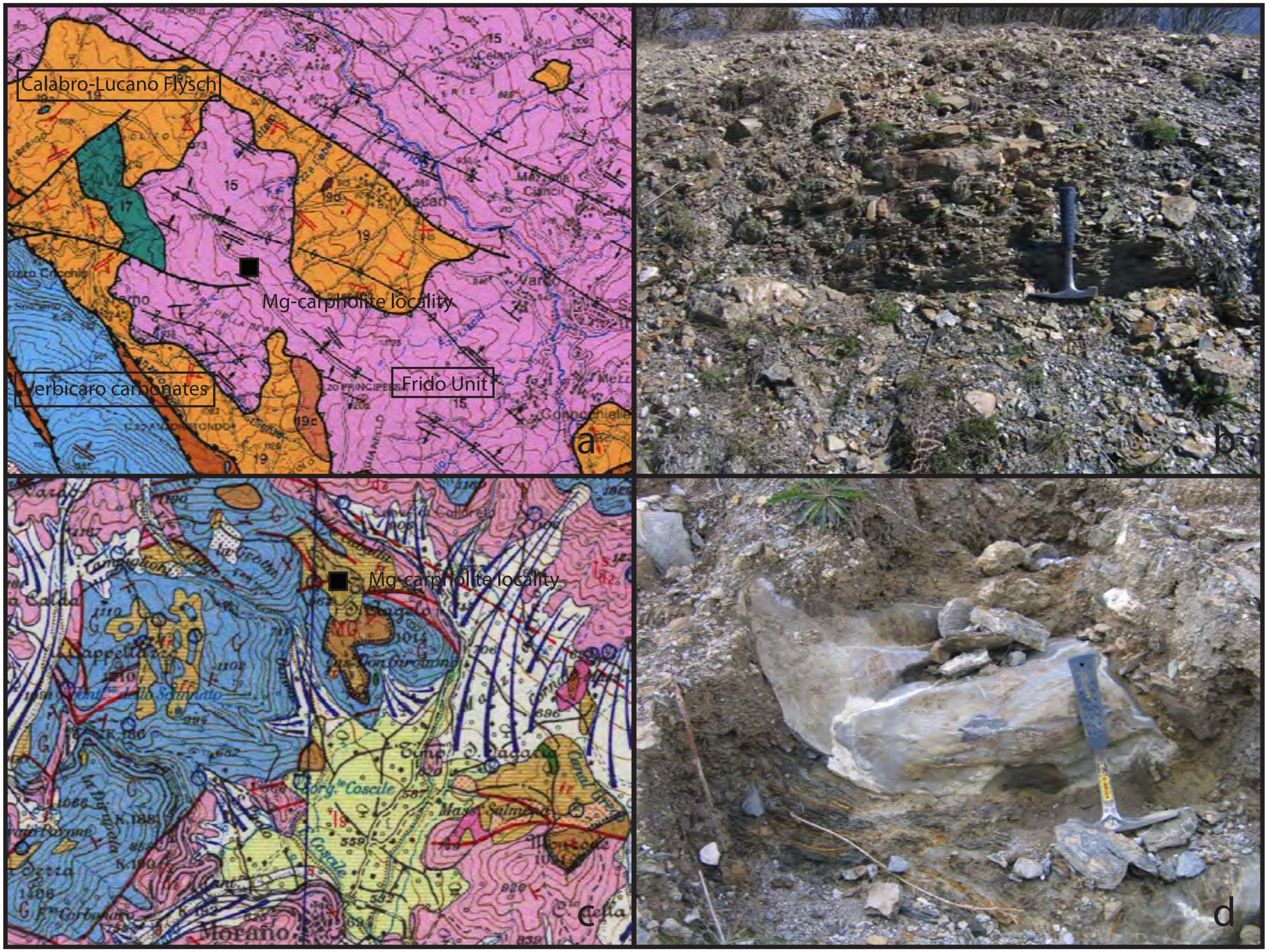


Figure 8. a) Mg-carpholite in Frido Unit west of Torrente Frido. Geologic map is from Monaco et al. (1995) b) Thinly-bedded shales and sandstones of the Frido Unit where carpholite is present in veins c) Timpa San Angelo, just north of Morano Calabro, where a flysch unit contains blocks of carpholite d) A block of carpholite-bearing carbonate in the shale-matrix melange at Timpa San Angelo.

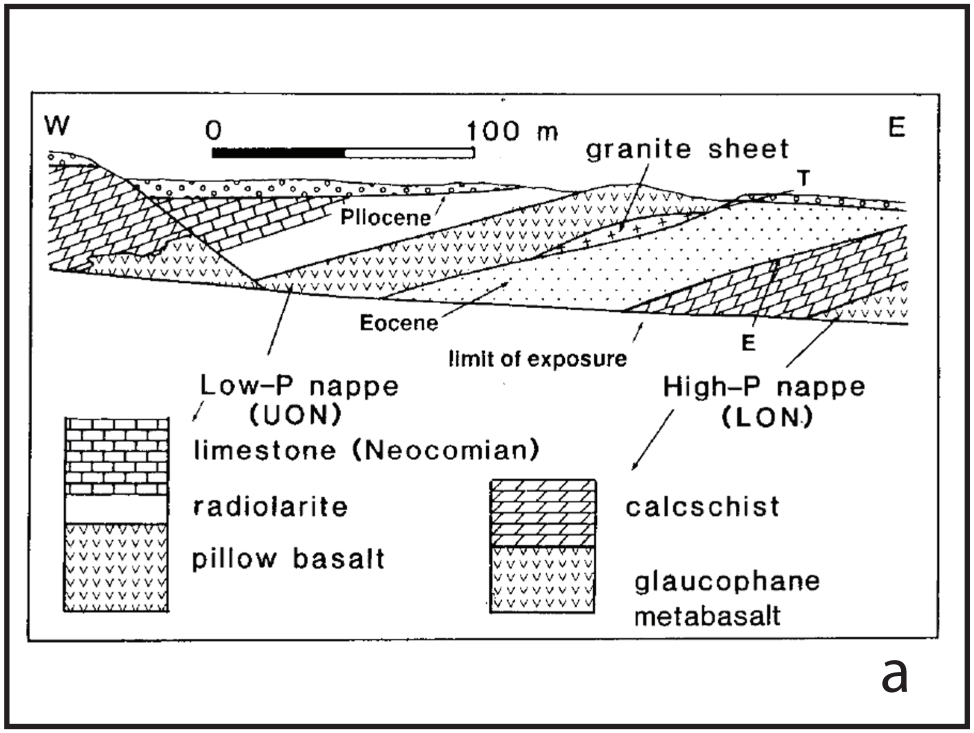


Figure 9. a) Inferred normal fault from Wallis et al. (1993) based on the juxtaposition of a HP and LP units.