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Correspondence to:
Anastasios Plougarlis
aplougar@geo.auth.gr

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THE TECTONOSTRATIGRAPHIC ARCHITECTURE OF THE SERBO-MACEDONIAN MASSIF IN THE VERTISKOS AND KERDILION MOUNTAINS (NORTHERN GREECE)

Anastasios P. Plougarlis *[1], Markos D. Tranos [2], Lambrini C. Papadopoulou[3]

[1] **Department of Geology, School of Geology, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece, aplougar@geo.auth.gr**

[2] **Department of Geosciences, CPG, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia, markos.tranos@kfupm.edu.sa**

[3] **Department of Mineralogy-Petrology-Economic Geology, School of Geology, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece, lambrini@geo.auth.gr**

Abstract

The lithologies and structural features of the exposed rocks of the Serbo-Macedonian massif in the Vertiskos and Kerdilion Mts. have been studied in detail by carrying out km-long cross-sections. Moreover, a new tectonostratigraphic architecture for the massif is proposed, based on the migmatization and anatexis that the rocks pertain, under which the specific exposed rocks have been placed into the Vertiskos and Kerdilion Units. The latter approach differs from the traditional view, which is based solely on the lithological difference between the units. In particular, in the Vertiskos Mt., mica schists, garnet-bearing two-mica gneisses, and predominantly two-mica gneisses, without a sign of anatexis and migmatization, overlie tectonically, biotite gneisses and layered amphibolite gneisses into which migmatization and anatexis takes place. The former constitute the Vertiskos Unit, whereas the latter have been grouped into the Kerdilion Unit, since they are of similar lithologies and affinities with rocks of the Kerdilion Unit. The Kerdilion Mt. is a large antiform made up of biotite gneisses alternating with marbles, which are similarly characterized by intense migmatization and anatexis. These rocks are intruded by the Oreskia granite, which is foliated and follows the general trend of the country rocks. All the rocks are folded with isoclinal to tight folds, and the contact between the two units is a mylonitic shear zone with a top-to-the-SW sense-of-shear. Also, a large volume of ultramafic rocks occurs between the Vertiskos and Kerdilion Mts., including metamorphosed rocks like metagabbros to massive amphibolites, which is assigned to the Therma-Volvi-Gomati Complex (TVGC). These rocks have been found in tectonic contact, i.e., shear zones with top-to-the-SW sense-of-shear, only with the rocks of the Kerdilion Unit. Taking into account *our new tectonostratigraphic architecture, the contact between the Vertiskos and Kerdilion Units is not located along the western side of the marbles, as the latter are exposed in the Kerdilion Mt. It is traced westerly in the Vertiskos Mt. dipping with intermediate angles towards the SW, due to NW-trending, map-scale, isoclinal folding. The ultramafic rocks of the TVGC are in tectonic contact with the rocks of the Kerdilion Unit, but not the two-mica gneisses of the Vertiskos Unit, and the Arnea granite intrudes not only the Vertiskos Unit as previously considered, but the rocks of the Kerdilion Unit, as well.*

Keywords: *Geology, Tectonostratigraphy, Metamorphic Terrain Analysis, Serbo-Macedonian massif, Greece*

Περίληψη

Τα λιθολογικά και τεκτονικά χαρακτηριστικά των πετρωμάτων της Σερβομακεδονικής Μάζας, στα Όρη Κερδυλίων και Βερτίσκου έχουν μελετηθεί λεπτομερώς σε χιλιομετρικού μήκους τομές. Επιπρόσθετα, μια νέα τεκτονοστρωματογραφική αρχιτεκτονική προτείνεται για την Σερβομακεδονική Μάζα, βασιζόμενη στην μιγματιτίωση και την ανάτηξη που εντοπίζεται στα πετρώματά της, και στις οποίες βασίστηκε η διάκριση των εκτειθέμενων πετρωμάτων στις Ενότητες Κερδυλλίων και Βερτίσκου. Η νέα αυτή προσέγγιση διαφέρει της κλασσικής αντίληψης για την γεωλογία της περιοχής, η οποία βασίστηκε αποκλειστικά στην λιθολογική διαφοροποίηση μεταξύ των ενοτήτων. Ειδικότερα, το Όρος Βερτίσκος δομείται από μαρμαρυγιακούς σχιστολίθους, γρανατούχους διμαρμαρυγιακούς γνευσίους, και κυρίως από διμαρμαρυγιακούς γνευσίους, πετρώματα στα οποία απουσιάζουν εικόνες ανάτηξης και μιγματιτίωσης. Τα πετρώματα αυτά που εντάσσονται στην Ενότητα Βερτίσκου υπέρκεινται τεκτονικά βιοτιτικών γνευσίων και ταινιωτών αμφιβολιτικών γνευσίων, στα οποία εντοπίζεται εκτεταμένη ανάτηξη και μιγματιτίωση. Τα τελευταία συγκροτούν την Ενότητα Κερδυλλίων, καθώς έχουν παρόμοια λιθολογικά χαρακτηριστικά αυτών που περιγράφονται για την Ενότητα Κερδυλλίων. Το Κερδύλιον Όρος αποτελεί ένα μεγάλο αντίμορφο, το οποίο δομείται από βιοτιτικούς γνευσίους σε εναλλαγές με μάρμαρα, με αντίστοιχα χαρακτηριστικά έντονης ανάτηξης και μιγματιτίωσης. Στα πετρώματα αυτά διεισδύει ο γρανίτης της Ορέσκειας, ο οποίος είναι φυλλωμένος και ακολουθεί την γενική διεύθυνση των πετρωμάτων του περιβλήματος. Τα πετρώματα εμφανίζονται πτυχωμένα με ισοκλινείς έως πολύ σφιχτές πτυχές, ενώ η επαφή μεταξύ των δύο ενοτήτων είναι μία εκτενής μυλονιτική ζώνη διάτμησης με κίνηση του υπερκείμενου προς τα ΝΔ. Ακόμα, υπερμαφικά πετρώματα καταλαμβάνουν μεγάλες περιοχές μεταξύ των ορέων Κερδύλιου και Βερτίσκου, περιλαμβάνοντας και μεταμορφωμένα πετρώματα, όπως μεταγάββρους –

μαζώδεις αμφιβολτίτες, τα οποία αποτελούν το Σύμπλεγμα Θερμά – Βόλβη – Γομάτι. Τα πετρώματα αυτά βρίσκονται σε τεκτονική επαφή, μέσω μίας ζώνης διάτμησης με κίνηση του υπερκείμενου προς τα ΝΔ και μόνο με τα πετρώματα της Ενότητας Κερδυλλίων. Λαμβάνοντας υπόψιν τη νέα τεκτονοστρωματογραφική αρχιτεκτονική που προτείνουμε, η επαφή των Ενοτήτων Κερδυλλίων και Βερτίσκου δεν υφίσταται κατά μήκος του δυτικού ορίου των μαρμάρων, που αυτά βρίσκονται στο δυτικό τμήμα του Κερδύλιου Όρους. Το ίχνος της επαφής ανάμεσα στις δύο ενότητες εντοπίζεται δυτικότερα, στο Όρος Βερτίσκος και κλίνει με ενδιάμεσες γωνίες προς τα ΝΔ, λόγω της ΒΔ διεύθυνσης και χαρτογραφικής κλίμακας ισοκλινούς πτύχωσης. Τα υπερμαφικά πετρώματα του Συμπλέγματος Θερμά – Βόλβη – Γομάτι βρίσκονται σε τεκτονική επαφή με τα πετρώματα της Ενότητας Κερδυλλίων, αλλά δεν παρατηρούνται σε επαφή με τους διμαρμαρυγιακούς γνευσίους της Ενότητας Βερτίσκου. Ο γρανίτης της Αρναίας διεισδύει όχι μόνο σε πετρώματα της Ενότητας Βερτίσκου, όπως θεωρείτο, αλλά και στα πετρώματα της Ενότητας Κερδυλλίων.

Λέξεις κλειδιά: *Γεωλογία, Τεκτονοστρωματογραφία, Μεταμορφικό Πεδίο, Σερβομακεδονική Μάζα, Ελλάδα*

1. INTRODUCTION

For many years, geologists considered the Serbo-Macedonian and Rhodope massifs in Central-Eastern Macedonian and Thrace to represent the Hellenic Hinterland (Fig. 1); a Precambrian continental part to the hinterland of both the Dinaric-Hellenic and Carpatho-Balkan Alpine mountain chains, which was already consolidated, and unaffected by any orogenic process since the Mesozoic era (Kober, 1928; Dimitrievic, 1966, 1974). However, new studies about the geology of both massifs have indicated that these massifs should be considered part of the Internal Hellenides. The latter was amalgamated from the convergence-related processes between the Eurasian plate and Gondwana-derived continental blocks (e.g., Dercourt et al., 1993; Papanikolaou, 1997; Stampfli and Borel, 2002; Jolivet and Brun, 2010) during the Mesozoic and Cenozoic times. The tectonostratigraphic architecture of the Serbo-Macedonian massif results from a multi-metamorphic and deformational history, at least from the Mesozoic onwards, that it is hard to unravel. Because of this, it is still under debate (e.g., Kockel et al., 1971, 1977; Ivanov, 1988; Sakellariou, 1989; Burg et al., 1990, 1996; Kilias et al., 1998; Himmerkus et al., 2006; Brun and Sokoutis, 2007; Tranos, 2011; Plougarlis and Tranos, 2014; Neofotistos et al., 2020). Therefore, the challenge about the Hellenic hinterland geology is to define and establish a modern tectonostratigraphic architecture.

Any attempt needs the juxtaposition and interrelation of the exposed rocks and their histories, regardless of their traditional grouping. The present article examines the structural geometry and kinematic evolution of the Serbo-Macedonian massif in the Vertiskos and Kerdilion Mts., based mainly on new detailed field data and observations collected along cross-sections. In particular, the different lithologies were grouped, their contacts were thoroughly examined, and the ductile deformation structures were analyzed to define and establish the stratigraphic architecture of the massif.

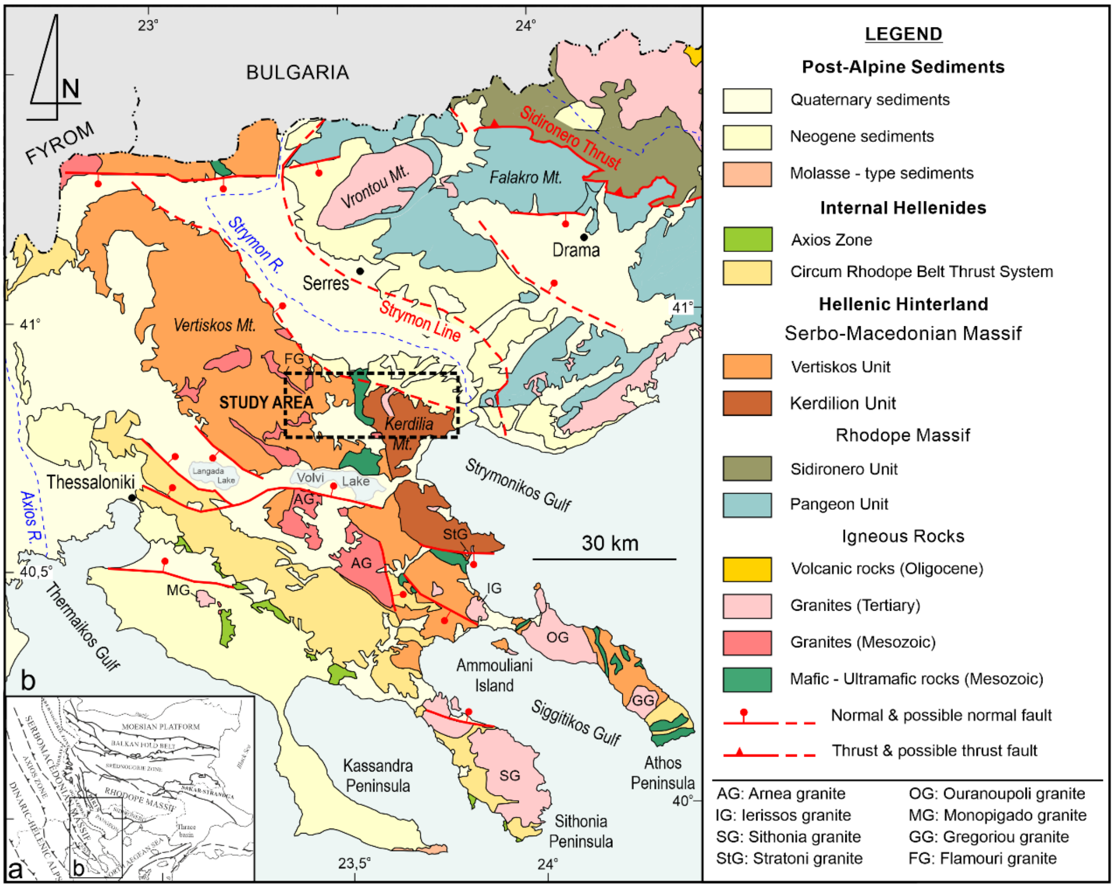


Fig. 1: (a) Map indicating the location of the geological map shown in (b) in relation to the main Alpine orogenic elements and the general geotectonic framework of the eastern Mediterranean region (modified after Tranos and Lacombe, 2014), (b) Simplified geological and structural map of the Chalkidiki Peninsula. Modified after Kockel et al. (1977).

2. GEOLOGICAL SETTING

The basic but most fundamental geological research of the Serbo-Macedonian massif (Fig. 1) in central Macedonia was carried out by Kockel et al. (1971, 1977), who presented a geological map at a scale of 1:100.000. This map and its linked pamphlet, which represents a pioneer and seminal work, distinguished the massif into the overlying Vertiskos and underlying Kerdilion Units. According to them, the massif is made up of Paleozoic or older rocks that have been subjected to multiple metamorphic and deformation events, which in general can be recognized in both units resulting in the assumption that the contact between the units is normal.

In particular, in their map, the Kerdilion Unit occupies the Kerdilion Mt., and the eastern part of the Chalkidiki peninsula to the south. It consists of monotonous fine- to medium-grained biotite gneisses, amphibolite gneisses, and marbles, as well as migmatites and migmatitic gneisses. In contrast, the Vertiskos Unit covers the Vertiskos Mt. and the main part of the Chalkidiki peninsula. This unit consists of monotonous two-mica gneisses and muscovite to garnet-bearing two-mica gneisses and borders to the west with the rocks of the Circum Rhodope Belt Thrust System (CRBTS) through a right-lateral transpression zone (Tranos et al., 1999). Sakellariou (1989) mentioned that in the Vertiskos Unit, there are also zones of augen gneisses, a few meters thick, which often present features of intense shearing and mylonitization. The rocks of the Kerdilion Unit are derived from a large-thick series of greywacke-arkose with limestone layers, whereas the rocks of the Vertiskos Unit represent a thick series of greywackes, arkoses, and shales (Kockel et al., 1971, 1977; Sakellariou, 1989). In contrast, Himmerkus et al. (2006, 2009a) has interpreted the Vertiskos Unit as orthogneisses of a continental magmatic arc.

More recent studies in the area of the Serbo-Macedonian massif have verified the very complicated geology of the region. For example, Dixon and Dimitriadis (1984) separated the basic and ultra-basic igneous rocks that are frequently exposed between the two units as the Therma-Volvi-Gomati Complex (TVGC). Sakellariou (1989) defined the Nea Madytos Unit between the Vertiskos and Kerdilion Units. Burg et al. (1995) subdivided the Vertiskos Unit into three sequences. Himmerkus et al. (2006) suggested the Pirgadikia Unit, and Plougarlis and Tranos (2014) defined the Ammouliani Unit between the Vertiskos and Kerdilion Units. Also, both the Vertiskos and Kerdilion Units have been considered as belonging or as being analogous to the units of the Rhodope Massif (Burg et al., 1995; Ricou et al., 1998; Brun and Sokoutis, 2004; 2007, Himmerkus et al., 2006; 2011). Himmerkus et al. (2006) following Burg et al. (1995) have shown in their Fig. 1 part of the Vertiskos Unit to belong to the Kerdilion Unit.

In addition, the contact between the two units has also been revised at parts by Sakellariou (1989), Sakellariou and Dürr (1993), and Plougarlis and Tranos (2014), who reported that the contact between the two units is tectonic. The last authors suggest that the contact is a wide shear zone along which the Ammouliani Unit, including anatectic and migmatitic rocks, has been formed. On the other hand, Dinter (1998) and Brun and Sokoutis (2007) interpreted this contact as a Tertiary extensional detachment or shear zone, whereas very recently Neofotistos et al. (2020), similarly with Plougarlis and Tranos (2014), suggested that the contact between the Vertiskos and Kerdilion Units should not be considered based on the different lithologies, i.e., the existence of the marbles in the Kerdilion Unit, but on the migmatization, which is a dominant feature of the Kerdilion Unit, but not of the Vertiskos Unit.

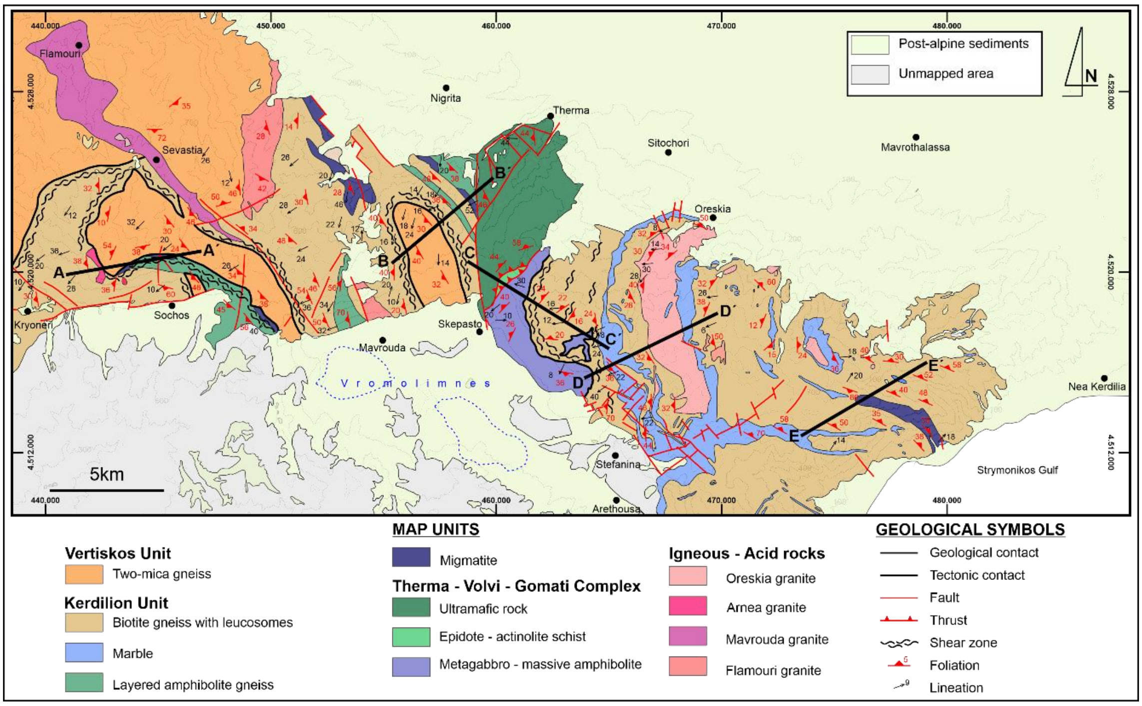


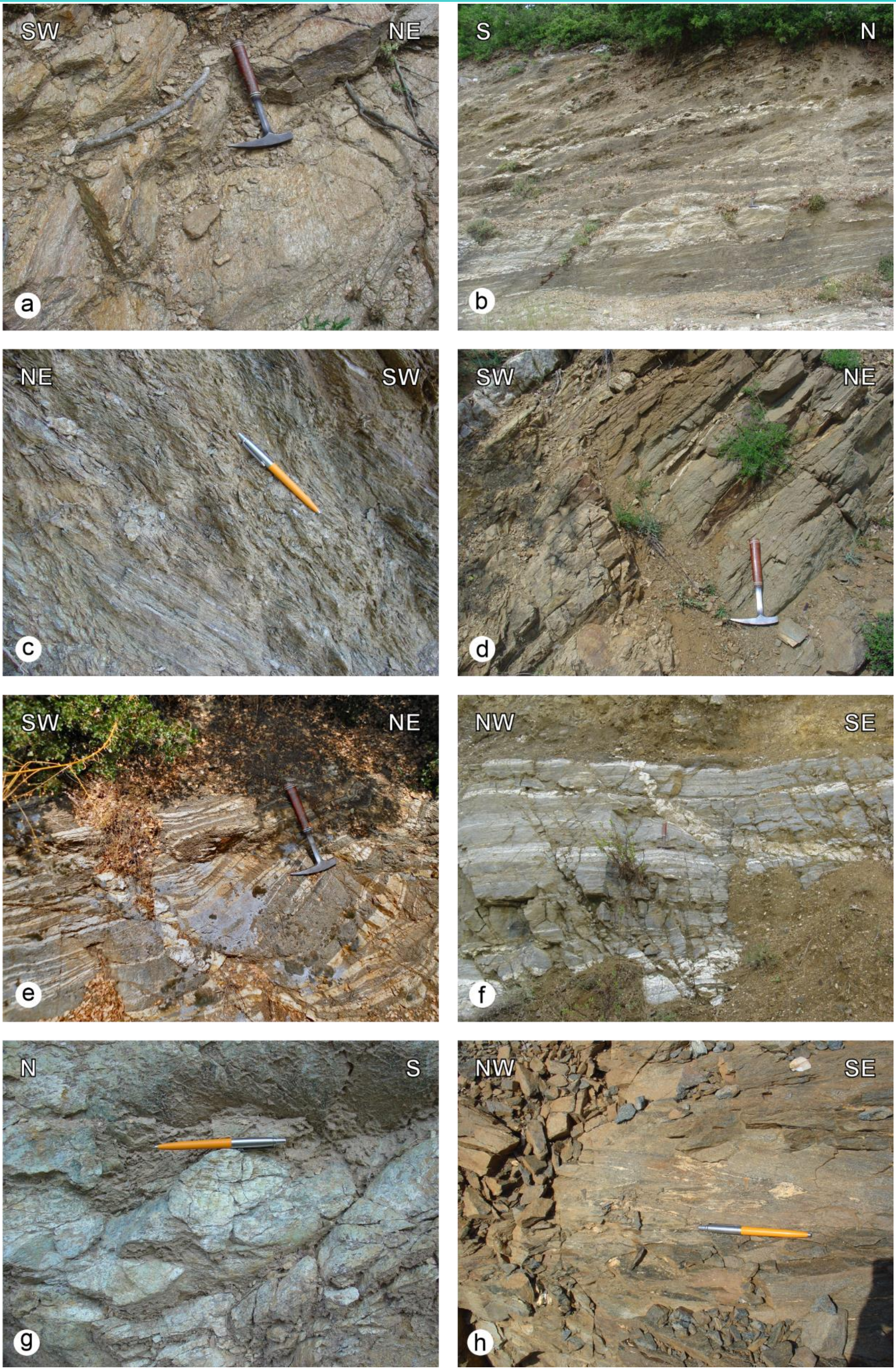
Fig. 2: Geological map of the study area (modified after Kockel et al., 1977). Cross sections A-A´ through E-E´ are shown in figures 4, 5.

The geology of the Serbo-Macedonian massif is more complex due to at least four magmatic events that have been reported in the Serbo-Macedonian Massif (Kockel et al., 1977). The first is associated with basic-ultrabasic bodies of Paleozoic (i.e., pre-alpine) age, which has been considered by Dixon and Dimitriadis (1984) as the TVGC. The second magmatic event refers to granite bodies, which have been mapped as plagioclase-microcline gneisses due to metamorphism (Kockel et al., 1971, 1977). They are described as Palaeozoic (Kockel et al., 1971, 1977) and were attributed to the Hercynian orogeny. The result of the third magmatic event is the intrusion of large granite bodies such as those of Arnea, Flamouri, and Monopigadon, the age of which is considered as either Jurassic (Kockel et al., 1977; Dixon and Dimitriadis, 1984; Papadopoulos & Kilias, 1985; De Wet et al., 1989; Ricou et al., 1998) or Triassic (ca. 240 Ma; Himmerkus et al., 2009b). Finally, the fourth magmatic event is associated with the Tertiary acidic granitic bodies of Sithonia, Ouranoupolis, Gregoriou, Ierissos, and Stratoni, and related to the Apulia-Eurasia convergence (see references in Pe-Piper and Piper, 2002; Tranos et al., 1993; Tranos and Lacombe, 2014).

3. GEOLOGY OF THE STUDY AREA

The study area (Fig. 2) is part of the Vertiskos and Kerdilion Mts., i.e., the NW-WNW trending mountainous terrain that separates the Strymon basin to the NNE from the Vromolimnes area to the south. It extends from Sochos village to the west as far to the east as the Nea Kerdilia village. It consists of a multi-metamorphosed and multi-deformed terrain of gneisses, schists, massive amphibolites, and layered amphibolite gneisses, ultramafic rocks, marbles, and migmatites (Fig. 3). In this terrain, small outcrops of metasedimentary rocks belonging to the Nea Madytos Unit and several igneous intrusive bodies of Arnea, Flamouri, Mavrouda, and Oreskia granites occur (Fig. 2). Based on mapping and detailed field observations of the exposed rocks, their fabric and deformation structures along km-long cross-sections, i.e., A-A΄ through E-E΄ (Figs. 4, 5), we defined the exposed lithologies, their structural features, as well as, the occurrence of anatexis and migmatization within the rocks. Recent studies have pointed out that the two units have rocks with a completely different sign of anatexis and migmatization (Plougarlis and Tranos, 2014; Neofotistos et al., 2020). This work is presented below by describing the different lithologies as they have been grouped into units, and afterwards, the detailed cross-sections.

(next page) Fig. 3: Field photographs of the crystalline rocks of the study area: a) light brown colored, monotonous and well foliated two-mica gneiss with pronounced stretching lineation (Vertiskos Unit), b) dark grey biotite gneiss with leucosomes (Kerdilion Unit), c) biotite gneisses - phyllonite (diapthorite) rocks (Kerdilion Unit), d) hornblende gneiss (Kerdilion Unit), e) migmatized – banded amphibolite gneisses (Kerdilion Unit), f) grey colored, well foliated marbles (Kerdilion Unit), g) serpentinized ultramafic rocks of the Therma-Volvi-Gomati Complex (TVGC), and h) metagabbros – massive amphibolites (TVGC).



4. DESCRIPTION OF MAP UNITS

This section includes the description of the exposed rocks as these have been placed into the different units after our field observations:

4.1 Vertiskos Unit

Two-mica gneisses: Brown to light brown in color, monotonous, well-foliated, fine- to medium-grained gneisses (Fig. 3a). The occurrence of muscovite and biotite in micro- and mesoscale varies among the outcrops so that the rock can be either muscovite-biotite or biotite-muscovite gneiss. In a few outcrops, the biotite diminishes or garnet is identified in others so that the rock can be characterized as muscovite gneiss and garnet-bearing two-mica gneiss, respectively. Very small aplitic and quartz veins and veinlets are often found, mainly parallel to sub-parallel and cross-cutting the main foliation close to the larger granitic bodies of Arnea type, but at their majority, the rocks do not have a sign of a voluminous anatexis and migmatization.

4.2 Kerdilion Unit

Biotite gneisses: Dark grey to dark brown, fine- to medium-grained, and well-foliated rocks. They host leucosomes of various sizes and migmatites, implying extensive migmatization and anatexis (Fig. 3b), whereas at some levels, they are characterized by intense diaphthoresis (Becke, 1909), which along with shearing, makes them occur as diaphthorites-phyllonites (Fig. 3c). In addition, they gradually pass to biotite-hornblende gneisses and hornblende gneisses. In places where the quartzofeldspathic component increases, the biotite gneisses are characterized as augen biotite gneisses, with intense shearing and the occurrence of σ- and δ-clasts. Aplitic and quartz veins are often found, mainly sub-parallel but also transverse to the foliation.

Layered amphibolite gneisses: Green to dark green colored, fine- to medium-grained and layered amphibolite gneisses (Fig. 3d), passing gradually to lithologies like amphibole-biotite gneiss or biotite-amphibole gneiss. Likewise, they host leucosomes, and from place to place, they appear as migmatites implying extensive migmatization and anatexis (Fig. 3e). At places, they also include quartz and feldspar augen and garnet porphyroclasts, which are characterized by intense shearing.

Marbles: White to grey colored but also grey to bluish, medium- to coarse-grained well-foliated and banded marbles with the aid of fine layers of graphite that align parallel to the main foliation (Fig. 3f). Two distinct marble horizons alternating with biotite gneisses prevail the Kerdilion Mt (Fig. 2). In addition, the marbles locally are intercalated with amphibolite gneisses and calc-silica biotite schists.

4.3 Acid Igneous Rocks

Arnea granite: It is a white to whitish grey, medium- to coarse-grained granite, mainly composed of quartz, plagioclase and feldspars, muscovite and biotite. In the study area, it crops out in the Vertiskos Mt., (Fig. 2) not as a single body but several larger or smaller, well-foliated bodies that intrude both the two-mica gneisses and biotite gneisses. These bodies are well-foliated with a foliation (sub)parallel to the main foliation of the country rocks. The Arnea granite, was dated either as of Triassic age (Himmerkus et al., 2009) or Jurassic age (Kockel et al., 1977; Dixon and Dimitriadis, 1984; Papadopoulos & Kilias, 1985; De Wet et al., 1989; Ricou et al., 1998).

Oreskia granite: It is a greyish white to white, medium- to fine-grained granite showing in a few places a light pink color. It crops out in the western part of the Kerdilion Mt., (Fig. 2) and it is weakly foliated. Its mineral composition includes the minerals quartz, muscovite and plagioclase. An Eocene age has been determined for the Oreskia granite (Harre et al., 1968). In addition, two more granitoid bodies crop out in the Vertiskos Mt. (Fig. 2), the Flamouri granite-granodiorite, and the Mavrouda granite for which no dating exist but according to Kockel et al. (1977) are of similar type with Arnea intrusion, attributed a Mesozoic age of emplacement. Their exposures are very limited due to intense vegetation of the area making their detailed study very hard. The former is a grey coloured, medium-grained granite-granodiorite consisting of quartz, feldspar, plagioclase, biotite and epidote. The second is grey, green-grey in color, medium-grained and consists of quartz, plagioclase, hornblende, chlorite and epidote. In both of these, a spaced cleavage is only recognized but no other deformational structures.

4.4 Therma-Volvi-Gomati Complex (TVGC)

This complex can be grouped into two parts: the first includes unmetamorphosed ultramafic rocks, and the second includes metamorphosed mafic-ultramafic rocks called herein metagabbros - massive amphibolites. The first part overlies tectonically the second one, whereas along their contact light green coloured epidotite-actinolite schists occur as a tectonic sliver (Fig. 2)

Ultramafic rocks: They are light green to dark green colored ultramafic igneous rocks such as peridotites, pyroxene peridotites and pyroxenites (Fig. 3g). Serpentinization predominates obscuring clear observation of the parent rocks.

Metagabbros – Massive amphibolites: They are green to dark green in color, usually medium-grained, massive gabbroic rocks metamorphosed to massive amphibolites (Fig. 3h). They consist mainly of hornblende, feldspar, quartz and epidote and mapped in the mountainous area east of the Skepasto village (Fig. 2). They have been found as small slivers within the biotite gneisses.

5. DESCRIPTION OF CROSS-SECTIONS

In the following the description of the cross-sections is given from the west part of the study area to the east one.

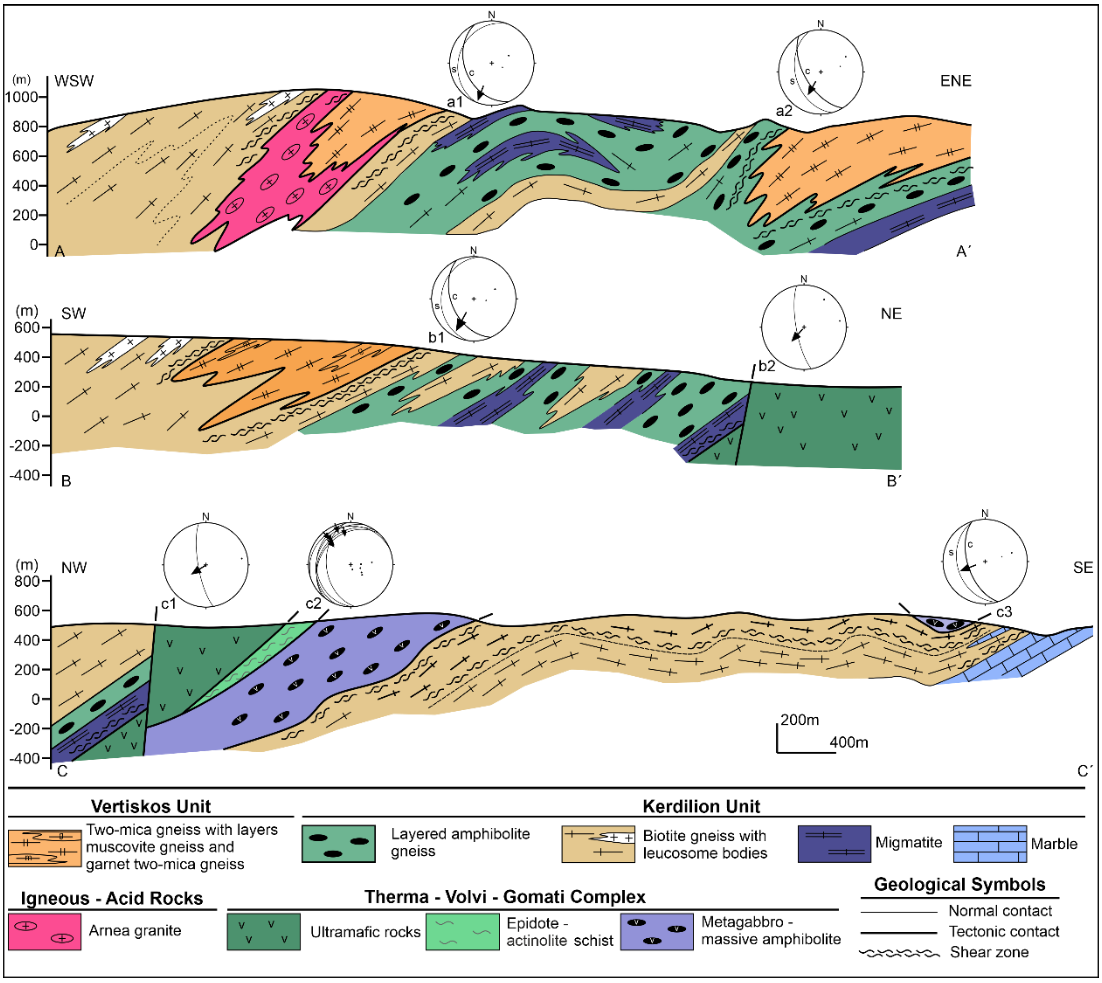


Fig. 4: Cross sections A-A´ through C-C´ of the study area (for location see Fig. 2).

5.1 Cross-Section A-A´ (ca. 6 km, Fig. 4 A-A´)

The ENE-WSW trending, A-A´ cross section with a length of ca. 6 km was carried out north of Sochos and Kryoneri villages (Fig. 2). To the west, the exposed rocks are biotite gneisses into which numerous concordant leucosome bodies have been found (Fig. 6a). They dip as a rule to the WSW with medium dips and are intensely folded due to NW-gently plunging, map-scale isoclinal folds (Fig. 7a). In contrast, in mesoscale, the rocks are folded by isoclinal sheath-type folds plunging mainly to SW (Figs. 6b, 7b) parallel to which a stretching lineation dominates (Fig. 7c). The leucosome bodies are coarse-grained, biotite quartzofeldspathic gneiss, which occasionally acquires a flaser to augen gneiss texture. Also, frequent pegmatoid bodies, constituting the leucosome, appear parallel or subparallel with the main foliation that are more prominent in the part underlying the two-mica gneisses. Towards the central part of cross-section, the biotite gneisses come in contact with two-mica gneisses, although small intrusive bodies of the Arnea granite have obscured the contact. The two-mica gneisses appear syn-folded with the biotite gneisses due to the same NW-SE isoclinal folding forming in that part a NW-plunging synform with the two-mica gneiss in its core. The contact between the biotite and the two-mica gneiss is a mylonite shear zone into which the rocks occur as mylonitic augen gneiss with mainly SW plunging stretching lineation, and top-to-the-SW sense-of-shear as defined by the S-C fabric (Figs. 4a1, 6c). More to the ENE, (gradual) alternations between the biotite gneisses and layered amphibolite gneisses occur, strongly implying the normal contact between the rocks, whereas, very often, layered migmatites are found within them. In the eastern part of the section, the layered amphibolite gneisses are in tectonic contact with the underlying two-mica gneisses forming an SW-dipping inverse synform like that previously described. Likewise, the contact between the layered amphibolite gneisses and the two-mica gneisses is a mylonite shear zone (Fig. 4a2) with similar features with the above-mentioned one.

5.2 Cross-Section B – B΄ (ca. 7 km, Fig. 4 B–B΄)

The NE-SW trending B–B΄ cross section with length ca. 7 km was completed in the mountainous terrain between Mavrouda and Therma villages (Fig. 2). The exposed rocks (Fig. 4) are similar with those described in cross-section A-A΄, and are characterized by the same features, apart from the fact that in the eastern part the ultrabasic rocks of the TVGC are exposed. Likewise, the contact between the biotite and two-mica gneiss is a mylonite zone along which mylonite augen gneiss with top-to-the-SW shearing dominates (Figs. 4b1, 6d). The two-mica gneiss lithology changes to muscovite gneiss and two-mica garnet gneiss at several exposures. The gradual alternations, but also the repetitions between biotite gneisses, layered amphibolite gneisses with migmatites are very frequent forming an array of synforms and antiforms which dip constantly to the SW. They imply both normal contacts and NW-SE map-scale isoclinal folding. In contrast, the contact between the latter rocks and the serpentinized peridotites that belong to the TVGC is a top-to-the-SW shear zone.

5.3 Cross-Section C – C′ (ca. 7.5 km, Fig. 4 C–C′)

This ~7.5 km long cross-section trends NW-SE and cross-cuts the mountainous terrain between the Vertiskos and the Kerdilion mountains (Fig. 2). In the NW part of the cross-section (Fig. 4), the exposed rocks are similar with those already described in cross-section B–B′ like biotite gneisses, amphibolite-hornblende gneisses and layered migmatites. However, here a W-steeply dipping normal fault (Fig. 4c1) totally obscures the contact between these rocks and the ultramafic rocks of the TVGC. The latter rocks thrust over light green epidote-hornblende schists, to the east, which in turn thrust over metagabbros to massive amphibolites representing a NW-SE shortening (Fig. 4c2). To the SE, the massive amphibolites tectonically overlie gneisses, which have been mapped previously as two-mica gneisses belonging to the Vertiskos Unit (Kockel et al., 1977). In contrast, based on our own field observations, this map unit is a biotite gneiss and is characterized by intense shearing, as shown by the frequently occurring shear zones that have a width of several or even tens of meters along which the rock becomes a phyllonite and much more easily erodible and discolored. These shear zones dip (sub)parallel to the main foliation, i.e., with intermediate angles to SW and transform the rocks to diaphthorites or phyllonites (Becke, 1909) (Fig. 6e). Likewise, the contact between the massive amphibolites and the biotite gneiss, although exposed in a few places, is a shear zone with sense-of-slip the top-to-the-SW. In addition, the biotite gneiss is folded with gentle to open folds and more to the east, a klippe of metagabbros-massive amphibolites (Fig. 2) is tectonically emplaced over the biotite gneisses with very gentle to subhorizontal angles showing that the described dips of the rocks vary as they belong to different parts of an antiform whose hinge is more eastwards. Finally, the biotite gneisses conformably overlie the whitish grey marbles.

5.4 Cross-Section D – D′ (ca. 6.5 km, Fig. 5 D–D′)

The NE-SW trending cross section D–D′ is located in the mountainous terrain of Kerdilion Mt. north of the Stefanina village (Fig. 2). Starting from the SW, the section shows metagabbros-massive amphibolites tectonically coming in contact (Figs. 5d1) with biotite gneiss, as already described in cross-section C-C′. The exposed biotite gneiss has features as described in cross-section C-C′ with lenses of epidote-bearing amphibolites close to the contact. The contact and the biotite gneisses dip to the SW with intermediate to steep angles, but at slightly different angles (Fig. 5) and are both sheared with a top-to-the-SW sense-of-shear. More to the east, the biotite gneiss comes in contact with the underlying marbles. In this part, thin interlayers of calc-silicates and marbles (Fig. 6f) were observed within the biotite gneisses, which vary up to a few meters. These interlayers imply the transitional nature for the contact. Both rocks were intruded by Oreskia granite body, whose emplacement age is considered as Eocene, though it has not been dated radiometrically. The granite is foliated but the intrusive contacts and the foliation of the granite are slightly less steep than the foliation of the country rocks although they trend as the country rocks. More to the NE, under the marble, biotite gneisses of significant thickness are found, within which thin horizons and lens-shaped marble bodies occur in places. At the eastern part of the cross section, biotite gneisses hosting small bodies of marble and granite underlie the marbles.

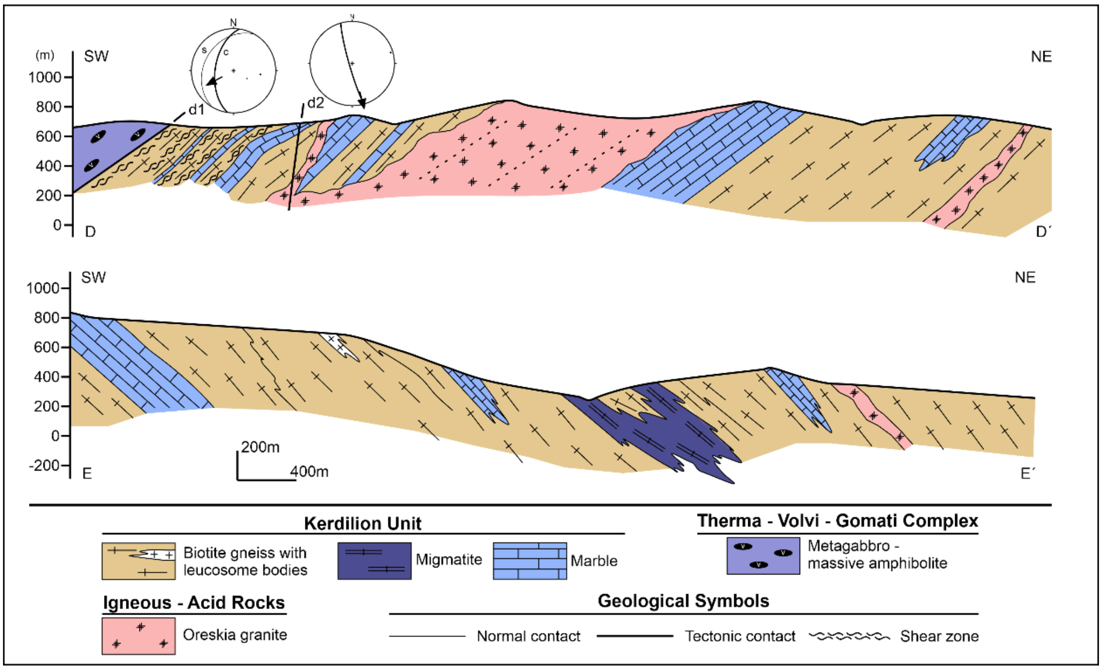


Fig. 5: Cross sections D-D´ and E-E´ of the study area (for location, see Fig. 2).

5.5 Cross-Section E – E´ (ca. 6.5 km, Fig. 5 E-E´)

The E-E´ cross-section trending NE-SW has been carried out in the eastern part of the Kerdilion Mt. In this part the rocks dip as a rule to the NE, showing that the whole Kerdilion Mt. represents a large open antiform (Fig. 5). The exposed rocks consist of alternations of marbles and biotite gneiss (Fig. 6g) and within the biotite gneiss interlayers of leucosome bodies and migmatites occur. In the central part of the section these migmatites are more prevalent strongly showing the migmatization-anatexis as large pegmatoid bodies (Fig. 6h) that characterizes the Kerdilion Unit.

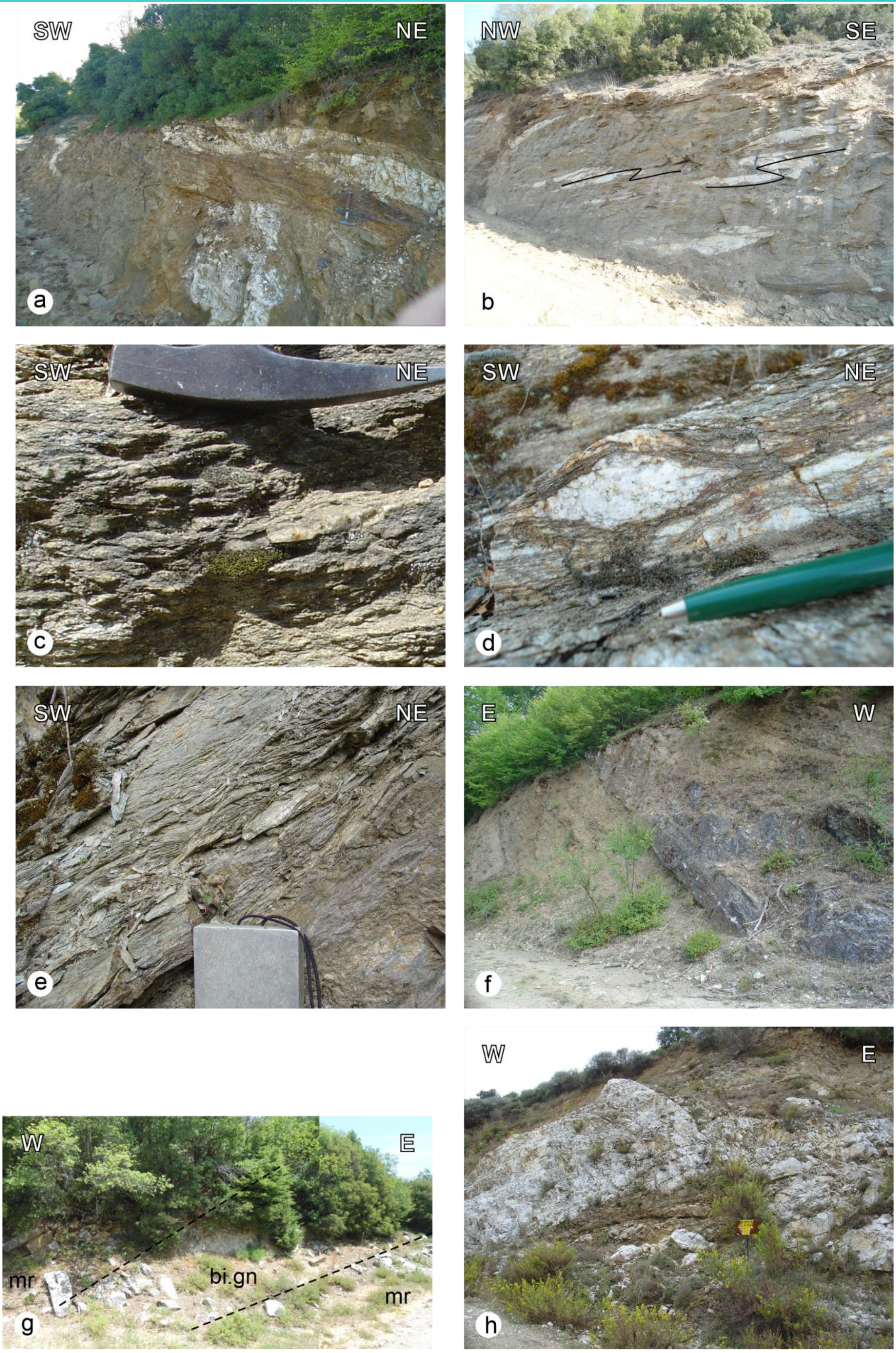


Fig. 6: Field photos of the crystalline rocks and their deformation structures along the cross-sections: a) biotite gneisses (Kerdilion Unit) with concordant leucosome bodies (cross-section A-A΄), b) s- and z-isoclinal sheath-type folds plunging mainly to SW in biotite gneisses (Kerdilion Unit) (cross-section A-A΄), c) C'-type shear bands indicating top-to-the-SW sense of shear in the biotite gneisses (Kerdyllion Unit), which underlie

the two-mica gneisses of the Vertiskos Unit (cross-section A-A´), d) quartz σ-clasts in the biotite augen gneisses (Kerdilion Unit) indicating top-to-the-SSW sense-of-shear (cross-section B-B´), e) shear zones transforming the rock to diapthorite or phyllonite. The shear zones dip to the SW and indicate top-to-the-SSW sense-of-shear (cross-section C-C´), f) interlayers of marbles and biotite gneisses (cross-section D-D´), g) alternations of marbles and biotite gneiss, and h) large leucosome bodies in biotite gneisses showing the intense migmatization-anatexis.

6. STRUCTURAL INTERPRETATION-CONCLUSIONS

According to the descriptions of the rocks and the detailed geological cross-sections carried out in the area of Vertiskos and Kerdilion Mts., we present a new tectonostratigraphic architecture for the Serbo-Macedonian massif. In this, the biotite gneiss, the layered amphibolite gneisses and the marbles form lithological interchanges or alternations, often gradual passages, implying the normal contacts among them. These rocks match with those described by Kockel et al. (1977) for the Kerdilion Unit, and are characterized by intense migmatization and anatexis as shown by the leucosome bodies and migmatites, which are similar with the rocks of the Ammouliani Unit (Plougarlis and Tranos, 2014; Neofotistos et al., 2020).

On the other hand, the two-mica gneisses along with the muscovite and garnet-bearing two-mica gneisses occupy smaller areas and tectonically overlie the previous rocks, although they are syn-folded with them. These rocks are similar with those described by Kockel et al. (1977) for the Vertiskos Unit. The contact between the two units is tectonic and dips to the SW with intermediate angles. It is folded with NW-SE map scale, isoclinal to tight folds, and sheared with top-to-the-SW sense-of-shear, as shown by the characteristic S-C fabric, the shear bands, and the σ- and δ-clasts along the contact.

Therefore, our observations verify previous identifications of the tectonic nature of the contact (Sakellariou, 1989, 1993; Burg et al., 1995, 1996; Plougarlis and Tranos, 2014; Neofotistos et. al., 2020). However, due to the non-continuous exposures of the leucosome bodies and migmatites along the contact of the two units, these leucosomes and migmatites, although similar with the rocks of the Ammouliani Unit, they have not been separated from the Kerdilion Unit.

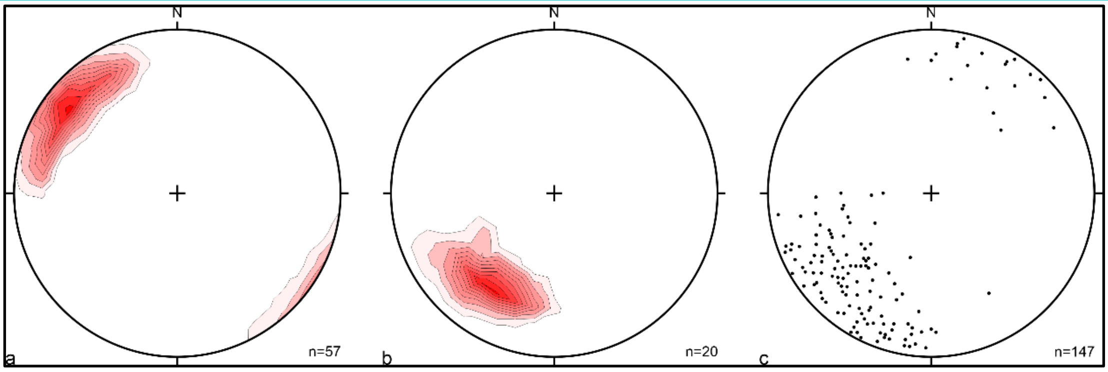


Fig. 7: Structural analysis of the basement rocks of the wider study area: a) fold axes of isoclinal to tight NW – SE folds, b) fold axes of isoclinal sheath NE – SW folds, and c) stretching and mineral lineation, generally trending about an NE – SW to NNE to SSW axis. Equal area, lower hemisphere projection.

Taking into account our new tectonostratigraphic architecture, the rocks of the Kerdilion Unit are exposed also in the Vertiskos Mt., much further to the west from the previously considered traditional boundary between the Vertiskos and Kerdilion Units, which was on the western side of the westernmost marble strip exposure of the Kerdilion Mt. Therefore, the distinction between the rocks of the Vertiskos and Kerdilion Units is not based simply on the lithology of the marbles as initially was considered by Kockel et al. (1977), but the intense migmatization and anatexis as well, which characterizes the rocks of the Kerdilion Unit but not those of the Vertiskos Unit.

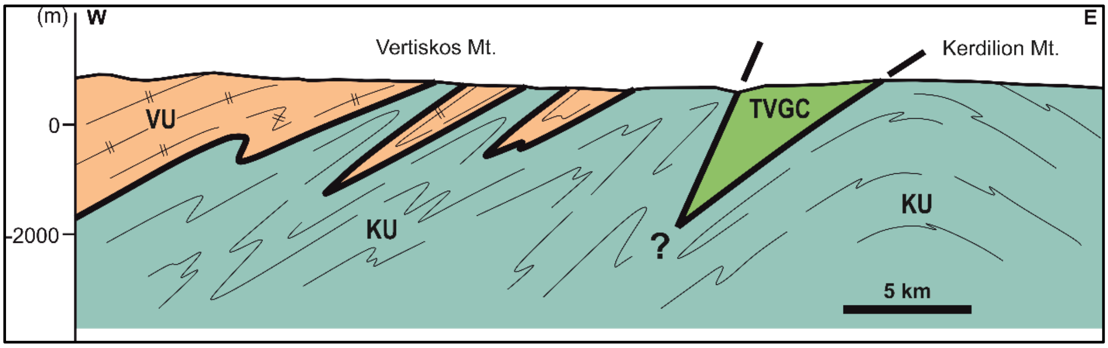


Fig. 8: Simplified cross section of the study area outlining the revised tectonostratigraphic architecture of the Serbo-Macedonian massif (scale approximate). Explanation: VU = Vertiskos Unit, KU = Kerdilion Unit, TVGC = Therma – Volvi – Gomati Complex. Tectonic contacts are shown with thick solid lines.

In addition, the ultramafic rocks of the TVGC are in tectonic contact with the rocks of the Kerdilion Unit, but not the two-mica gneisses of the Vertiskos Unit, and the Arnea granite intrudes not only the Vertiskos Unit as previously considered, but the rocks of the Kerdilion Unit, as well. The contact between the Kerdilion Unit and the TVGC is a top-to-the-SW shear zone, although it is obscured at a large part by a W-steeply dipping normal fault.

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