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THE XERIAS WINDOW NEAR ARGOS (PELOPONNESUS) - AN EXAMPLE OF A REGIONAL GEOLOGICAL STRUCTURE OF INTERREGIONAL IMPORTANCE

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Abstract

The Argolic-Arcadian border range is built up by rocks of the Tripolitza and the Pindos Zones. Its tectonic architecture is deeply exposed in the area of the Xerias Window. Key structures are worked out in this article. The nappe-shaped superposition of the Tripolitza Zone by the Pindos Zone is obvious in the frame of the Xerias Window. The vergence of the key structures of the latter varies everywhere between W and SW, which proves a relative transport of the Pindos Zone as a whole in that direction. After finishing the nappe transport both Pindos and Tripolitza Zone experienced further, collective deformations, which are brought in a probable chronological order.

Round about since Upper Miocene, the compressive stress of the Hellenides was followed by young extensional tectonics, which continues until today. Its influence on the development of the window and on the forming of its frame is described. The most important faults that can be related to the spreading tectonics are called within this investigation as Xerias Faults. Finally, the impacts of the strong regressive erosion, of the numerous landslides, and of the widespread slope waste both on exposing and on covering the tectonic elements are regarded.

Keywords: *Tripolitza Zone, Pindos Zone, Xerias Window, compressive tectonics, extensional tectonics, key structures*

Περίληψη

Η οροσειρά στα σύνορα Αργολίδας – Αρκαδίας αποτελείται από πετρώματα της ζώνης Τρίπολης και της ζώνης της Πίνδου. Η τεκτονική της είναι πλήρως εκτεθειμένη στην περιοχή του παραθύρου του Ξεριά. Οι βασικές δομές της παρουσιάζονται σε αυτό το άρθρο. Η υπέρθεση σε σχήμα καλύμματος της ζώνης Τρίπολης από τη Ζώνη Πίνδου είναι εμφανής στο πλαίσιο του παραθύρου του Ξεριά. Η φορά κίνησης των βασικών δομών της τελευταίας ποικίλλει παντού μεταξύ Δ και ΝΔ, γεγονός που αποδεικνύει μια σχετική μεταφορά της ζώνης της Πίνδου συνολικά προς αυτή την κατεύθυνση. Μετά την ολοκλήρωση της μεταφοράς του καλύμματος τόσο η Πίνδος όσο και η Ζώνη της Τρίπολης παρουσίασαν μεταγενέστερες παραμορφώσεις, οι οποίες παρουσιάζονται με πιθανή χρονολογική σειρά. Γύρω από το Ανώτερο Μειόκαινο, η θλιπτική τάση των Ελληνίδων ακολουθήθηκε από νεώτερη τεκτονική εφελκυσμού, η οποία συνεχίζεται μέχρι σήμερα. Περιγράφεται η επιρροή του εφελκυσμού στην ανάπτυξη του παραθύρου και στη διαμόρφωση του πλαισίου του. Τα σημαντικότερα ρήγματα που μπορούν να συσχετιστούν με την τεκτονική έκτασης ονομάζονται σε αυτή την έρευνα ως Ρήγματα Ξεριά. Τέλος, εξετάζονται οι επιπτώσεις της ισχυρής οπισθοδρομούσας διάβρωσης, των πολυάριθμων κατολισθήσεων και των εκτεταμένων εδαφικών ροών των πρανών στην αποκάλυψη αλλά και στην επικάλυψη των τεκτονικών στοιχείων αυτής της μελέτης.

Λέξεις - Κλειδιά: *Ζώνη Τρίπολης, Ζώνη Πίνδου, παράθυρο Ξεριά, συμπιεστική τεκτονική, εφελκυστική τεκτονική, κύριες δομές*

1 Introduction

1.1 Geographic and tectonic position of the studied area

The area considered in the frame of the present investigation is situated between the cities of Argos and Tripolis (Fig. 1). It comprises a section of the mountains that separate the regions of Argolis and Arcadia, and that was called Argolic-Arcadian Border range by Philippson (1892). This mountain range is part of the Hellenides, and it’s built up by the rock sequences of Tripolitza and Pindos Zone. The division of the Hellenides as a whole in zones was developed by Renz (1940), Marinos (1957), Aubouin et al. (1963), Dercourt (1964), Fleury (1980) a. o. (overview in Bordne-Madadaki, 2001). These zones, which the above-mentioned belong to, are defined both by their particular rock sequence and their tectonic position.

According to investigations on paleoenvironment, Ionian and Pindos Zone are interpreted as pelagic basins, and the Tripolitza Zone, situated between them, as a shelf area under shallow water (e.g., Dercourt et al., 1993). Richter et al. (1978), Craddock et al. (2009) and others described their particular development of sedimentation.

Papanikolaou (2021) divided the Gavrovo-Tripolitza Zone into Gavrovo-Pylos Zone (western subzone) and Tripolitza Zone (eastern subzone), which were neighbouring on the same shelf during the geosynclinal stage up to the Middle Eocene. Since the Upper Eocene, however, they experienced a different tectonic imprint. Within Papanikolaou‘s model, the studied area is situated completely within the Tripolitza Zone. Therefore, exclusively the latter term is applied in the continuing text.

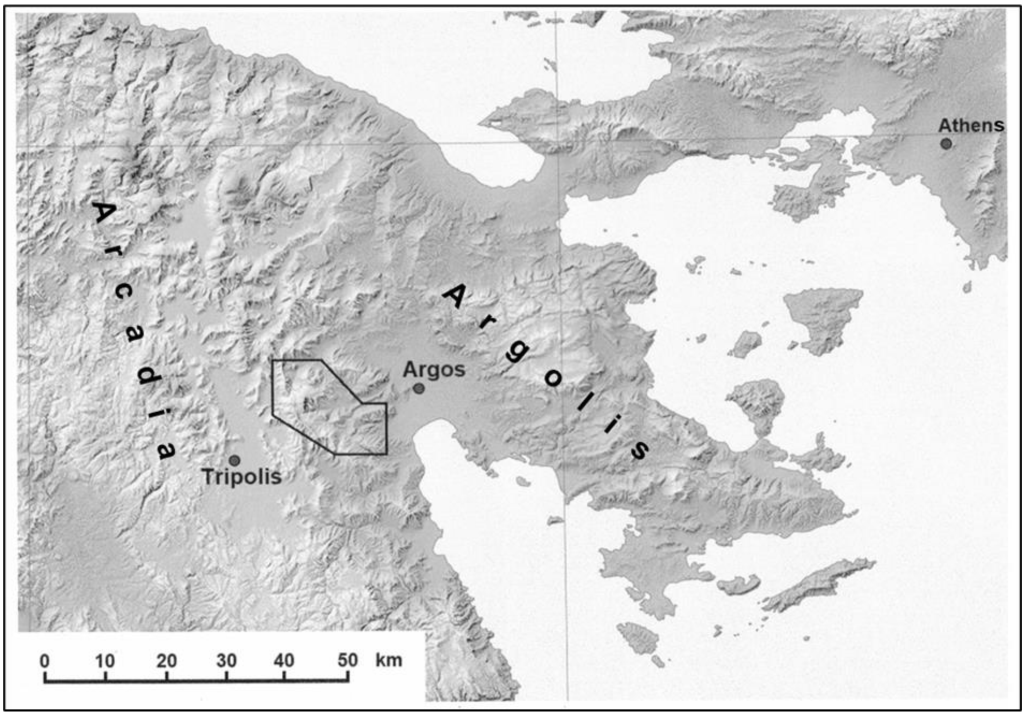

Fig. 1. Situation of the studied area (Baba 2007, modified)

1.2 Aim of the work, methods and definitions

The investigation of development and relationship of the tectonic units in the northeastern Peloponnesus was part of the research programme of the Deutsche Forschungsgemeinschaft (DFG) “The geodynamics of the Mediterranean area”. My part within this project was:

- description and interpretation of the inventory of the small feature tectonics within the lithological units as observed in the area defined above,
- working out of the key structures, and on that base,
- reconstruction of the succession of the tectonic deformations in the large scale.

Important terms, that are frequently used in this article for the description of the ensemble of tectonic features, are applied as follows in the sense of Schwan (1964, 1973), according to the Lexikon der Geowissenschaften (2000), and after Wikipedia (2016):

- Small feature tectonics in the broadest sense comprises the fields of microtectonics and of small feature tectonics in a narrower sense.
- Small feature tectonics in a narrower sense investigates the tectonic structures within the dimensions from hand rock sample to outcrop size. Task and aim of it are
  - the investigation of the structures for the sake of themselves (description, formation conditions) and
  - the use of the smaller structures for clarifying the large-scale architecture of mountains. Thereby, a focus of work is laid to carve out the so-called key structures.
- Key structures are tectonic features immediately observable in the field. They correspond to the large-scale structures of the mountains in relation to their direction (pathway of the main strike line), their three-dimensional positioning (strike and dip of the planar and linear elements), their type of shape, their symmetry and their tectonic intensity as well as to their age (chronological context), or they indicate the type of the large-scale structures indirectly, due to their genetic relation. The large-scale structures, that mostly become apparent not before imaging on the geological map (especially in the scales 1 : 25,000 up to 1 : 200,000) by their direction and their contours, aren't clear in general - because of their dimension – and therefore not directly identifiable and often problematic. The genetic connection between large-scale structures and small featured key structures of an area includes mechanical, geometrical and temporal relationships, and allows, thereby, conclusions from the latter on the large-scaled architecture (Schwan, 1973, modified):
- Large-scale tectonics considers the tectonic structures that aren’t clear in an outcrop and, therefore, often problematic. It becomes clear
  - by the combination of the single observations in the outcrops,
  - by the geological mapping, and
  - by aerial and satellite images (Google Earth, Google Maps).
- Compression means the tectonic shortening of a crustal segment. It’s calculated from the shortening between two points:
  - absolute compression $\Delta l = l_0 - l$ with l_0 = distance before compression and l = distance after compression

- relative compression $\varepsilon = (l_0 - l)/l_0$.

According to Jacobshagen (1986), I'll speak about the Xerias Window within the present article (Fig. 2). In my first approach in 1976, I called this structure Window of Mazi – Karya (Kunz, 1977), which is dispensed herewith. The Xerias Window, for its part, forms the southern end of the bigger Pheneos Window (Dornsiepen et al., 1986), which is in turn identical with the Chelmos Window (Xypolias and Doutsos, 2000).

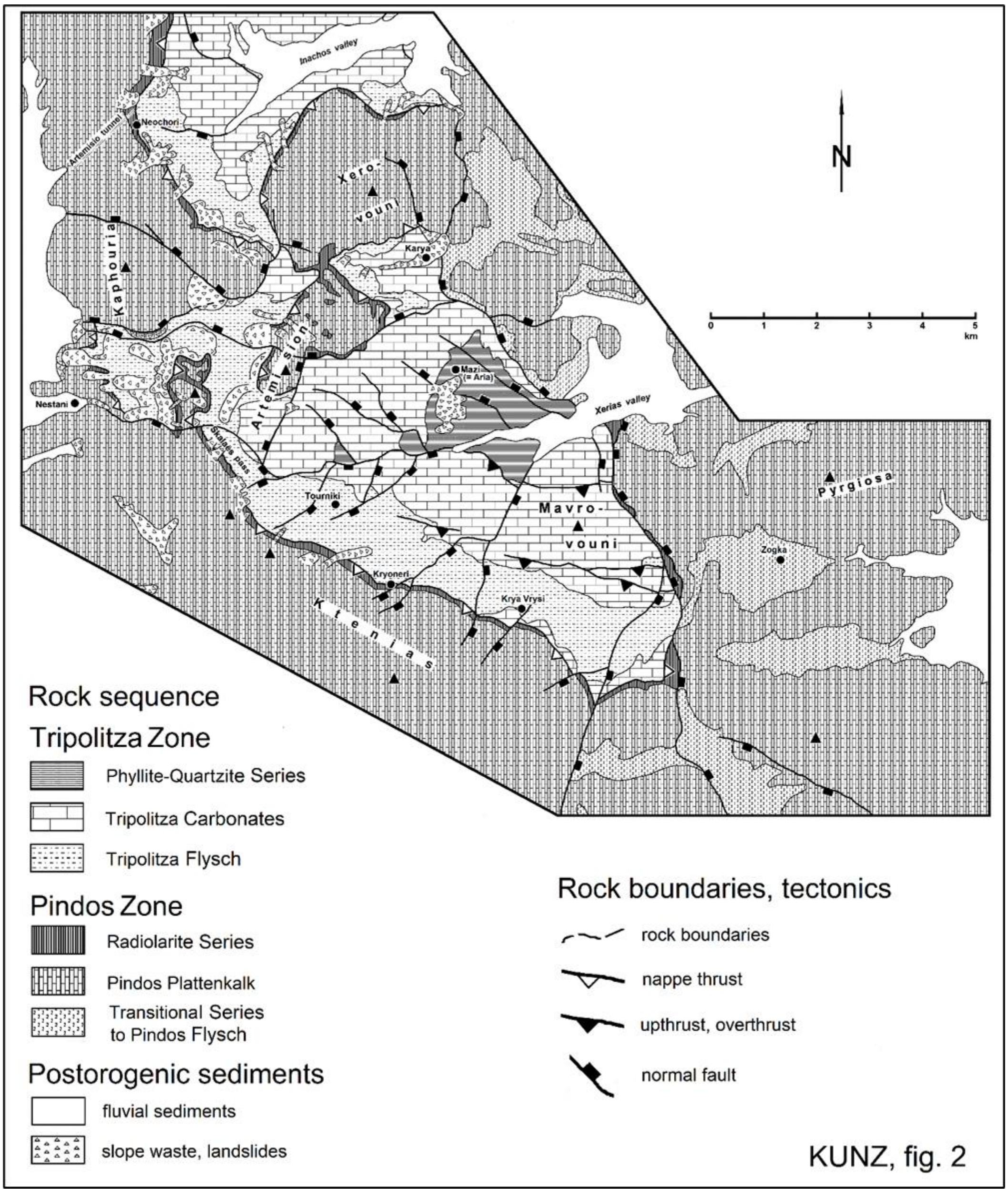

Fig. 2. Generalised geological map of the Xerias Window (Jacobshagen, 1986) and its frame.

2 Tripolitza Zone

2.1 Rock sequence

The rock sequence of the Tripolitza Zone on the northern Peloponnesus was described by Hinsbergen et al. (2005). In the studied area, it starts in the upper part of the Phyllite-Quartzite Series. The thickness of this series is unknown here because of the intensive deformation on the one hand and the lack of outcrops of the underlying rocks on the other. There is a depositional gap between Phyllite-Quartzite Series and the overlying Tripolitza Carbonates, and its length depends on the beginning of the carbonate sedimentation. According to the geological map (GSR 1960, 1970 and IGME 1988), the sedimentation of carbonate rocks started approximately in the Middle Jurassic at Melidoni mountain (scarcely north of the studied area), in the deeper Cretaceous at the Mavrovouni, and in the Upper Cretaceous at the Artemision. Parts of the so-called Tyros beds or of volcanic rocks between both members of the rock sequence, which are described by Ktenas (1924) and Jacobshagen (1986) from the east coast of Peloponnesus, by Hinsbergen et al. (2005) from the northern Peloponnesus and by Xypolias and Doutsos (2000) from the northern part of the Chelmos Window, weren’t found in the studied area.

Besides the already sedimentary varying thickness of the Tripolitza Carbonates (s. a.), secondary modifications of the outcrop width of this rock unit must be expected due to its tectonic deformation (flat, widely spanned folding, up- and overthrusts and normal faults). The numerical estimation of these deformations is difficult. Therefore, the thickness of the Tripolitza Carbonates can be specified only inaccurately by about 900 to 1000 m at Mavrovouni and about 800 m at Artemision. The Tripolitza Flysch that is deposited on the top of the Carbonates consists of an alternating sequence of sandstone layers, sandy claystones and sandy marls. Its basis and, thereby, the contact to the carbonates is formed by marls to marly limestones. Its thickness cannot be specified because of the intensive folding and of the probable shearing of material during the advance of the Pindos Nappe.

Investigations by Richter and Mariolakos (1972, 1973) on the Peloponnesus established, that after the end of the carbonate sedimentation and before the beginning of flysch sedimentation a widespread karst relief on the surface of the carbonates was generated (Richter and Mariolakos 1973, p. 9). That means, there was a time period of emergence above sea level and of karstification. Furthermore, in the course of their investigations (Richter, 1973, Richter and Mariolakos 1972, 1973), also olistholiths of Tripolitza Carbonates and “olisthotrymmata”, that means carbonate blocks of kilometres in size, were found embedded in the flysch. Correspondent observations of the latter I couldn’t state, however, in the present area. The Tripolitza Flysch represents the youngest stratigraphic member of the Tripolitza Zone. It's arranged to Oligocene and Lower Miocene times. The sedimentation ended by the advance of the rock sequence of the Pindos Zone resp. by the subduction of the Tripolitza Zone below the Pindos Zone (chapter 6). It can be expected that upper parts of the flysch were sheared off in the course of this process.

2.2 Tectonic structures in outcrop scale

Intensive tectonic stress and varying rock properties within the Tripolitza Zone led to the generation of a specific variety of forms in each of the three rock members.

2.2.1 Phyllite-Quartzite Series

From the view of morphology, the Phyllite-Quartzite Series represents a gently undulating slope, which rises from the Xerias valley to the west and to the north. Concerning the tectonic deformation of this area, two phases can be differentiated:

- Older phase:
  - Generation of recumbent folds in centimetre to decimetre dimension,
  - low grade-high pressure metamorphosis [Jacobshagen, 1994],
  - and intensive shearing parallel to the axial planes.
- Younger phase:
  - Flexural and kink folding in decimetre dimension, and
  - tectonic drag of the phyllite in the footwall by an overthrust, and special folds in decimetre dimension (Fig. 3).

Especially in the older phase, a high tectonic mobility of the rock sequence is represented (Jacobshagen, 1986). Xypolias and Doutsos (2000) submitted a systematic, detailed analysis about metamorphosis and tectonic deformation of the Phyllite-Quartzite Series within the Chelmos Window. From this extensive investigation of numerous samples, they developed a basic model of the tectonic evolution of the northern Peloponnesus. Also, the results of Dornsiepen and Manutsoglu (1994) from Crete and the Peloponnesus agree with this conclusion. An example of the younger tectonic deformation of the Phyllite-Quartzite Series is represented in Fig. 3. These folds and this overthrusting can be seen in context – temporally as well as genetically – with the tectonic deformation of the Tripolitza Carbonates, especially with their imbrication (chapter 2.3.1): The trend direction of the younger fold axes in the metamorphic rocks varies around the west-east direction and the folds show a vergence towards N to NNE.

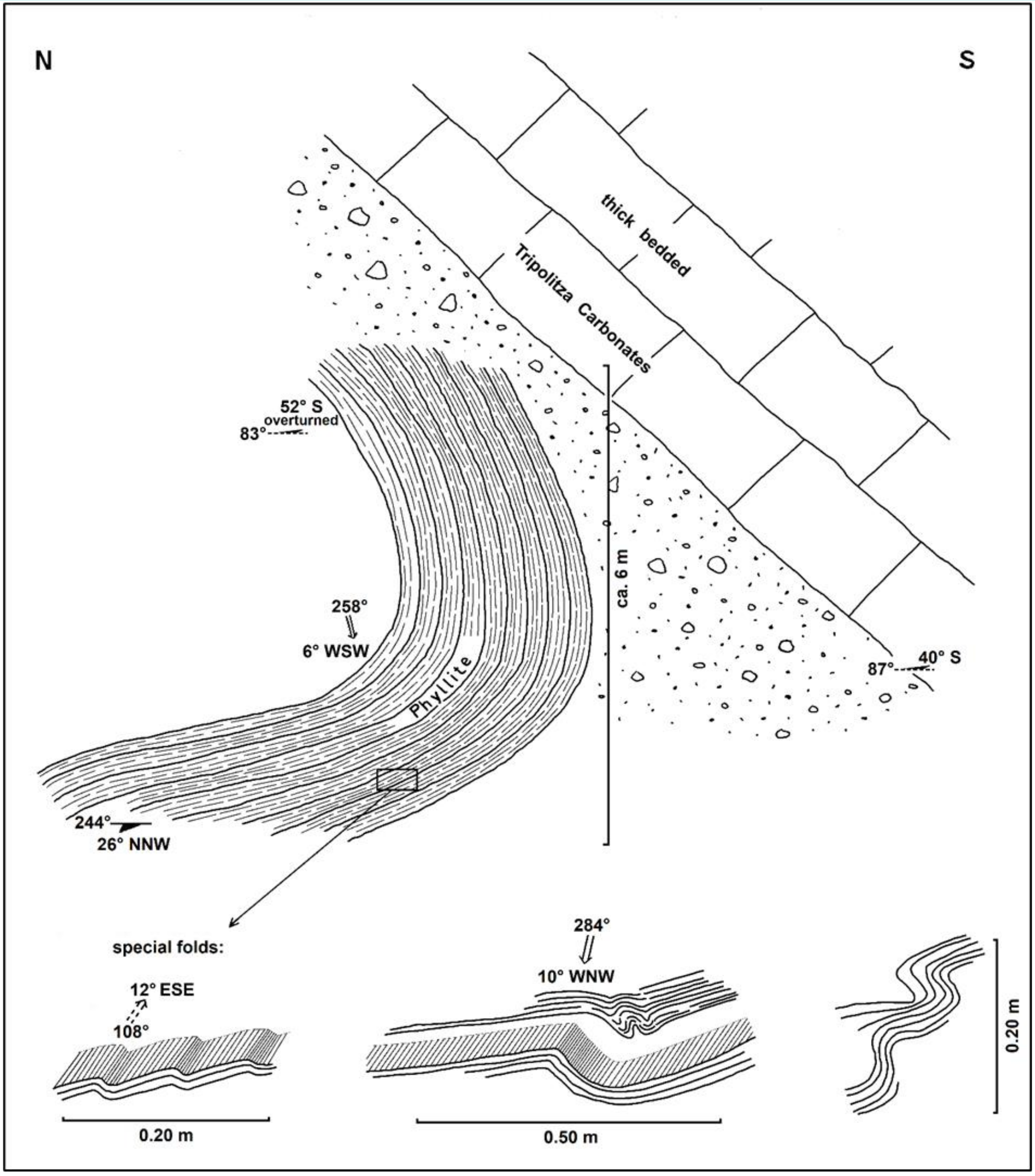

Fig. 3. Contact of the Tripolitza Carbonates with the metamorphic rocks in a southern tributary valley of the Xerias: Tectonic drag of the phyllite in the footwall by an overthrust; special folds in decimetre-range in the phyllite with b-axes round about parallel to the axis of the drag. Note: The presentation of the three-dimensional position of linear elements (e. g. fold axes) and planar elements (e. g. bedding, faults) in outcrop sketches is carried out in this item as defined by Schwan (1973, modified): From the view of the observer, who stands in front of the outcrop, the symbol of the element is oriented (perspectively shortened) forward-turned to the right or the left, if the corresponding linear or planar element gets out of the rock in place “forward” (symbol not dashed). However, the symbol of the element is orientated (perspectively shortened) backward-turned to the right or the left, if the corresponding linear or planar element gets into the rock in place “backward” (symbol dashed).

2.2.2 Tripolitza Carbonates

The Tripolitza Carbonates form the morphology by steep slopes and mountain flanks and by pyramid-shaped summits. The dark rock gives a massive, firm impression. In the outcrop scale, a thick-bedded stratification and a distinct, wide-spaced jointing can be stated. From the near, the latter can easily be mistaken with the bedding. In that case, the observation of the rock in situ is recommended from a somewhat greater distance. At Mavrovouni and in the small carbonate massifs along the southern frame of the Xerias Window, the evaluation of pole diagrams of the joints results in fold axes that trend between 101° and 138°, and vergence angles between 18° and 35° to the NNE or SSW. Further to the north, in the area of Karya, a trend direction of the fold axes of 25° and vergence angles of 14° to 30° to the WNW or ESE can be derived from the joint system. Obviously, there are two directions of fold axes in the Tripolitza Carbonates around the central area of the Phyllite-Quartzite Series.

Furthermore, the Tripolitza Carbonates show in many places marks of an intensive mechanical stress in the form of thin cracks, that are often filled by calcite and that in parts show small offsets in mm-range and stepped tear-off edges. Here and there, traces of movements in the bedding plane or of tectonic breccias healed by calcite occur. The key structures within the Tripolitza Carbonates exceed in most cases the outcrop dimension and can be overlooked in a few places only. It’s a matter of a *widely bent folding* (large wavelength, small amplitude) that mostly becomes apparent on the map or by aerial or satellite imaging (chapter 2.3). In the carbonate massive in the south of the village Krya Vrysi, a correspondent structure can be observed as a whole (Fig. 4).

Besides the folding, a tectonic imbrication occurs in the Tripolitza Carbonates, which caused the stairs-like slope of the mountain and the thrusting of the carbonates over the flysch near Krya Vrysi (Fig. 4). At the Mavrovouni and the Gaidourovouni, which joins to the west, an imbrication is present, as well, that is considered in chapter 2.3 in the context with the large-scaled tectonics. Furthermore, the overthrust reproduced in Fig. 3 (s. a.) is also a part of the imbrication.

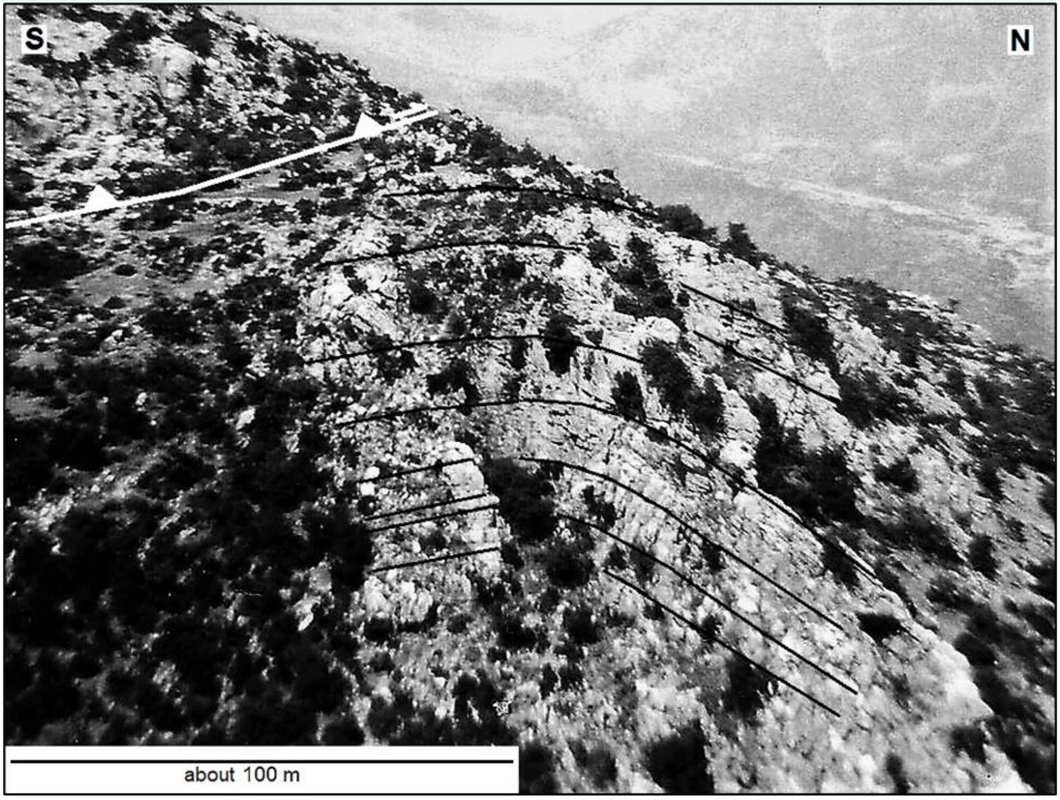

Fig. 4. Upright to slightly NNE-verging anticline in the Tripolitza Carbonates south of Krya Vrysi (trend of the anticline axis 125°; relative compression ε = 0.07) (bedding retraced in parts) and NNE-verging overthrust in the carbonates (white); the basis of the Pindos Nappe is located further to the south at the mountain slope (out of the Figure)

2.2.3 Tripolitza Flysch

The Tripolitza Flysch forms morphological flattening between the carbonate massifs. However, these flattenings are drawn through numerous deep, V-shaped valleys because of a strong linear erosion. The rocks are strongly broken by intensive tectonic deformation and tend to a fragmentary disintegration. Partly isoclinal, partly upright folds in the range of metres to decametres can be regarded as key structures in this unit (Fig. 5). The strong compression is in clear contrast to the widely bent folding of the Tripolitza Carbonates (disharmonic folding). The fold axes fluctuate in their trend direction, but on average they coincide with the WNW – ESE trend of the flysch area between Mavrovouni and Ktenias. This flysch area can be understood on the whole as a strongly compressed synclinorium.

Besides the intensive folding, both up- and overthrusts and normal faults occur within the Tripolitza Flysch. The fault system represented in Fig. 6 can probably be related to the younger extensional tectonics (chapter 4), which obviously proceeded in several phases. Faults of different ages interfere with each other. The individual faults show a considerable variation in their strike direction.

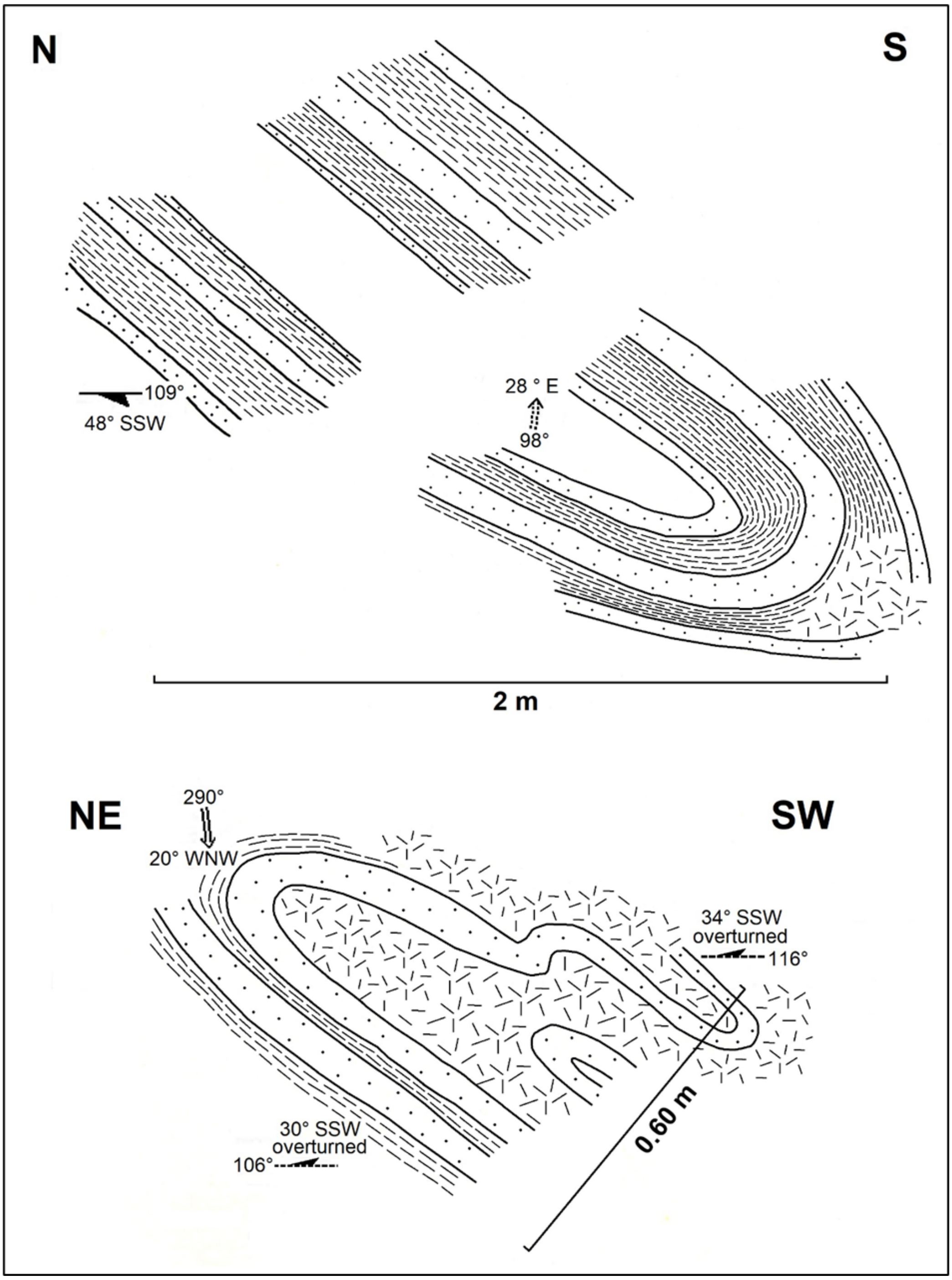

Fig. 5. Examples of isoclinal, N to NNE verging folds in the Tripolitza Flysch (east of Krya Vrysi) (relative compression ε = 0,50); tectonically effected thickness reduction of the limbs and increase of the apex sector predominantly in the incompetent claystones.

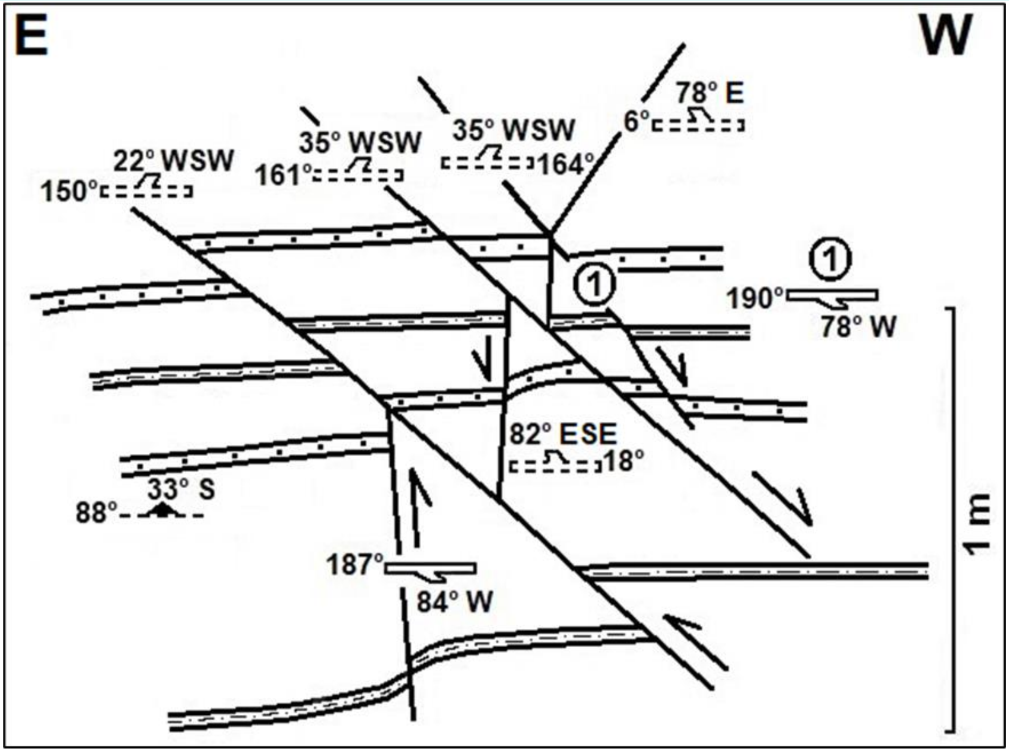

Fig. 6. System of intersecting faults in the Tripolitza Flysch near Krya Vrysi (steep slope at the road to Zogka).

2.3 Large-scale tectonic structures

The large-scale architecture of the Tripolitza Zone becomes visible when the setting of stratification in the Tripolitza Carbonates is carved out (Fig. 7). For this purpose

- measurements in the field,
- data from the geological map (GSR 1960, 1970 and IGME 1988), and
- satellite images (Google Earth and Google Maps since 2005)

were used. Especially the latter connect the separate measurements to a general view.

2.3.1 Mavrovouni and southern frame of the Xerias Window

From the view of large-scale tectonics, the Tripolitza Carbonates of the Mavrovouni, the Tripolitza Flysch in the area of Tourniki and Krya Vrysi, and the smaller occurrences of Tripolitza Carbonates at the southern frame of the Xerias Window form a synclinal structure (Fig. 8), whose axis trends from WNW to ESE. The folds in the Tripolitza Flysch, that can be observed in the outcrops, are integrated in this large-scale architecture with regard to the strike of the axes and the vergence of the folds.

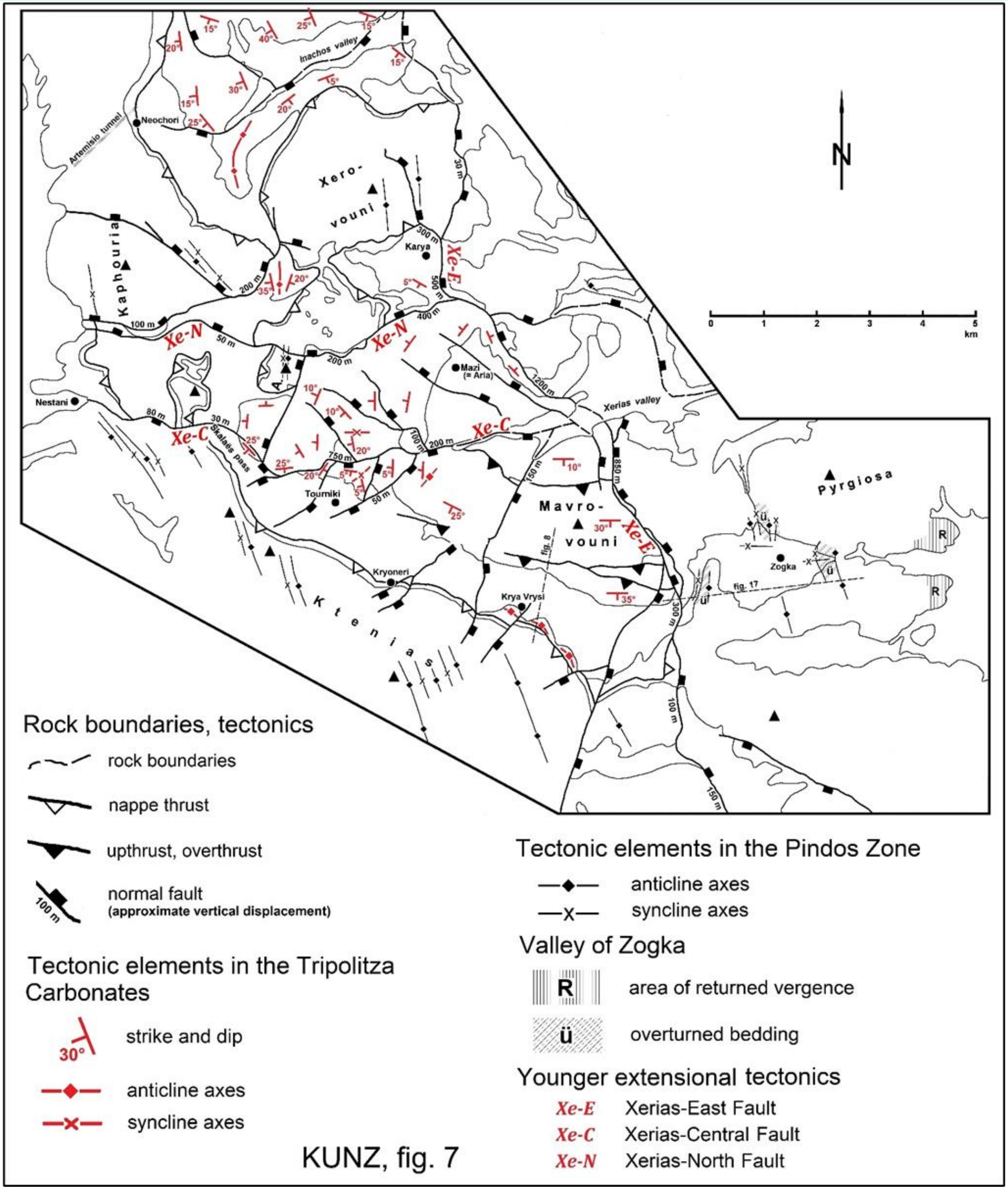

Fig. 7. Tectonic elements and bedding of the Tripolitza Carbonates, tectonic elements in the Pindos Zone, and younger extensional tectonics (slope waste and landslides removed).

The Tripolitza Carbonates of the Mavrovouni dip on an average by 30° to SSW. The dip angle decreases to the north towards the Phyllite-Quartzite Series to 10°. A steadily bent fold limb is present. By detailed analyses of rock facies and microfossils at the southern slope of the Mavrovouni, Fleury (1980) established an internal imbrication in this fold limb with displacements (normal to the bedding) of about 60 m in total. The overthrusts dip nearly parallel to the bedding also to SSW. By means of the satellite images (Google Earth and Google Maps since 2005), they can be traced to the west till the vicinity of the village Tourniki.

A further fault that can be added to this NNE verging imbrication at the Mavrovouni is the above described overthrust at the contact between Tripolitza Carbonates and Phyllite-Quartzite Series (Fig. 3). This fault can be traced to the east till the Xerias-East fault (chapter 4.2). The occurrence of Tripolitza Carbonates at the southern frame of the Xerias Window (Fig. 4, Fig. 7) south of Krya Vrysi represents an anticlinal structure with a trend direction of WNW – ESE. This structure can be extended to the SE by the satellite image (Google Earth and Google Maps since 2005). Furthermore, these occurrences are tectonically imbricated and thrusted to the NNE over the Tripolitza Flysch (Fig. 8). Further overthrusts south of the Mavrovouni within the flysch and parallel to the others are possible but not visible in the field. The distinct disharmonic folding between flysch and carbonates – the compression of the flysch apparently comprises a multiple of the carbonates – allows the conclusion on further folds and overthrusts in the carbonates unrecognisable at the surface on the one hand, and on shearing horizons within the flysch and at its basis on the other hand. The idea of the origin of the intensive tectonical stress of the Tripolitza Flysch due to the crossing by the Pindos Nappe, cannot be confirmed in the studied area. Neither the structures and NNE-vergences in the flysch nor in the Tripolitza Zone in total (chapter 6) provide evidence for this. Concerning the carbonate massif near Krya Vrysi (Fig. 4), the fold axes in the flysch are laid round it, and, therefore, the axes can locally be bent off the general NW – SE trend of the synclinorium till the N – S direction.

2.3.2 Eastern flank of Artemision

Mount Artemision with its characteristic top of Pindos Plattenkalk is built in its main part by the rocks of the Tripolitza Zone. Thereby, the eastern and western side of the mountain differ significantly. The eastern flank consists of thick-bedded Tripolitza Carbonates, that form a steep slope. Slope waste and landslides are existing scarcely, because they probably found no hold there (remains are present on the Phyllite-Quartzite Series). The dip of the carbonates is orientated in general with 10° to 15° to W till WNW. Folds and imbrication couldn’t be found here in the field.

However, the thick carbonate sequence is strongly affected by the young extensional tectonics, that created a branching fault system (chapter 4). The rock layers are dragged and inclined at the faults. Also, the connection of the Tripolitza Carbonates between Mavrovouni (chapter 2.3.1) and Artemision doesn’t happen by a continuous bending of the dip direction from SW via W to WNW. In fact, it happens discontinuously by kinks along the faults (Fig. 7).

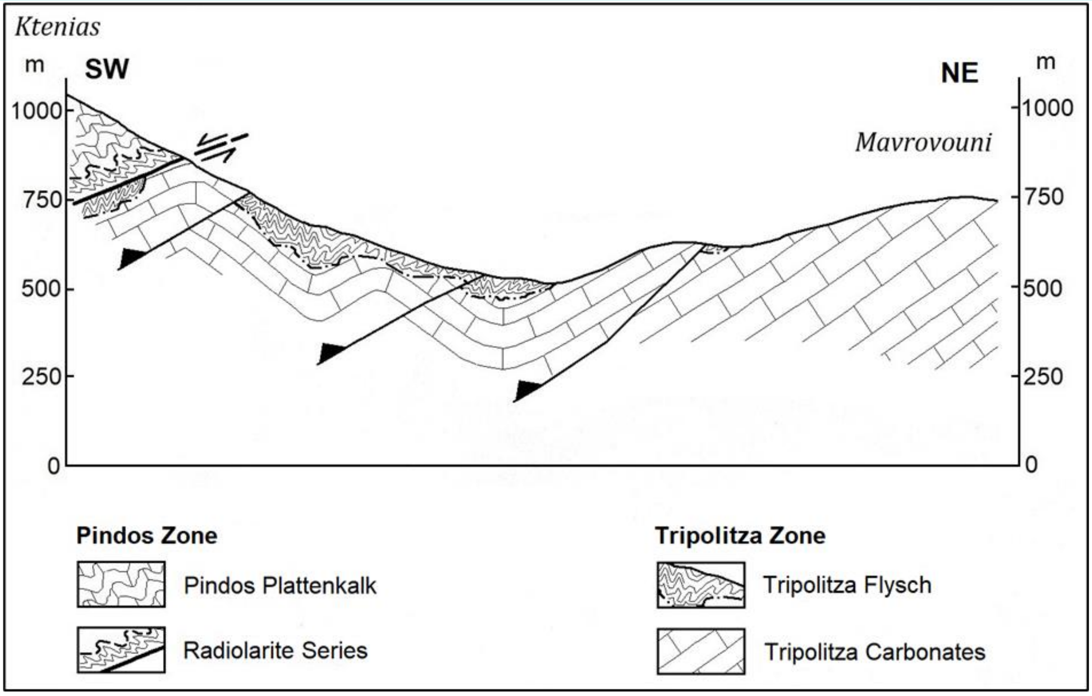

Fig. 8. Cross section through the southern part of the Xerias Window in the area of Krya Vrysi: Synclinorium with NNE vergent fold and imbricate structures of the Tripolitza Zone (simplified), (see Fig. 7).

2.3.3 Western flank of Artemision

The western flank of Artemision is largely taken by Tripolitza Flysch, which is covered, however, in three areas by rocks of the Pindos Zone:

- on the top of the mountain,
- on a secondary top (Balou Spylia) western underneath the main top, and
- at the foot of the flank near Nestani.

These klippes are remnants of the originally certainly complete Pindos Nappe. The extensive erosion of the nappe can be explained by the morphological-tectonic uplifted position of the mountain flank (chapter 3.3.2). Additionally, the Tripolitza Flysch is covered here by numerous slope waste and by landslides (predominantly Pindos Plattenkalk). The post-orogenic sediments cover in parts also the Radiolarite Series and the nappe thrust of the above-mentioned Pindos klippes. Tripolitza Carbonates don’t outcrop at the western flank of Artemision. They can be expected here, however, in a comparatively shallow depth below the surface. No data can be given concerning bedding and tectonic structures in the flysch, because of the extensive cover by slope waste. In the large-scaled tectonic connection, a synclinorium with an axis trending approximately N – S can be supposed.

2.3.4 Basis of Xerovouni and southern flank of Melidoni

The light-coloured Pindos Plattenkalk of the Xerovouni in the north of Karya doesn’t allow here a view of the underlying Tripolitza Zone. The dark Tripolitza Carbonates stand out marginal underneath as follows:

Along the western side of the Xerovouni, an anticlinal axis can be traced in the Tripolitza Carbonates with a NNW – SSE strike (Fig. 7). At the northern side of this mountain, the beds of the Tripolitza Carbonates bend to a southeastern to southern inclination, that means they dip under the Pindos Nappe. Therefore, a flat, bowl-shaped syncline with Tripolitza Flysch can be suspected there, which is covered by the Pindos Nappe of the Xerovouni. Further to the north at the southern flank of the Melidoni mountain, the beds of the Tripolitza Carbonates incline to the SW to S by 25° to 35° on an average. This steepening of the inclination indicates a dome-shaped structure in the depth northward of the studied area. It concerns the window of Kephalovrison – Exochi, which is another part of the Chelmos Window (chapter 1.2) that Eckl (1979) investigated in particular.

2.3.5 Tectonic architecture and position of the Tripolitza Zone on the whole

Regarding the tectonic position of the Tripolitza Zone on the whole, the following can be stated in the studied area:

- The Tripolitza Zone gives the impression of an independent unit with a dome-shaped arching in the centre. South of this, a NNE-verging synclinorium is present, and in the west of the dome N – S trending, upright folds seam to follow up.
- I couldn’t find any structures that indicate a nappe transport of the Tripolitza Zone to the west or southwest.

These findings don’t correspond with results of research in other areas of the Peloponnesus, whereby the Tripolitza Zone is considered in general as a nappe, which was transported to the west over the Ionian zone resp. was subducted by the latter (e. g. Dercourt et al. 1976 and 1993, Jacobshagen 1986 and 1994, Kaberis et al. 2013, Papanikolaou 2013 and 2021). Often, the Phyllite-Quartzite Series is regarded, thereby, as an independent, intercalated nappe. On the basis of intensive investigations on southern Peloponnesus, Thiébault and Triboulet (1982 and 1984) could divide the Quartzite-Phyllite Nappe still further in three partial nappes, that got between the Ionian and the Gavrovo-Pylos (Tripolitza) Nappe and suffered a multiphase-deformation in the Lower Miocene.

In order to clarify the tectonic history and position of the Tripolitza Zone on the NE-Peloponnesus, further investigations of its key structures seem to be necessary.

3. Pindos Zone

3.1 Rock sequence

The rock sequence of the Pindos Zone was described by Fleury (1980) and Jacobshagen (1994) from Kato Klitoria on the Chelmos. It isn't completely present in the studied area. Triassic and Lower Jurassic sediments lack here, probably because of tectonic shearing. Therefore, the Radiolarite Series (Upper Jurassic to Cenomanian) form the basic member of the sequence, but this is also reduced tectonically at its basis. Its thickness is unknown due to the intensive folding, probably about 50 m or less. The Pindos Plattenkalk (Turonian to Maastrichtian), which follows to the roof, seems to be present completely. But also in that case, the thickness can be specified only very roughly by 250 – 500 m, again because of the intensive folding.

The so-called Transitional Series ("couches de passage au flysch") (Maastrichtian to Paleocene), that occur in tectonic deep positions of the eastern frame of the Xerias Window, are classified in the roof of the Pindos Plattenkalk. Foraminifera were found therein (Dercourt 1964, Doert et al. 1977), that support a classification of Maastrichtian to Paleocene age. Their thickness that can be estimated again only roughly amounts approximately 50 to 100 m.

Due to the lack of appropriate tectonic locations (syncline, graben), the Pindos Flysch is missing in the studied area. It is present, according to Blumenthal (1933), Dercourt (1960) and geological map (GSR 1960, 1970) further to the east near Argos and Kephalari.

3.2 Tectonic structures in outcrop scale

3.2.1 Radiolarite Series

The Radiolarite Series is morphologically a little peculiar due to its small outcrop width; in places it forms planes of small area. However, it is eye-catching, because of its red-violet colour in the field, and usually well traceable. The basic member of the Pindos Nappe in the studied area can be missing completely in parts, probably due to tectonic shearing during the nappe transport.

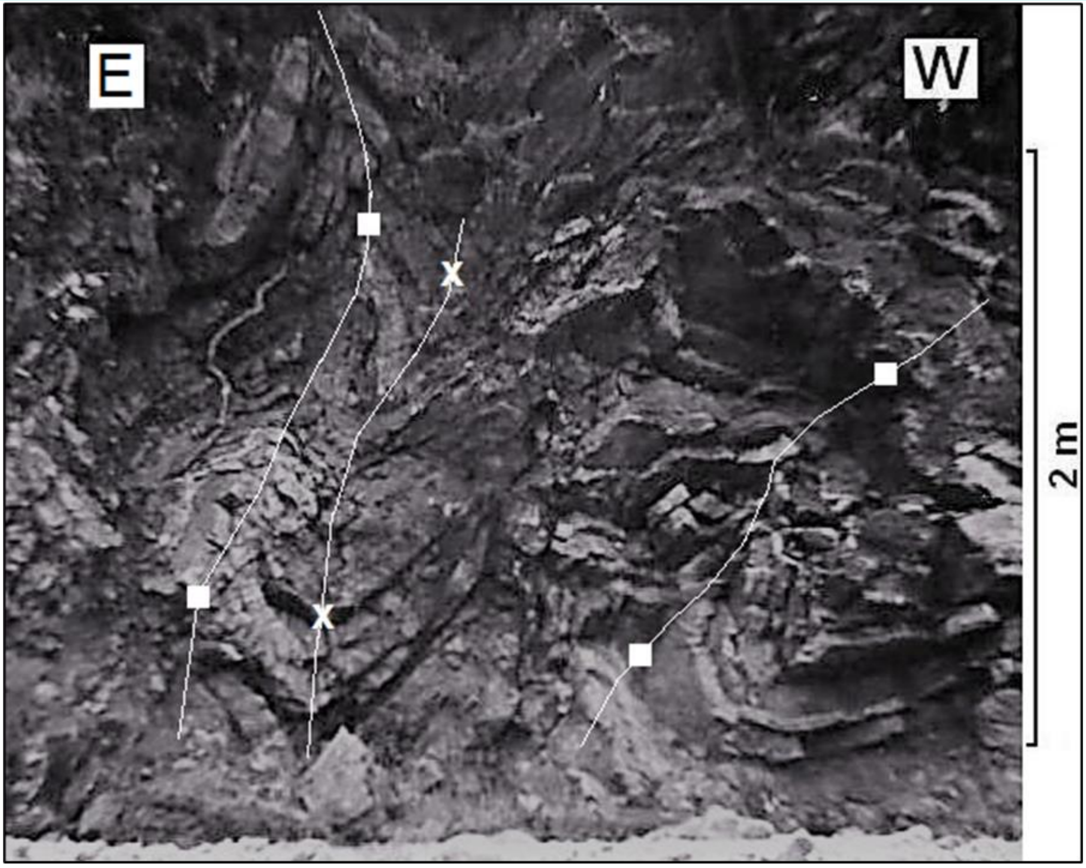

Fig. 9. W-verging folds in the Radiolarite Series near Kryoneri (NE-flank of Ktenias); thinning and thickening of rock layers, orientation of fold axes 7°/ 22°S; axial planes (white) bent.

The Radiolarite Series represents a tectonically mobile alternating sequence of radiolarites and claystones in layers of centimetres in thickness. It shows a *well-defined folding, rich in details*, in the range of decimetres and metres. Thinning and thickening are frequent due to the plastic materials, especially the claystones. The vergence of the folds is straightened between W and S; backward vergence is possible, but rare. The planes of the fold axes vary between upright and recumbent. Examples are given in Fig. 9 and 10.

3.2.2 Pindos Plattenkalk

The Pindos Plattenkalk is a lithological unit, which sets a characteristic element of the landscape. Because of its light colour, it forms a strong contrast to the dark Tripolitza Carbonates. Also, it features only poor vegetation, whereas the latter is largely covered by dense, dark green bushes. At the eastern side of the Xerias Window, the surface of the ridges, which are built of Plattenkalk, is more table-shaped (limestone plateau). In the southwest, west and north of the Xerias Window, the Pindos Zone presents another morphological feature. There, the Plattenkalk forms steep flanks, spiky ridges, and some prominent peaks. The limestone plateau doesn’t continue there.

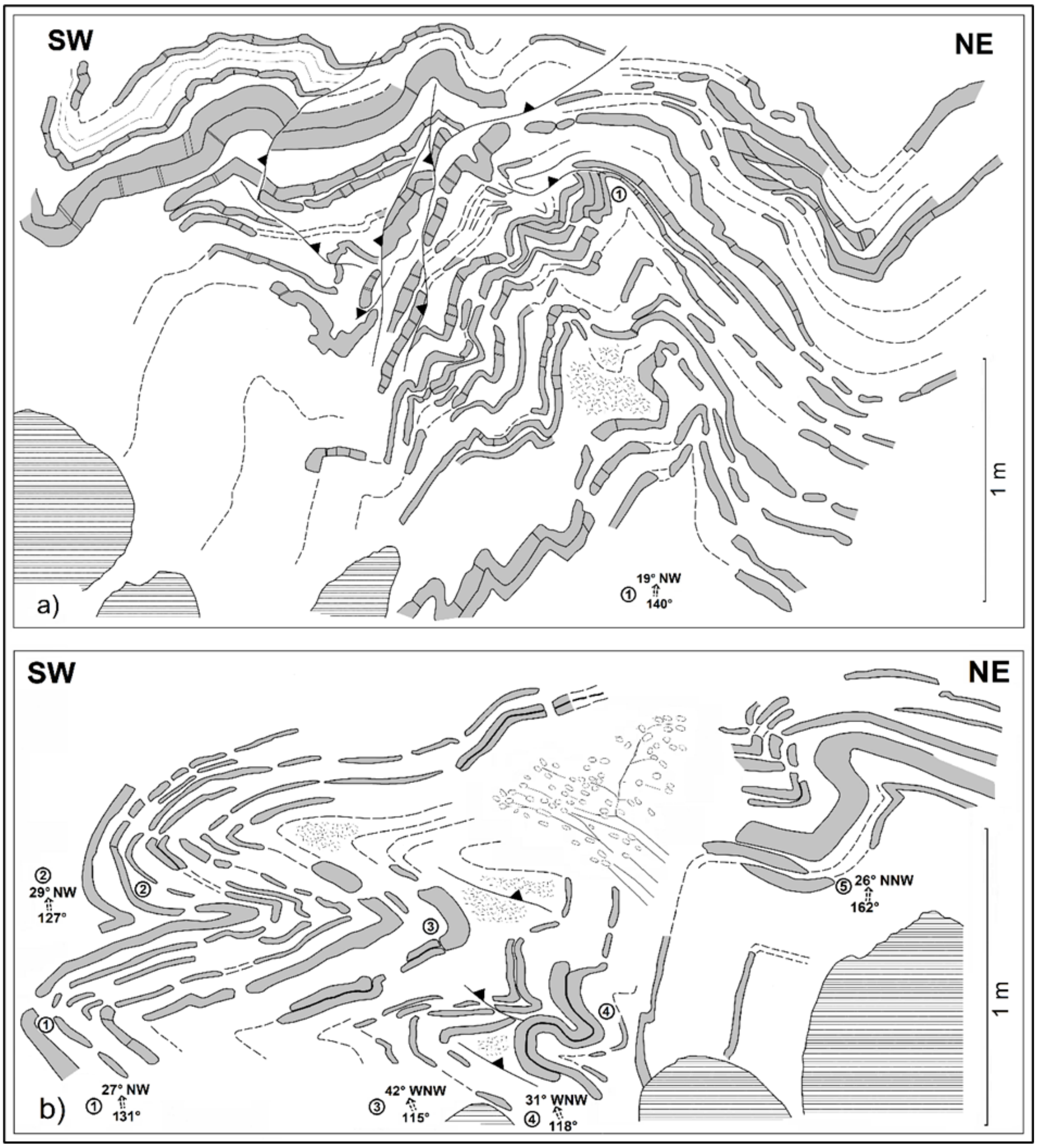

Fig. 10. Folds in the Radiolarite Series (southeastern end of Ktenias in the open cut of a creek): laminated radiolarite layers, etched by erosion, and claystone intercalations, upright to slightly SW-verging (10a) resp. recumbent folds (10b).

3.2.2.1 Eastern side of the Xerias Window (limestone plateau)

A distinct folding of different dimensions occurs within the Pindos Plattenkalk of the eastern side of the Xerias Window. The *vergence of these folds is oriented predominantly in western direction.* Backward vergence is possible, regionally frequent. *The folds with western to southwestern vergence often present recumbent flanks.* The dip angles are mostly flat, except in the fold hinges, whereby the table-shaped morphological character of the ridges is originated (limestone plateau). The folds with backward vergence, in contrast, feature inclined, steep dipping axial planes. Figures 11 to 13 illustrate the intensive folding of the Pindos Plattenkalk in different dimensions.

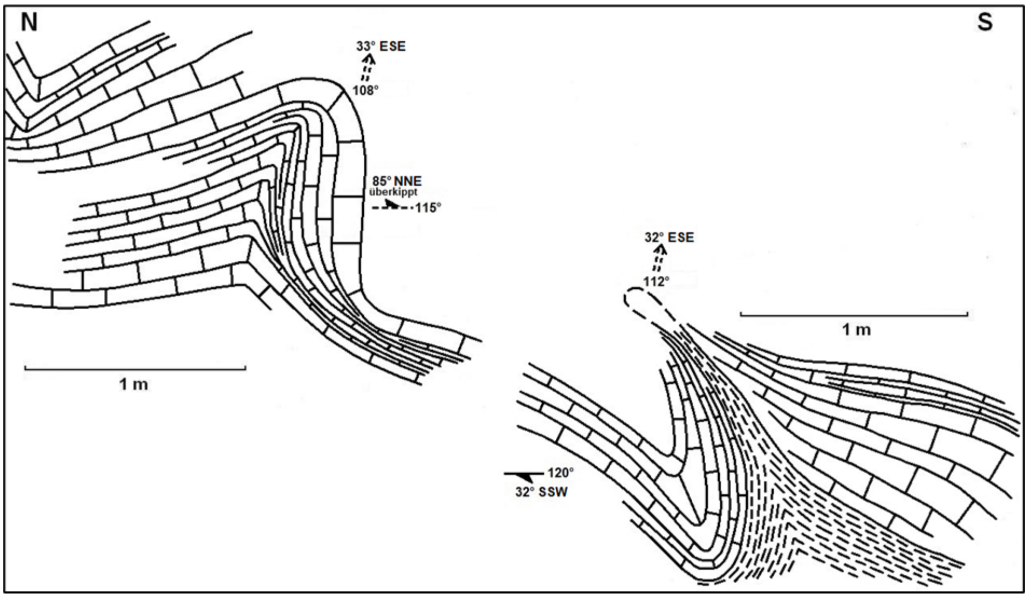

Fig. 11. Upper part of the Pindos Plattenkalk in an open cut of a creek northeast of Karya: Double frontal fold with NNE- and SSW-vergence.

Fig. 12. Recumbent, SW-verging anticline in the uppermost Pindos Plattenkalk at the road Argos – Karya near Agios Stephanos: Fold axis (130°/5° SE) runs acute to the face; surface irregular; thereby strong variation of the outcrop width of the single layers (face height about 8 m; folds at the right side partially retraced).

About 8 km to the south of the valley of Zogka, W-verging, recumbent folds were exposed in the uppermost part of the Plattenkalk during construction works along the road Myli – Achladokampos – Tripolis. These folds became documented by Doert, Richter & Mariolakos (1977). The authors asserted that *these folds can be considered as key structures, because they correspond to the flat bedding, which dominates in the* *large-scale view (limestone plateau).* An area with backward vergence (that means east vergence) is present in the very east of the limestone plateau immediately before its diving down below the young sediments of the plain of Argos, such as near the village Elleniko. Blumenthal (1933) describes east verging folds of larger dimension (range of some hundred metres) from the entrance into the Xerias valley near Chouni (about 4 km north of the studied area).

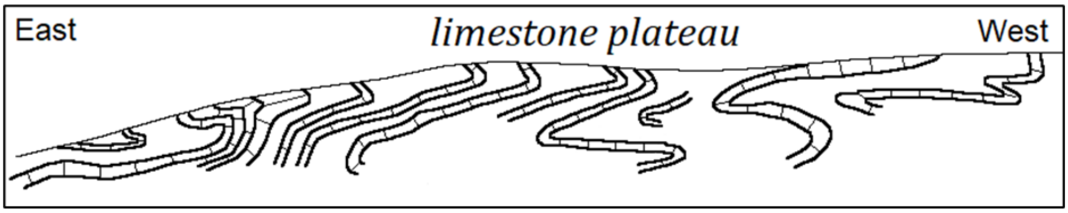

Fig. 13. Eastward Zogka, view southbound to the mountain ridge: recumbent, WSW-verging folds in the Pindos Plattenkalk (length of the Figure about 900 m) (trend of the fold axes about 150°); the large outcrop widths in the fold hinges are essentially caused by the morphology, which flattens at the back of the mountain.

3.2.2.2 Southwestern side of the Xerias Window (Ktenias ridge)

The Ktenias ridge extends over about 10 km from Achladokampos in the SE till Nestani in the NW. It frames the Xerias Window to the SW and is built predominantly by Pindos Plattenkalk. The Plattenkalk is characterised here by isoclinal, SW verging folds, whose axial planes are inclined. An example is given in Fig. 14.

Fig. 14. Ktenias ridge between Kryoneri and Krya Vrysi seen from the south: Isoclinal, WSW-verging folding in the Pindos Plattenkalk in deca- to hectometres range (bedding partially retraced) (Google Earth, since 2005).

3.2.2.3 Remaining window frame (west of Karya, Artemision summit area and western flank till Nestani, Kaphouria, Xerovouni)

West of Karya in the rise to Artemision, the rock sequence of the lowermost part of the Pindos Plattenkalk is present. The layers feature a disharmonic folding in the range of decimetres to metres. Thinning and thickening of rock layers and transport of plastic material into the fold hinges are frequent. The vergence of the folds is mostly orientated between W and S. The axial planes are often round about in horizontal position (Fig. 15). Again, backward vergence is possible, but rare. A similar example of the folding style of the lower part of the Pindos Plattenkalk was documented by Doert (1981; in Jacobshagen, 1986) from the western Peloponnesus. The summit area of Artemision is featured by an isoclinal, west-verging folding that is comparable with that of the Ktenias ridge (Fig. 14). The top of the mountain is situated on the hinge line of an anticline striking from N to S; west of it, approximately at the foot of the summit area, the axis of the following syncline is running.

Further to the west downward to Nestani, the Pindos Nappe features a *cascade-shaped folding*, that was described already by Blumenthal (1933) (chapter 3.3.3). The solid rock called “the castle”, which preserved a SW-verging recumbent anticline, is part of these folds (Fig. 18).

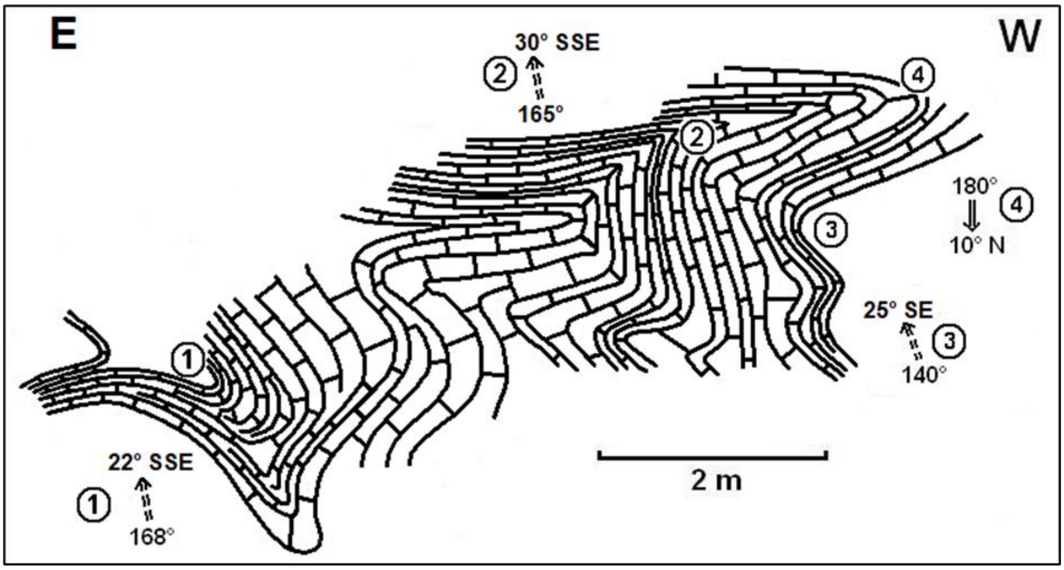

Fig. 15. West of Karya in the rise to Artemision: Recumbent to diving, west verging folds; in parts thinning resp. thickening of layers.

3.2.3 Transitional Series

The Transitional Series to the Pindos Flysch are the youngest member of the rock sequence of the Pindos Zone in the studied area. They occur exclusively in the east of the Xerias Window and form morphologically broadened valleys, which are sunk in the limestone plateau. These broadened valleys are structured within by planes and narrow, V-shaped valleys.

The predominantly marly rocks tend to decompose in small pieces due to their intensive tectonic deformation. Therefore, the possibilities of observing the tectonic structures are comparatively unfavourable. The dimension of the exposed folds lies in the range of decimetres to metres (Fig. 16).

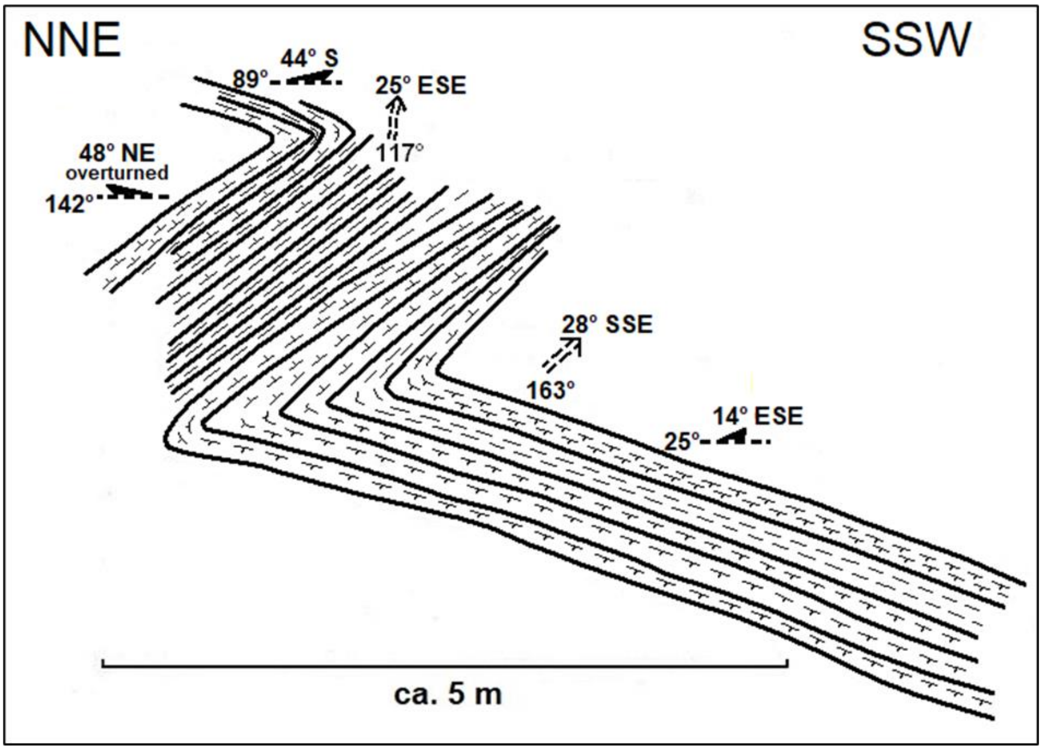

Fig. 16. Recumbent folds in the Transitional Series in the open cut of a creek near Zogka.

From the trend direction of the fold axes in the Transitional Series, no clear indication of the compressional direction can be derived. In fact, it scatters largely, and it deviates in parts widely from that of the key structures. Two causes can be identified for this:

- In the case of flat fold planes, the trend of the B-axes generally scatters largely [Schwan, 1965].
- Another, younger compression took place and created thereby a cross folding of the axes (chapter 3.3.1).

The major direction of compression can be expected to the west till southwest, like in the above-described Pindos Plattenkalk.

3.3 Large-scaled tectonic structures

3.3.1 Pindos Zone in the east of the Xerias Window

At the east side of the Xerias Window, the broadened valleys attract attention, that are sunk in the limestone plateau and where the Transitional Series are present. Besides their morphological deep level – the valley of Zogka, for example, lies about 200 m deeper than its surroundings –, these occurrences are stretched noticeably in the W – E direction.

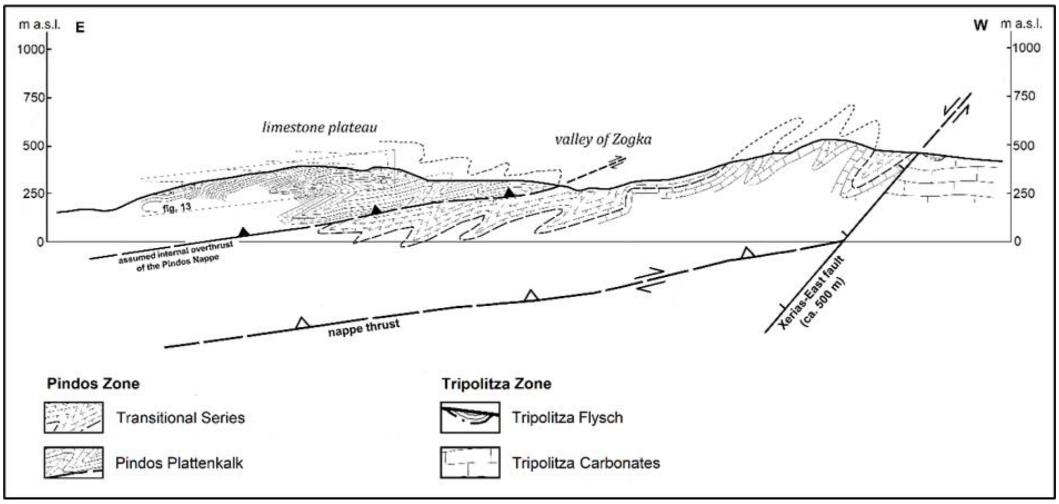

Fig. 17. Cross section through the Pindos Zone along the valley of Zogka (see Fig. 7).

In order to clarify their tectonic position, the occurrence of inverse bedding in the valley of Zogka is important. This can be found around the valley along the boundary between the Transitional Series and the Pindos Plattenkalk, thereby however not continuous, but at the eastern side of synclinal axes resp. the western side of anticlinal axes (Fig. 7). In contrast, the bedding is normal each between the inverse sections. These findings suggest that the Transitional Series, according to the key structures, are folded in recumbent, W-verging synclinoria (Fig. 17). In the case of E-vergence, the inverse bedding would occur – vice versa – at the western side of the synclinal axes resp. at the eastern side of the anticlinal axes. A flat dipping overthrust inside the Pindos Nappe, which complements this model, is possible, couldn't be verified in the field, however (Fig. 17). Anyway, difficulties with the rock volumes in the section can be corrected by the deeply wrapped, internally overthrusted synclinorium. Furthermore, the Pindos Zone eastward of the Xerias Window seems to be shaped additionally after the end of the nappe transport by axial depressions due to transverse bending of the major folds (cross folding). Two observations support this assumption:

- The areas of extension of the Transitional Series are elongated noticeably in the W – E direction, and
- W – E trending fold axes occur within them.

The model of bag-shaped synclines for the Transitional Series, which are sunk in the limestone plateau, was considered at times. In that case, steep to vertical bedding along both flanks of the valley should accompany the outcrop of the Transitional Series, which isn't present, however. The erosive baring of the Transitional Series within the limestone plateau was possibly intensified by younger, W – E striking faults. This is indicated by steep to vertical rock faces along the narrow entrance into the valley of Zogka. Great magnitudes in dislocation can't be realised here, in fact, but these lines enabled an intensified erosion.

3.3.2 Remaining window frame

Within the remaining window frame, the Transitional Series doesn't exist. The lower part of the Pindos Zone consisting of Radiolarite series and Pindos Plattenkalk is present. At the Ktenias, the Pindos Plattenkalk shows isoclinal, W- to SW-verging, overturned folds (Fig. 14). The folding at the northern window frame (Kaphouria, Xerovouni) is shaped in the same style. At the top of Artemision and from the NW-end of the Ktenias down to Nestani, however, it's a matter of recumbent, SW-verging folds. Blumenthal (1933, p. 471) speaks colourful about "serpentine fold stairs" (Fig. 18). Small areas of Pindos Plattenkalk and Radiolarite Series at the western flank of Artemision (left outside of Fig. 18) must be understood as remains of the formerly complete Pindos Nappe. They cover

- the top of the mountain,
- the secondary peak (Balou Spylia) western below the main top and
- the foot of the mountain flank near Nestani.

3.3.3 Tectonic architecture and position of the Pindos Zone in a whole

The Pindos Zone constitutes the frame of the Xerias Window. Along the complete window frame, west and southwest vergence of the key structures can be observed, especially along the Ktenias ridge and at the mountains Artemision and Xerovouni. The window isn't a synclinal structure that became pushed from both sides between two anticlines. There is no area with eastern vergence along the frame. The east verging folds, which can be observed further to the east in the limestone plateau – not at the window frame – can be regarded as local backward vergence.

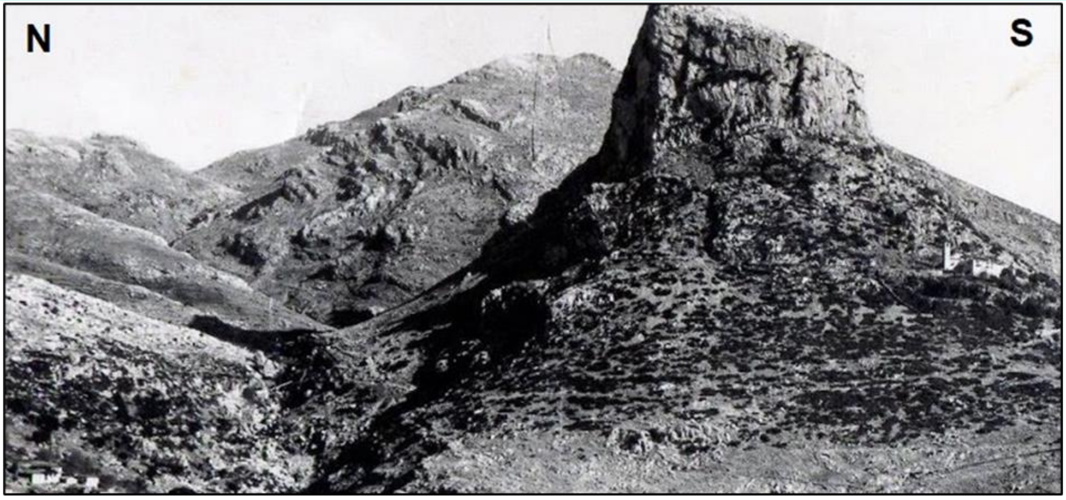

Fig. 18. View to the east over Nestani onto the Goula-rock (foreground) and the northwestern end of Ktenias: SW-verging folds ("serpentine fold stairs"; Blumenthal, 1933, Wikimedia Commons since 2004); axes ascending to the north; the rock preserved the hinge of a SW-verging, recumbent anticline (B-axis 140°/5° SE).

Thus, the Pindos Zone lies as a nappe on the Tripolitza Zone. However, the elevation of the nappe basis varies significantly. It declines from a high altitude at Artemision (approximately 1330 m a. s. l.), and at Skalaës pass (appr. 1300 m a. s. l.) towards Nestani (to appr. 1000 m a. s. l.), and towards the ESE till the southern end of the Xerias Window (to appr. 600 m a. s. l.). From Artemision to the north it declines to the southern flank of the Xerovouni (to appr. 800 m NN), and through under this mountain to its northern flank (to appr. 600 to 400 m a. s. l.). From a deep altitude at Neochori (appr. 600 m a. s. l.), it rises in a northward direction versus Melidoni mountain (to appr. 800 m a. s. l.). The collective deformation of Tripolitza and Pindos Zone after the nappe transport is reproduced by this up and down of the nappe basis. The indications in the valley of Zogka supply evidence on a deeply wrapped, recumbent, west-verging synclinorium in the upper part of the Pindos Nappe. An internal overthrust couldn't be verified, in fact, in the field, but it appears likely (Fig. 17).

4. Younger extensional tectonics

The Neogene to Quaternary fault tectonics contributed significantly to today's morphological appearance of the Xerias Window. By uplifts resp. lowerings, it brought the tectonic units again in different altitudes, and it opened, furthermore, pathways for an intensive retrogressive erosion.

Position and pathway of the younger extensional tectonics as given at the geological map (Fig. 2 and 7) are based on

- the outcrops,
- the geological field mapping and

- the analysis of satellite images (Google Earth and Google Maps, since 2005).

4.1 Outcrop scale

Normal faults in the outcrop range could be observed at different locations in the Tripolitza Flysch (e. g. Fig. 6). The dipping directions of these faults vary but show maxima around eastern and northeastern dipping. Doert, Richter and Mariolakos (1977) described numerous examples of the young extensional tectonics of this area from the uppermost Pindos Plattenkalk, which are exhibited at the road Myli – Achladokampos south of the studied area. There, a "predominance of east to southeast dipping fault planes" was found (p. 383). Several, approximately vertical faults are exposed, also in the uppermost Pindos Plattenkalk, at the outcrop of Fig. 12 (following the image to the right). The striking direction of these faults is west – east, and they show partly downthrown, partly strike-slip effects. The younger faults, that can be observed in the outcrops, coincide in their strike directions with those identifiable and traceable on the map. The latter are examined more closely in the following chapters.

4.2 Eastern side of the Xerias Window and Xerias-East fault

The eastern side of the Xerias Window with the limestone plateau of Pindos Plattenkalk is crossed by generally west – east striking, steeply dipping normal faults, along which the valleys with the Transitional Series extend (chapter 3.3.1). These faults lead to the west into the major Xerias-East fault, which limits the window at this side. Their prolongation further to the west across the Xerias-East fault isn't clear. Possibly, they are displaced at this fault and are connected to Xerias-Central and Xerias-North fault (s. b.). Among others, the Xerias-East fault is exhibited near Karya on the road to Argos (Fig. 19). Its vertical displacement can be estimated there at 500 m. Further to the north, the fault branches out in faults of minor displacement. To the southeast, the displacement increases significantly and reaches in the Xerias valley approximately 1200 m; along the further pathway it decreases gradually on 100 to 150 m.

4.3 System of the Xerias-Central fault

The Xerias-Central fault runs along the correspondent valley; to the west it continues over the Skalaës pass towards Nestani. Its displacement amounts in the centre of the window up to 750 m and decreases both to the west and to the east significantly. It features especially within the Tripolitza Carbonates numerous branches. Furthermore, there is dragging and tilting of carbonate blocks alongside this fault in the slope to the Skalaës pass (Fig. 7). The Xerias-Central fault and its branches ruptured the Tripolitza Carbonates and established thereby starting lines for the retrograde erosion. The latter penetrated deeply into the eastern flank of Artemision and the northern flank of Ktenias and exposed the metamorphic area. It was accelerated, yet, in the present times by human activities.

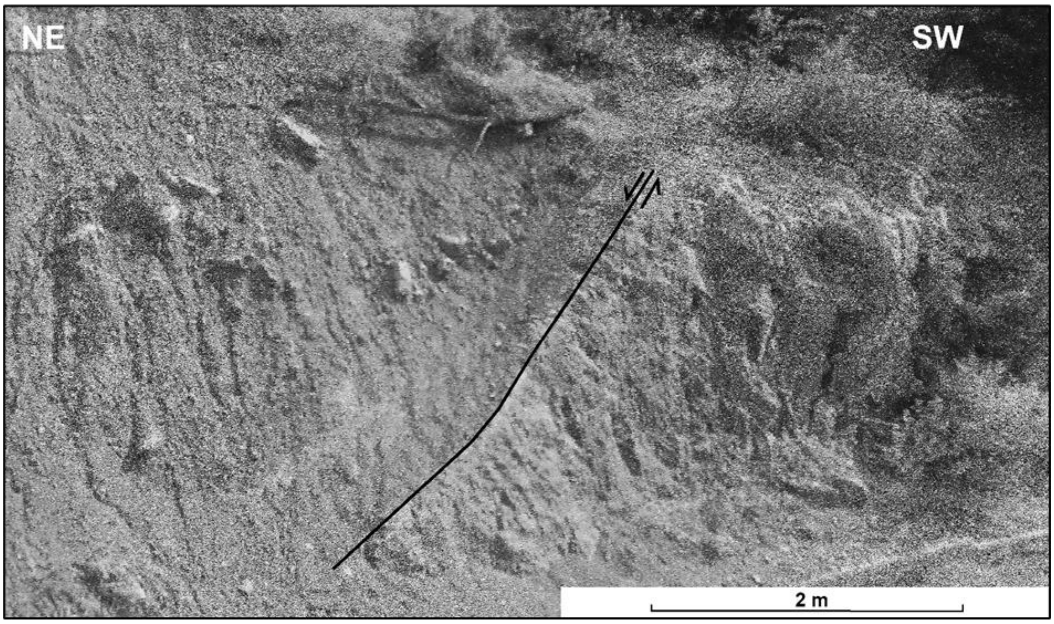

Fig. 19. Xerias-East fault 300 m east of Karya at the road to Argos (left side: Transitional Series of the Pindos Zone, right side: Tripolitza Carbonates).

4.4 Western flank of Artemision, Xerias-North fault

The western flank of Artemision forms tectonically a generally west – east striking horst between the south dipping Xerias-Central fault (s. a.), and the north dipping Xerias-North fault. The latter branches off the Xerias-East fault in the south of Karya, runs to the west across the summit of Artemision and down to the Basin of Nestani. This horst, that is formed by both faults, interrupts the primarily complete distribution of the Pindos Nappe, so that the latter is preserved only in residual areas on this mountain flank (chapter 3.3.2). For the most part of this area, the erosion exposed the underlying Tripolitza Flysch.

4.5 Further surroundings of the studied area

The investigations of Papanikolaou, Chronis and Metaxas (1994) in the Argolic Gulf resp. of Skourtsos & Lekkas (2011) in the Parnon Mountains provide examples for the younger extensional tectonics in the further surroundings of the studied area, and for its temporal sequence. The two major striking directions of the faults, that are present there (NNW – SSE till NW – SE and W – E till WSW – ENE), were also found in the studied area.

5. Slope waste and landslides

Slope waste and landslides are an important morphological and also geological element within the studied area. They occur particularly along the edge of the Pindos Nappe at numerous places, e. g.

- near Neochori,
- at the northern flank of the Xerovouni,
- at the northeastern flank of the Artemision,
- as underlayer of Karya,
- at the western flank of the Artemision, and
- at the northern flank of the Ktenias.

They disguise resp. cover the Radiolarite Series and the nappe thrust, and they extend in parts widely over the Tripolitza Zone. South of the village of Mazi, the remnant of a large landslide of Tripolitza Carbonates debris lies on the Phyllite-Quartzite Series, that came off the eastern flank of Artemision.

6. Conclusions

From the described findings, the following conclusions can be derived:

a) The tectonic arrangement of the Phyllite-Quartzite Series, which forms the centre of the Xerias Window, can be divided in an older and a younger phase. The older phase was thoroughly investigated by Xypolias and Doutsos (2000), and chronologically arranged in Upper Oligocene to Middle Miocene. The deformation was characterised by west to southwest shearing and took place contemporaneous with the emplacement of the Pindos Zone onto the Tripolitza Zone (Xypolias and Doutsos, p. 92).

b) The younger phase created flexural and kink folding in decimetre dimension in the Phyllite-Quarzite Series, and overthrusting of the Tripolitza Carbonates on the phyllite along its southern border (Fig. 3).

c) These elements are part of a compression of the Tripolitza Zone at the window's southern part that show altogether an NNE-vergence. Both Tripolitza Carbonates and Tripolitza Flysch were included in this compressive phase (see also points i and j).

d) A significant disharmonic folding exists between Tripolitza Carbonates and Flysch due to their different mechanical behaviour during deformation.

e) Strangely, the Tripolitza Zone shows no evidence for a nappe transport towards the west within the studied area. It gives the impression of an independent tectonic unit. This contradiction can be clarified only in a larger geological context.

f) In contrast, the nappe position of the Pindos Zone is evident. Isoclinal to recumbent, SW- to W-verging folds can be found within the complete frame of the Xerias Window, especially also on its southwest and west side. There is no evidence that the Xerias Window is in principle a syncline pushed together from two opposite sides.

g) After the end of the nappe transport (Middle Miocene), the formation of several nappe anticlines and synclines with NW – SE trending axes followed on the central Peloponnesus (Jacobshagen 1986, pp. 45 – 47). Also, the Pheneos Nappe Anticline, on which the Xerias Window is situated, is among these anticlines.

h) The Pheneos Nappe Anticline features a cross folding that was probably created together with its main axis. At the culminations of this cross folding, the Tripolitza Zone crops out (Mavrovouni, Artemision, Melidoni), whereas the Pindos Zone is preserved in the depressions (Xerovouni, Kaphouria, southwestern side of Ktenias).

i) In the course of the latter, Tripolitza and Pindos Zone underlay a collective compression directed from SSW versus NNE. This compression becomes manifest in the flysch synclinorium of Krya Vrysi and in the imbricational tectonics at the Mavrovouni (points b and c).

j) Furthermore, this compression becomes manifest in the synclinoria in the east of the Xerias window with the Transitional Series in the core. Here, a cross folding took place with the main folds of the Pindos Nappe.

k) The NW – SE striking Xerias-East fault was probably formed in the first phase of the extensional tectonics (approximately since Upper Miocene), because the pattern of the extensional tectonics west and east of this fault differs significantly.

l) In the second extensional phase, the fracturing of the East – West striking faults in the west of the Xerias-East-fault took place (Xerias-Central fault and its branching, Xerias-North fault). Besides partly high vertical displacements, also greater horizontal movement components can be supposed at them.

m) The extensional tectonics enabled an intense linear erosion from the east till the flanks of Artemision and Ktenias and the exposure of the metamorphic area.

n) The proceeding erosion also created the remnants of the Pindos Nappe at the Artemision and on its western flank.

o) Widely spread slope waste and numerous landslides complete the present-day scenery. In the present, the erosion is intensified by anthropogenic activities.

Acknowledgements

In the years 1972 and 1973, geological-tectonic investigations in the frame of the research programme of the Deutsche Forschungsgemeinschaft (DFG) "*Geodynamik des mediterranen Raumes*" led me to the northeastern Peloponnesus. The works were carried out by suggestion and support of Prof. Dr. W. Schwan, the former head of the Geological Institute of the University of Erlangen-Nürnberg. The investigations provided the background for my diploma thesis, which I completed in 1975. The essential results were published in Kunz, (1977).

By means of the present work, I want to join my former results, and to complement and reinterpret them. Moreover, the results of later geological research on the NE-Peloponnesus put many observations in a new light. They were taken into account, as far as available for me. Furthermore, the construction of the new motorway Korinthos – Tripolis, and especially the driving of the Artemision tunnel in the years 2010/11 (Charalampidou et al., 2011), enabled additional insight into the tectonic architecture of the investigated area.

I give sincere thanks to my honoured mentor professor Dr. W. Schwan for his scientific supervision and guidance, and for all his understanding and goodwill. Furthermore, my very special thanks are due to the people whom I learned to know in the area. Their patience, support and hospitality were an inestimable help.

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