Cenozoic Extensional Features in the Geology of Central Mainland Greece

by

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Abstract

The Hellenides of Greece have undergone a series of extensional deformation events from early Miocene to present time. Two of the fault systems that accommodate this deformation in central Greece are the Itea-Amfissa detachment and the Parnassos detachment. The Itea-Amfissa detachment is known to have been active during Middle Miocene (Langhian and Serravallian time) from dating of marine sediments within the syn-tectonic hanging wall basin. The Parnassos detachment is probably younger, based on the Lower Pliocene sediments deposited in the hanging wall, but stratigraphically lower sediments are undated. The North Giona fault extends east-west from near the northern end of the Itea-Amfissa detachment to near the northern end of the Parnassos detachment. This steeply north-dipping normal fault probably truncates the Itea-Amfissa detachment, and approaches the Parnassos detachment in an area where the topography is low and highly irregular, suggesting that it may connect to and absorb some of the motion along the Parnassos detachment. Structural mapping in this area between the North Giona fault and the Parnassos detachment demonstrates that the limestone and flysch of the Parnassos nappe are folded without significant faulting. Folds occur in two orientations; the northwest-oriented structures are older and are probably related to nappe emplacement; the younger, east-west trending folds are probably related to Late Cenozoic extension. The lack of through-going faults indicates that the North Giona fault and the Parnassos detachment do not connect. Structural relations also show that the Parnassos detachment is younger than the east-west trending fold structures within the field area, and also probably younger than the North Giona fault.

Introduction

Subduction, accompanied by upper plate extension, has dominated the tectonic evolution of the Mediterranean region since 30 Ma. Today, the Hellenic system is the only one of these systems that displays rapid rates of subduction and upper plate extension. Within the Hellenides, the rate of subduction varies along strike, with subduction beneath the northern portion of the system (north of Kephalonia) occurring at rates of 5-10 mm/yr, while subduction beneath the southern portions of the system occurs at ~35 mm/yr, as constrained by GPS observations. GPS data also show a broad zone of dextral shear and extension within the upper plate lithosphere, with a total rate of displacement that is approximately equal to the difference in subduction rate between the northern and southern Hellenides. This zone, referred to as the Central Hellenic Shear Zone, divides the upper plate above the northern Hellenides from that above the southern Hellenides and appears to provide structural accommodation for the differences in subduction rate along the Hellenic arc (Papanikolaou and Royden, 2007).

The modern rate of subduction and dextral shear are well constrained, but the evolution of slip rates and displacement over geologic time, even over the past 10-15 Ma, is more poorly known. One means of constraining the temporal history of subduction along the Hellenic arc is by documentation and dating of faults within the Central Hellenic Shear Zone. In this paper, we examine an area adjacent to one of these older extensional faults located near the northern boundary of the Central Hellenic Shear Zone, the Parnassos detachment (Figure 1). The goal of this study is to constrain how the northern boundary of the Central Hellenic Shear Zone may have moved through time, and how the older extensional features may have connected and interacted during the initial development of the Central Hellenic Shear Zone. This paper describes the field relations near the northwestern portion of the Parnassos detachment and its implications for the extensional history of the region.

Regional Geology

The Hellenic subduction system off the western coast of Greece (Figure 1) is the major geologic feature that has created and shaped the Hellenides. Subduction occurred along the Hellenic Arc from Jurassic time until present, imbricating sedimentary and basement rocks that have been scraped from the down going plate and, at times, pieces of the upper plate, into a series of thrust sheets emplaced to the south and southwest (Mariolakis et al, 2001 and references therein). The imbricated sequences of nappes trend roughly north-northwest in mainland Greece.

From Eocene time to present, this imbrication has resulted in the emplacement of the continental internal Hellenides, the continental Parnassos unit, the deep water Pindos unit, and then the external carbonate platforms. The external Hellenides were emplaced from Eocene time in their eastern section to recent time in their western section. They are defined as those units with no lower Cretaceous unconformity (Mariolakis et al, 2001 and references therein). The Parnassos unit, which is exposed in the field area, is one of the most internal (westernmost) units of the external Hellenides. This unit consists of Mesozoic to early Cenozoic marine rocks deposited on continental lithosphere that were thrust over the external Hellenides during subduction of the Pindos Ocean.

Beginning in Oligocene time, the nappes in the back-arc area, from the Aegean to the Sterea Hellas, underwent extensional deformation. In places, this extension is expressed by gently-dipping detachment faults within the Aegean region and mainland Greece (Figure 1).

During Miocene time in the southern part of the Hellenic arc, dense oceanic lithosphere of the Ionian Sea region entered the trench, increasing its rate of subduction and retreat relative to the northern Hellenides, where subduction continued at ~8 mm/yr. This difference in rate is accommodated along the Kephalonia transform (Figure 1).

During Pliocene time, the extensional deformation style within the northern Aegean underwent a transition, with younger faults trending more east-west and being more steeply dipping at the surface. These young faults are localized to the Central Hellenic Shear Zone, and appear to accommodate the difference in trench retreat rate between the northern and southern Hellenides. They extend westwards to the Kephalonia transform and eastwards to the North Anatolian Fault. In Pliocene time, the rate of slip along the North Anatolian Fault also increased to 25 mm/yr.

Evidence for extension and shear in the Central Hellenic Shear Zone can be observed in the structures exposed on mainland Greece. The earlier extension was accommodated along gently-dipping faults such as the Parnassos detachment. This fault has an overall northwest-southeast trend and forms the southern boundary of the Voiotikos-Kifissos basin. Its continuation towards the northwest, beyond the basin is unclear. At least some part of the displacement continues northwest to merge with the active north-dipping fault that bounds the southern side of the Malea Kos Gulf. A morphological break in the footwall near the northern end of the Parnassos detachment also suggests that a splay of the detachment may trend west to connect to the North Giona fault. This fault trends nearly east-west and has a strong morphological expression, with

Mesozoic limestone in the footwall forming a steep slope south of a down-thrown Cenozoic flysch. How the Parnassos and the North Giona faults interact is not well known.

This paper describes the field relations near the northwestern portion of the Parnassos detachment, near Gravia (Figure 2), in order to document the northward continuation of the Parnassos Detachment at the western end of the Voiotikos-Kifissos Basin, and understand its implications for constraining the interactions of several extensional faults in the area.

Stratigraphy

The field area sits in the footwall of the Parnassos detachment, and all units exposed here belong structurally to the Parnassos nappe. The Parnassos nappe consists of a sequence of sedimentary rocks that have been folded and imbricated during early Tertiary emplacement by thrust faults. These rocks span an age from upper Triassic to lower Tertiary, but in the area mapped only upper Cretaceous to Eocene-Oligocene rocks are exposed (Papastamatiou, 1960). The unit consists of massive limestone grading upwards to a fine- to medium-grained flysch.

The lowermost, massive limestone unit is generally without foliation or bedding except near its upper boundary. It is commonly white in the southern portion of the field area, but can be varying shades of light gray. It is a cliff-forming unit, capping nearly all the ridges in the area. Cenomanian bauxite horizons, heavily mined, are present in the lower part of the limestone sequence. Near the outcrops of bauxite, the limestone weathers to bright orange or rusty red. Rudists are present in the upper part of the limestone section, indicating an Upper Cretaceous age (Figure 26). This limestone unit grades upwards into flysch and near the transition, the limestone becomes thinly bedded and displays a pronounced foliation (Figure 13 and 23).

This transitional limestone unit ranges in thickness from 1 to 35 m and may be absent, perhaps reflecting tectonic modification of its original thickness. In general, the transitional limestone beds appear similar to the flysch above, but are lighter in color (Figures 13, 22 and 23). Locally, the transitional beds are fine-grained and yellowish in color.

The flysch unit is a fine-grained siliciclastic sequence, usually mudstone or siltstone with occasional sandier layers. It shows a strongly developed slaty cleavage, although bedding can be observed in some coarser grained layers. Locally, the layers may be sheeny and almost phyllitic in appearance. This unit is generally maroon but locally may be green. It is readily weathered into platy pieces and forms the valleys in the area. The red flysch grades upwards into yellow flysch that is medium-grained and composed predominantly of sandstone interbedded with finer-grained layers, with beds 2-5 cm thick. Its color variations include gray, brown, and orange. It generally crops out poorly and, when weathered, crumbles into rounded pieces. The yellow flysch generally displays more prominent bedding than the red flysch.

Structure

The field area sits structurally beneath the north-dipping Parnassos detachment fault and potentially contains structures related to early Cenozoic thrusting along the Hellenic arc as well as to younger unroofing along the detachment fault. The structures developed in the field area were primarily mapped by following the contact between the white limestone below and the foliated red flysch above. The mapped contact is defined as the color break between the foliated upper portion of the white limestone (the "transitional unit") and the lowest red-colored flysch bed. Two dominant structural trends, defined by folds and normal faults, are present in the area. The first set of structures is oriented northwest-southeast, and the second is oriented east-west.

The oldest structural feature in the field area is a slaty cleavage that is generally sub-parallel to the limestone-flysch contact or heavily deformed. It generally trends northwest-southeast although is highly folded in some localities (Figure 25).

The northwest-southeast trending structures are well-developed in the southern portion of the field area (areas near A, B, and C on Figure 3). The largest is an anticline trending 120°, plunging 15°, and forming a limestone ridge that crosses the field area (area B on Figure 3). The fold limbs are steep, and the northeastern limb is slightly overturned. At the western edge of the field area, the limestone-flysch contact along the northeastern limb is missing the transitional unit, indicating minor faulting. The limestone-flysch contact on the southwestern limb shows evidence of small-scale slip and its straight-line surface trace implies a steep orientation. Bedding in the limestone unit near the contact dips 18° southwest (Figure 13). Near the nose of the fold, the limestone beds dip ~20° southeast (Figure 14). On top of the limestone ridge a small outcrop of flysch has undergone parasitic folding.

North of area B (Figure 3), a large synclinal valley contains flysch in its core, with foliation striking ~320° and dipping 30-40° north-northeast. Parallel to and northeast of this valley, another limestone ridge trends northwest and contains porpoising folds southeast of the fold nose (Figures 4, 8, 9 and 10). This anticlinal ridge displays an irregular limestone-flysch contact along its southwestern limb, and displays a flexural slip surface near the fold nose (just east of D, Figure 3). This minor faulting surface has corrugations trending 63° and plunging 53° (Figure 15, 16). The limestone-flysch contact along the northern part of its northeastern limb is faulted, with bauxite-rich limestone juxtaposed against red flysch (Figure 21).

The south-westernmost portion of the field area (area A, Figure 3) is a valley cored by red flysch with cleavage striking 320-350° and dipping 40-60°, sub-parallel to those by area C (Figures 3, 4). A highly folded area near the letter A shows cleavage orientations that define a fold axis that plunges 3° towards 327° (Figure 5). Measured fold axes are similar (eg 5° towards 308°). South of area F, the limestone-flysch contact shows small-scale folds around a similar axis of 4° towards 129° (Figure 6).

East-west trending structures are present, in areas E and F (Figure 3) and include two synclines with yellow flysch in their cores (Figures 9, 10). The southernmost syncline shows well-developed (~325° /25°) cleavage in the red flysch and bedding in the yellow flysch. Its southern edge is truncated by a steeply dipping normal fault (Figure 17) with corrugation axes plunging 45° towards 4°. The proximity of the yellow flysch to the bauxite limestone (between D and E, Figure 3) indicates omission of section, and the fault's continuation beneath the mine cover.

The northern syncline shows depositional contacts between the limestone, red flysch, and yellow flysch (Figures 22 and 23). The southern contact shows thinning of the red flysch unit, probably tectonic (Figures 4 and 10). North of area E, a steeply-dipping fault oriented 288°/76°, displays corrugations and mineral lineations plunging 71° towards 27° (Figure 20). The hanging wall contains limestone and flysch units, with a tightly folded contact between (Figure 7).

Structures in the area with neither northeast nor east-west trends include a north-south trending fault found in the eastern part of the field area (southeast of area E), and the contact between limestone and flysch in the northwestern part of the field area (area G). The north-south trending fault juxtaposes bauxite-rich limestone against red flysch (Figure 18). This steep fault shows multicolored bands of flysch folded upwards in a drag fold (Figure 19), and is truncated by one of the east-west trending faults.

The northwesternmost flysch-limestone contact (area G, Figure 3) shows small-scale undulations, and dips 45° to 85° NW (Figure 24). This steep contact is on the northwestern limb of a broad anticline north of area F (Figure 3).

The foliation within the flysch and transitional beds is the oldest structural feature in the area, and is interpreted to have formed during the emplacement of the nappes because it trends subparallel to the overall trend of the nappes. This foliation is folded by the northwest- trending folds, so it probably corresponds to an early phase of nappe emplacement.

The northwest-trending folds are also interpreted to have formed during nappe emplacement because their orientation is subparallel to that of overall nappe structure in this part of the Hellenides. The northwest trend of the fold hinges is dominant, even in areas that have been refolded by east-west trending structures (e.g. north of E) (Figures 5, 6, and 7). The northwest-trending folds fold the foliation, indicating that the foliation probably corresponds to an early phase of nappe emplacement. The east-west trending structures in the field area are probably the youngest structures and truncate or fold all other structures. It is likely that the east-west trending folds are the same age as the east-west trending faults.

The northeast-trending anticline has no clear cross-cutting relationships. It may be of similar age to the North Giona fault because it differs in strike by only ~30° and both structures result in downward displacement to the north.

The age of the North Giona fault relative to the structures in the field area cannot be determined definitively. However, it seems likely that the east-west trending structures in the field area and the northeast-trending anticline may be related to the activity along the North Giona fault. This is suggested by Figures 11 and 12, which shows that these folds splay out from the eastern end of the North Giona fault.

The Parnassos detachment appears to be younger than all of the structures mapped in the field area. The east-west trending structures, projected eastward to the detachment surface, do not affect the trace of the Parnassos detachment. While the eastward continuation of these structures is difficult to observe within the massive limestone that forms the immediate footwall for the detachment, the synclines containing flysch outcrops project eastward into morphologic saddles, and the anticlines project eastward into morphologic ridges and peaks. This suggests that the east-west trending folds continue to the detachment surface and are truncated by the detachment. It also appears that the Parnassos detachment truncates the northeast-trending fold between F and G (Figure 3).

Interpretation and Discussion

The field map shows unambiguously that the Parnassos detachment fault, exposed to the east of the field area, and the North Giona fault, exposed to the west of the field area, do not connect to one another through the area mapped (Figure 4). Therefore the Parnassos detachment must continue to the north, connecting with the north-dipping fault system that bounds the Malea Kos Gulf. Slip along the North Giona fault must decrease and end towards the east, but its down-to-the-north displacement could be taken up in the field area by folding distributed over a width of several kilometers.

The structures in this area and their interrelationships help constrain the relative timing of regional deformational events. Below I outline a chronology for these events that is consistent with the geological evidence.

1) Nappe emplacement along the Hellenic arc likely occurred in a west-southwest direction, perpendicular to the orientation of the thrust faults, folds and foliation. This occurred during the Oligocene when these sedimentary rocks that make up the thrust sheets were stripped from the top of the subducting slab (Papanikolaou et al 2008).

2) The Itea-Amfissa detachment is sub-parallel to the nappe structures, consistent with early extensional deformation prior to the disruption of the Hellenic arc by cross-cutting normal faults. Fossils found in the sedimentary rocks in the valley formed by the Itea-Amfissa detachment indicate that it was active from ~18-8 Ma, Burdigalian to Tortonian time (Papanikolaou et al, 2008). This fault shows an increase in structural omission towards the south, and east-northeast trending transverse faults developed in the lower part of the sequence contribute to a greater displacement to the south. This fault has decreasing displacement towards the north, until no displacement is detected just south of Mt. Giona. It may continue into three splays with lesser displacement at its northern extent, but it is difficult to trace these minor faults into the Itea-Amfissa fault. If these are indeed splays, then the North Giona fault appears to truncate them (Figure 27).

3) The North Giona fault has poor age constraints. If it truncates the Itea-Amfissa detachment and its possible northward continuation into a series of splays, and if the

folds in the field area are in fact related to the North Giona fault, then the age of the North Giona fault must be between that of the Itea-Amfissa and the Parnassos detachments. This interpretation is speculative.

4) If the assumptions above are correct, then the Parnassos detachment must be younger than the Itea-Amfissa detachment. This would give an age younger than Serravallian. This is consistent with the age determination of Kranis and Papanikolaou, (2001), which is based on the assumption that the Parnassos detachment underlies the Lokris basin and that the Late Miocene and early Pliocene sediments in the Lokris Basin correspond to the age of the Parnassos detachment.

5) Central Greece has been undergoing extension along east-southeast trending faults since the Upper Pliocene (Kranis and Papanikolaou, 2001). These faults truncate the older detachment faults, including the Itea-Amfissa and Parnassos detachments, and have formed the Gulfs of Corinth and Evia (Kranis, 2007, and Papanikolaou and Royden, 2007).

Conclusions

The geological structures within the Parnassos nappe in the field area show that there is no through-going fault between the North Giona fault and the Parnassos detachment. Structures in the field area include mostly folds, and some small faults, in two distinct orientations, with younger east-west trending structures truncating older northwest-southeast structures. The east-west trending features may be related to displacement along the North Giona fault. If so, their truncation by the Parnassos detachment would indicate that the North Giona fault is older than the Parnassos detachment. If North Giona fault is younger than the Itea-Amfissa detachment, then the Parnassos detachment is younger than the Itea-Amfissa detachment as well.

An interpretive chronology of events affecting rocks in the and around the field area can be summarized as: 1) Oligocene nappe emplacement forms a north to northwest-trending foliation that is then folded by subparallel folds; 2) Extension that is upper plate to the Hellenic subduction system causes north to northwest-trending detachment faults to form parallel to the trend of the thrust belt, such as the Itea-Amfissa detachment; 3) At the same time, or subsequently, the North Giona fault and the east-west and northeast-trending folds in the field area form; 4) The Parnassos detachment forms, perhaps related to the propagation of the North Anatolian Fault westward into the Hellenides. 5) East-west trending faults of Upper Pliocene and Quaternary age accommodate extension throughout the Hellenides, including those along the Gulf of Evia and Corinth.

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Figures

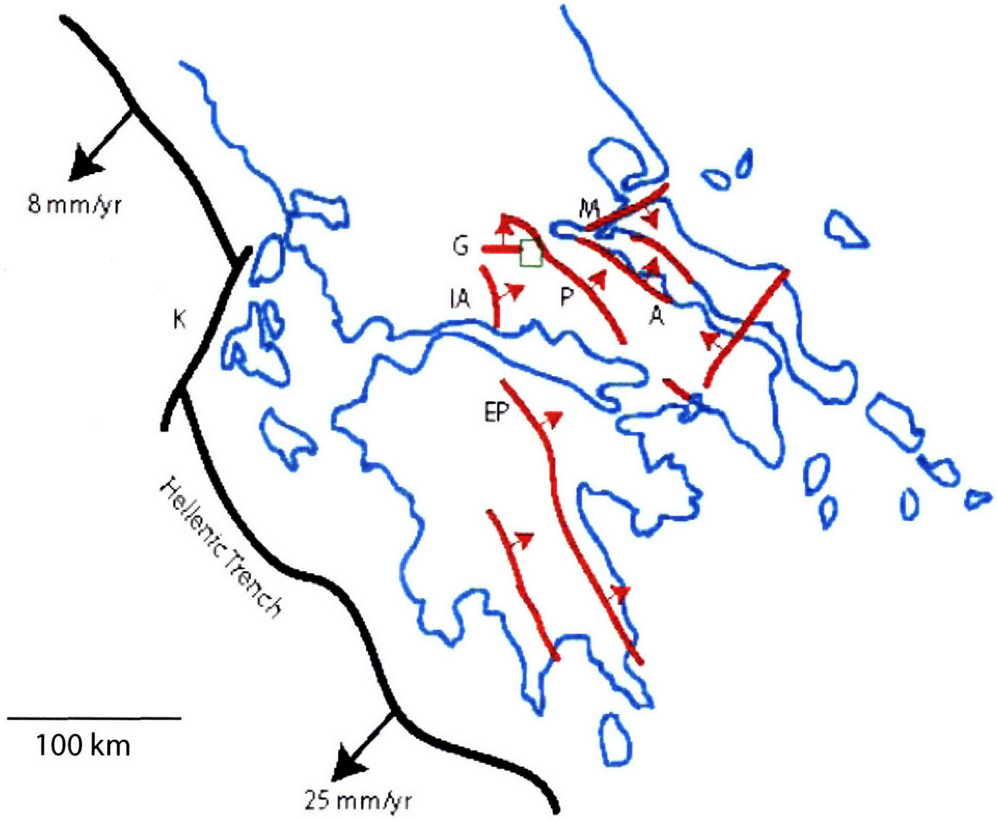

Figure 1: Extensional features in Greece. Green box shows location of field area in this study. EP, East Peloponnese Detachment; IA, Itea-Amfissa Detachment Fault; G, N. Giona Fault; P, Parnassos Detachment; AK, Arkitsa Fault; M, Maliac Detachment; K, Kephalonia Transform. Arrows give rates of trench migration. From Papanikolaou and Royden (2007).

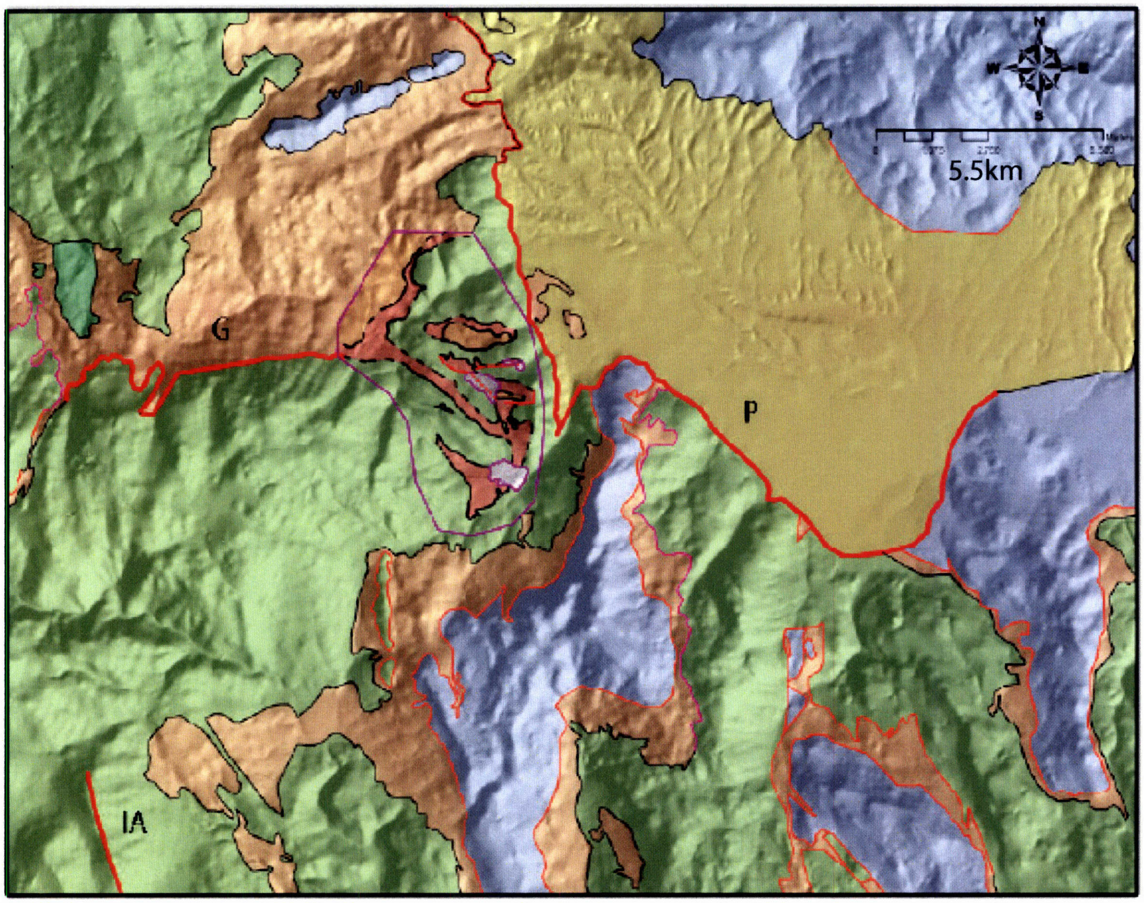

Figure 2: Map showing field area in relation to regional faults. Area mapped in this study outlined in purple. Blue - Western Thessaly-Beotia nappe; red and orange - flysch of the Parnassos nappe; green - limestone of the Parnassos nappe; yellow -Pliocene and younger sediments. IA, Itea-Amfissa Detachment; G, North Giona Fault; P, Parnassos Detachment.
From Papastamatiou (1960).

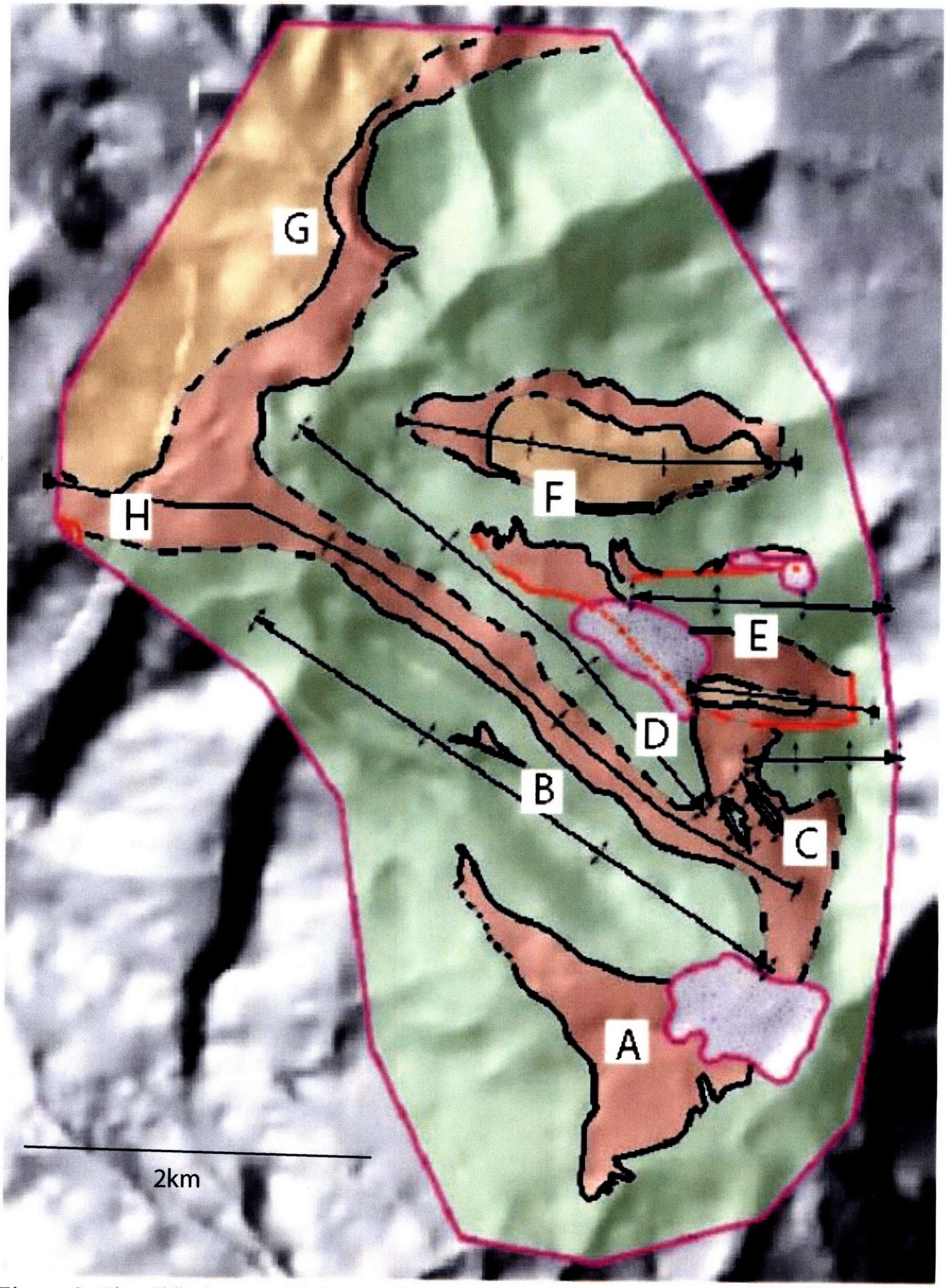

Figure 3: Simplified map with letters for reference within the paper. See Figure 4 for colors and symbols.

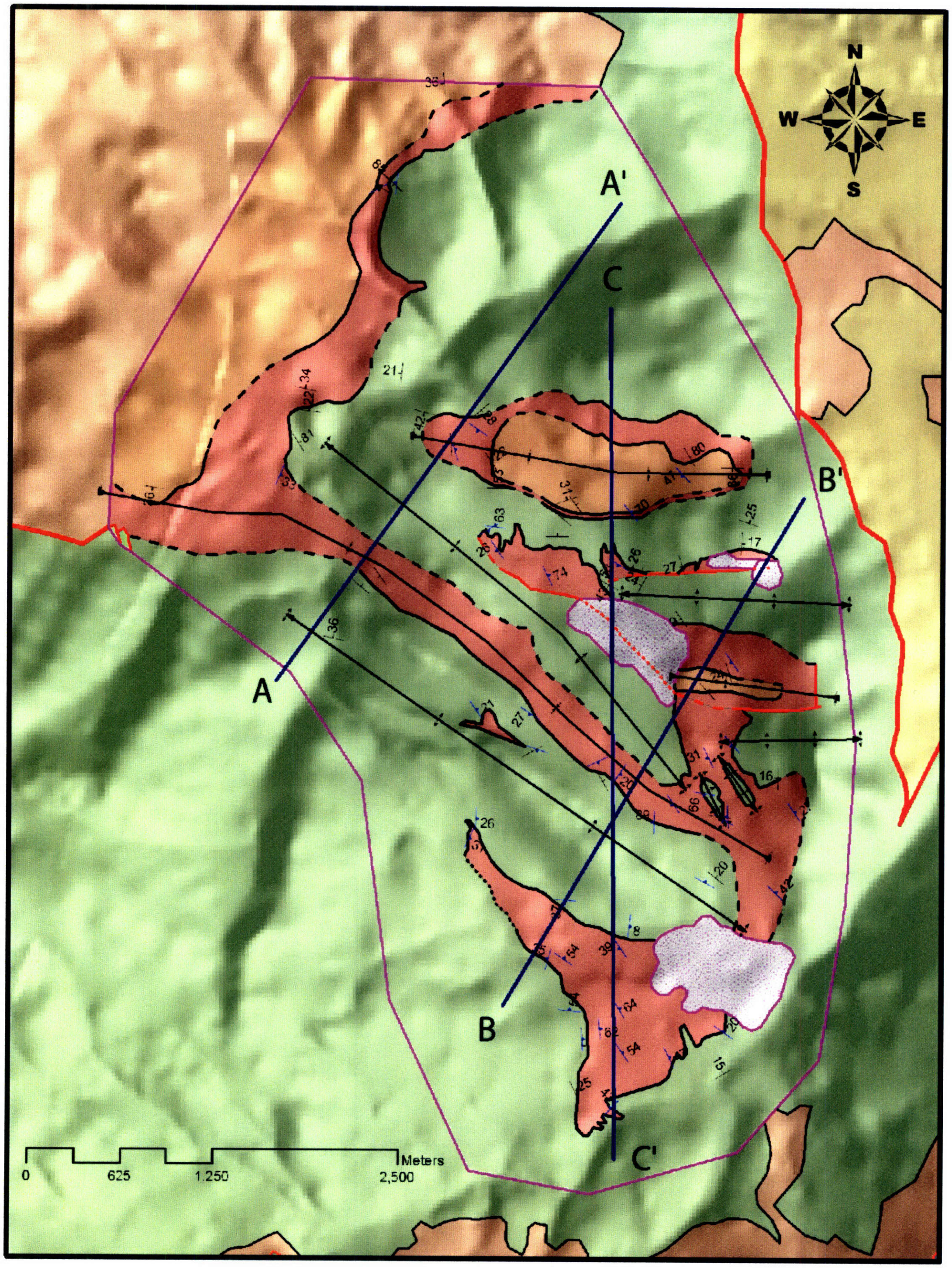

Figure 4: Geologic field map, with black strike and dips symbols for bedding, blue strike and dips symbols for foliations; purple line for outline of field area, black lines for depositional contacts; red lines for faults; black lines with arrows for fold hinges; blue lines for location of cross-sections (Figures 8, 9, and 10). Green- limestone; red- red flysch; yellow- yellow flysch; purple stippled- mine-dump covered.

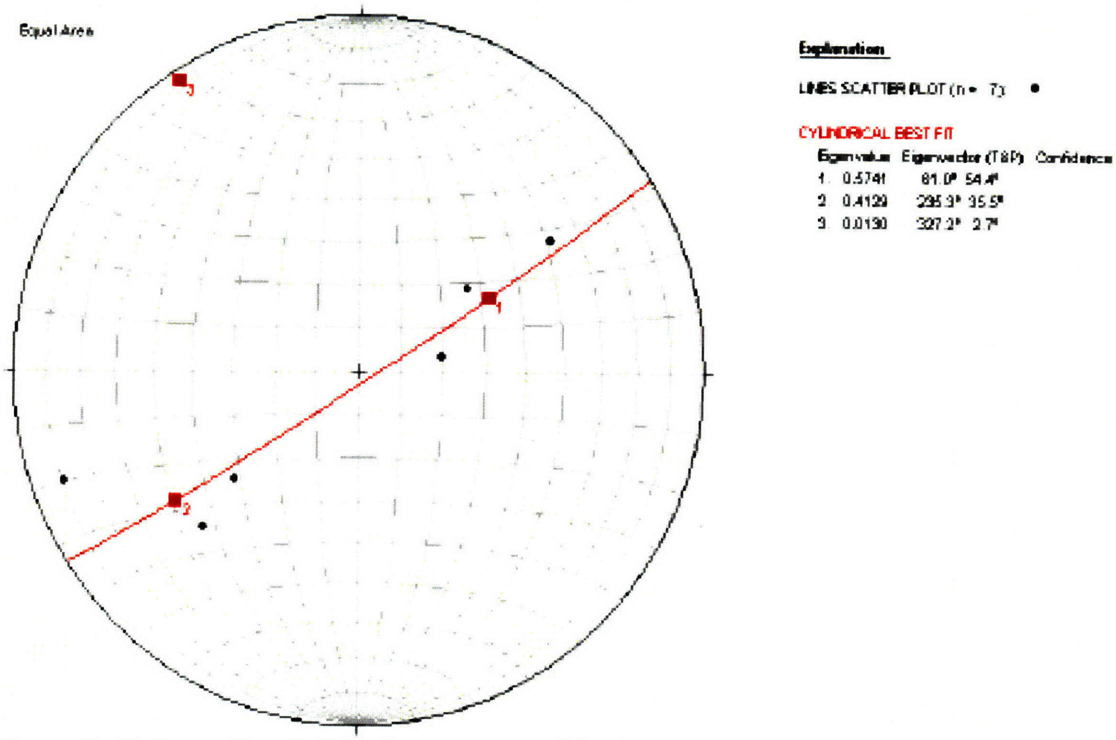

Figure 5: Poles to flysch foliations measured in flysch valley around area A. The foliation poles define a fold with a hinge plunging 3° towards 327°.

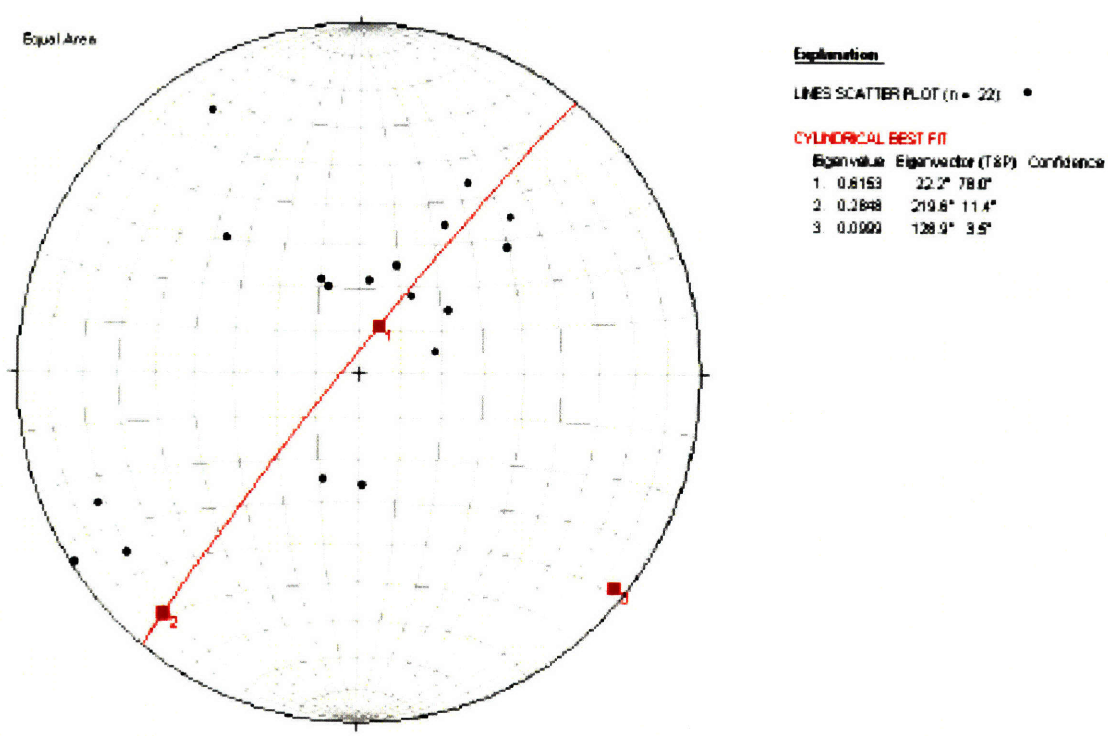

Figure 6: Poles to flysch foliations measured south of area F where the two dominant deformation styles appear to interact. The northwest-trending folds appear to dominate, with the east-west trending folds slightly increasing the scatter.

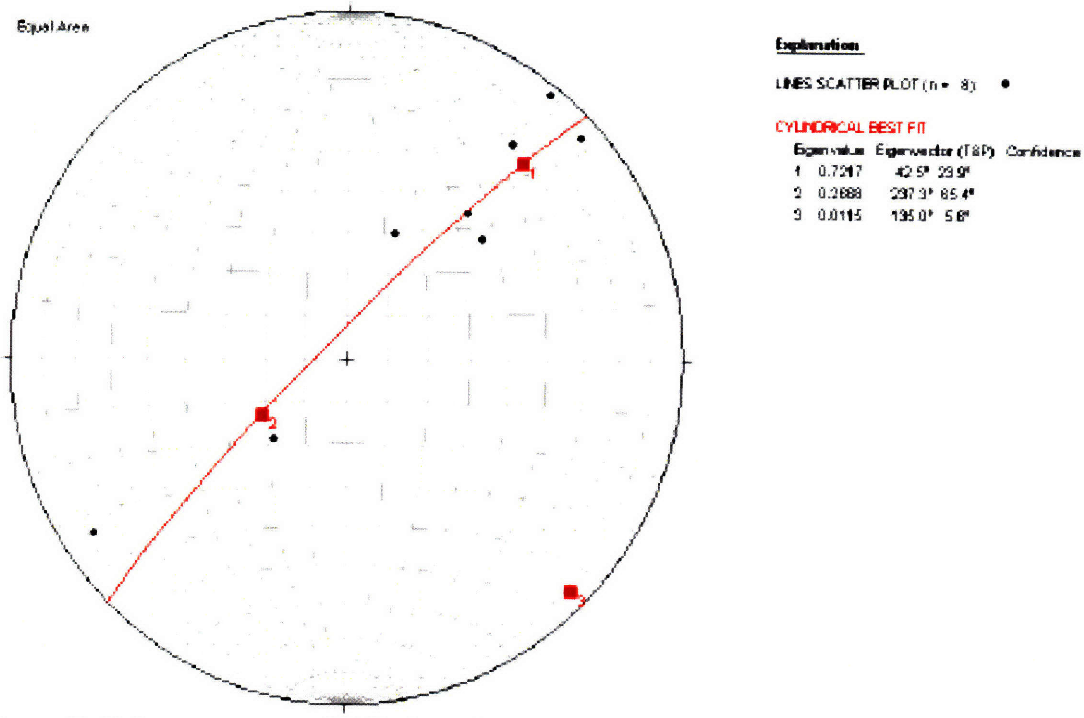

Figure 7: Poles to measured foliation planes of red flysch within a 10m radius near limestone-red flysch contact north of the mine dump, just north of E. The fold hinge that best fits this set of orientations plunges 6° towards 135°.

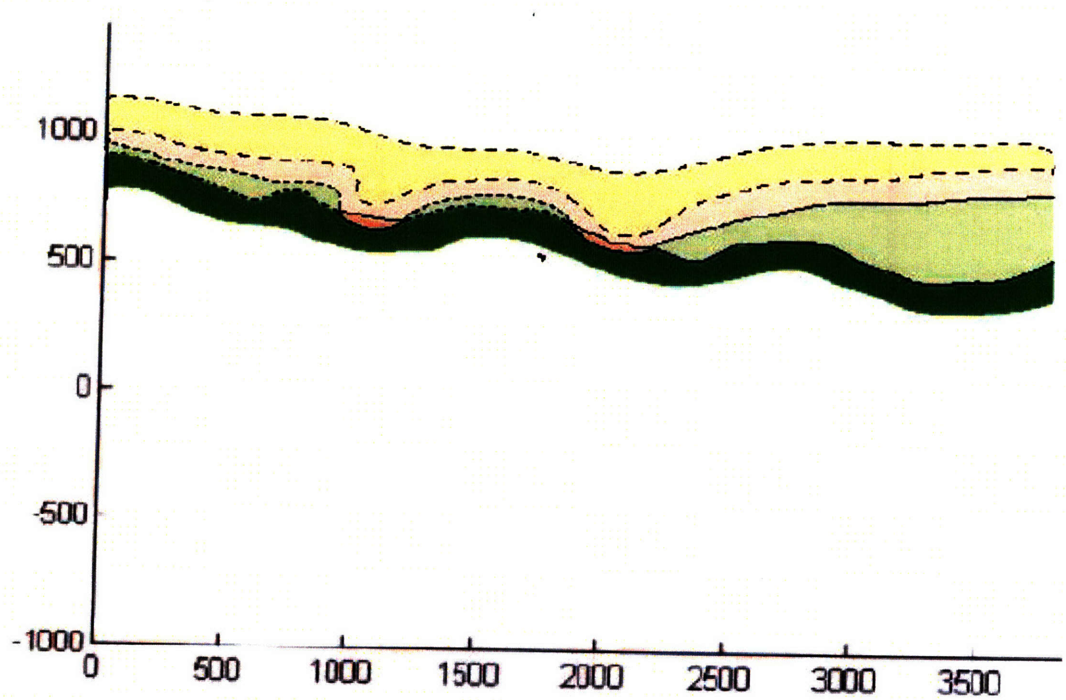

Figure 8: Cross-section showing sub-surface features from A-A'. Colors the same as in Figure 4.

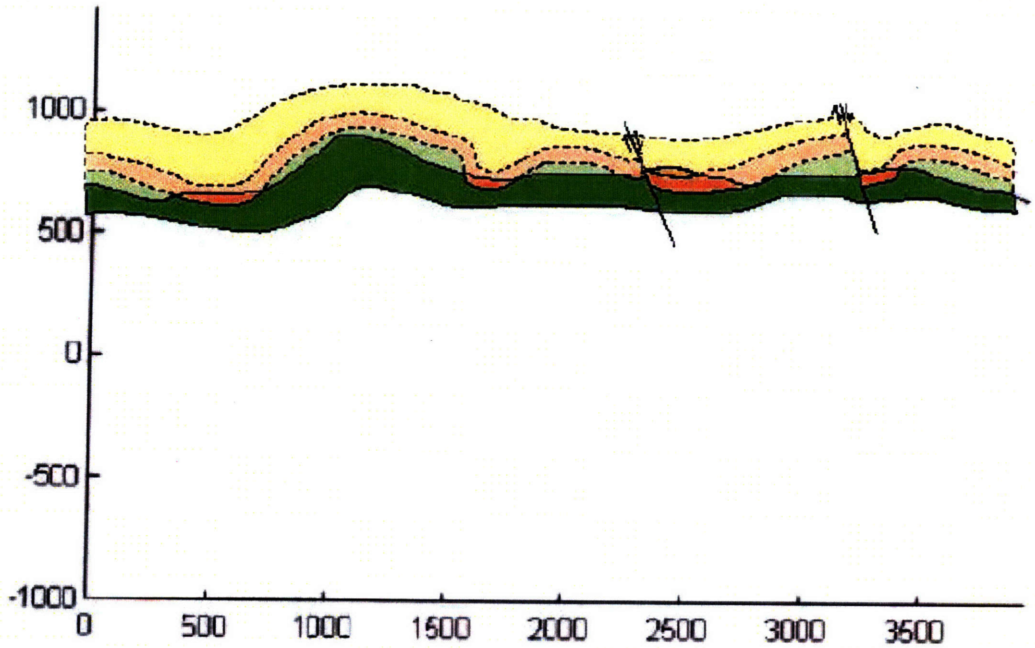

Figure 9: Cross-section showing sub-surface features from B-B'. Colors the same as in Figure 4.

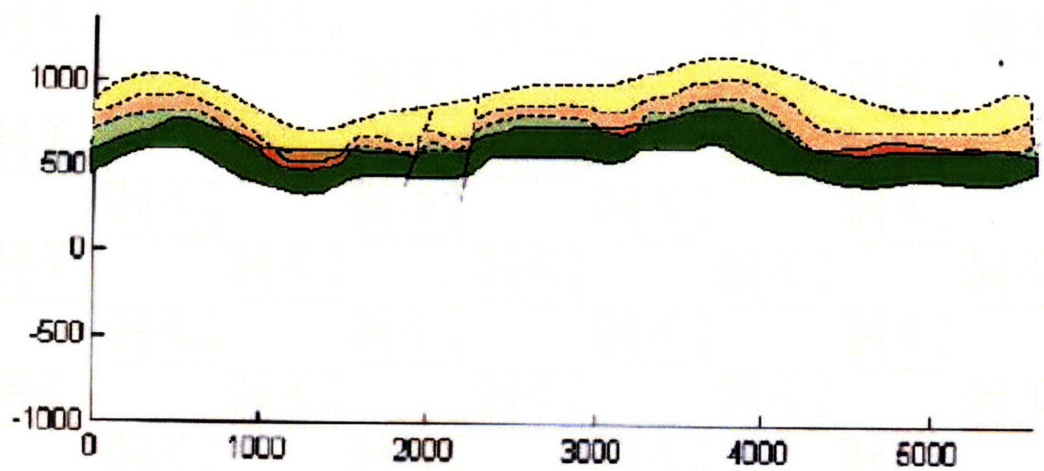

Figure 10: Cross-section showing sub-surface features from C-C'. Colors the same as in Figure 4.

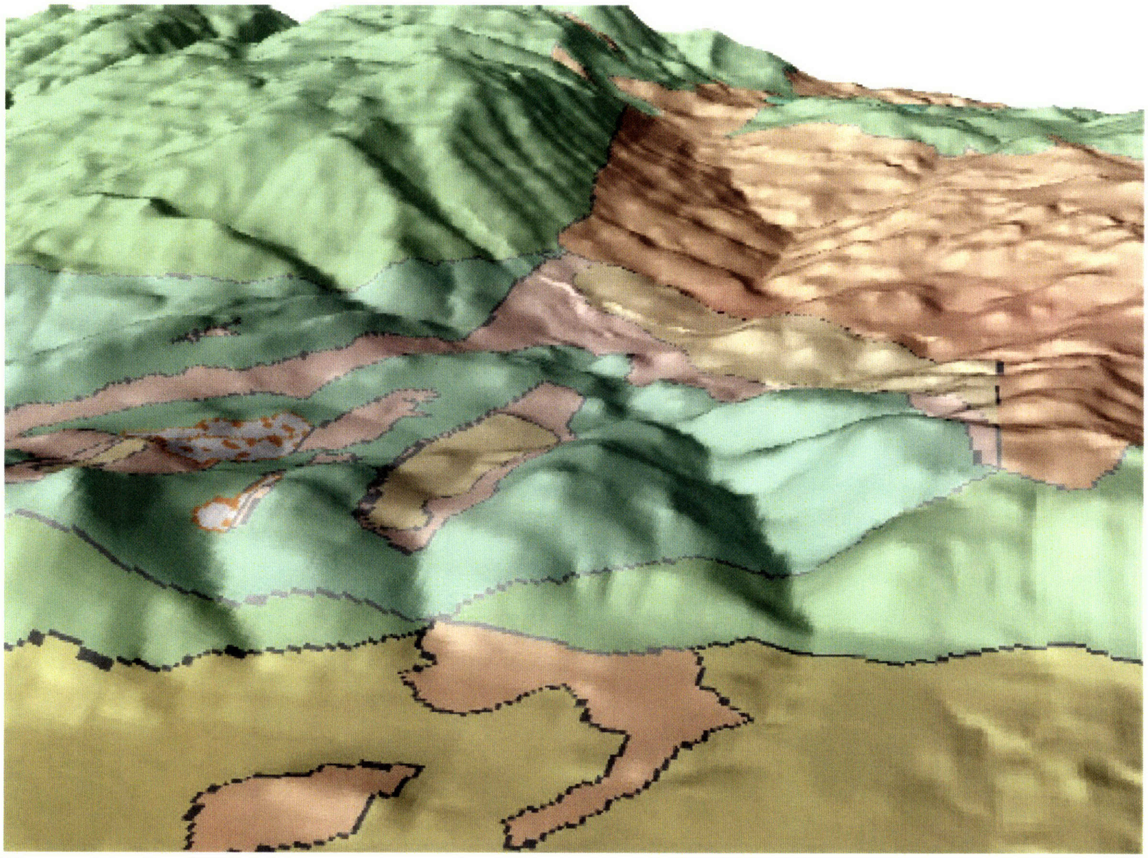

Figure 11: Geological structures projected onto topography. View to the west-southwest. Northeast-trending anticline is in the foreground. Colors the same as in Figure 4.

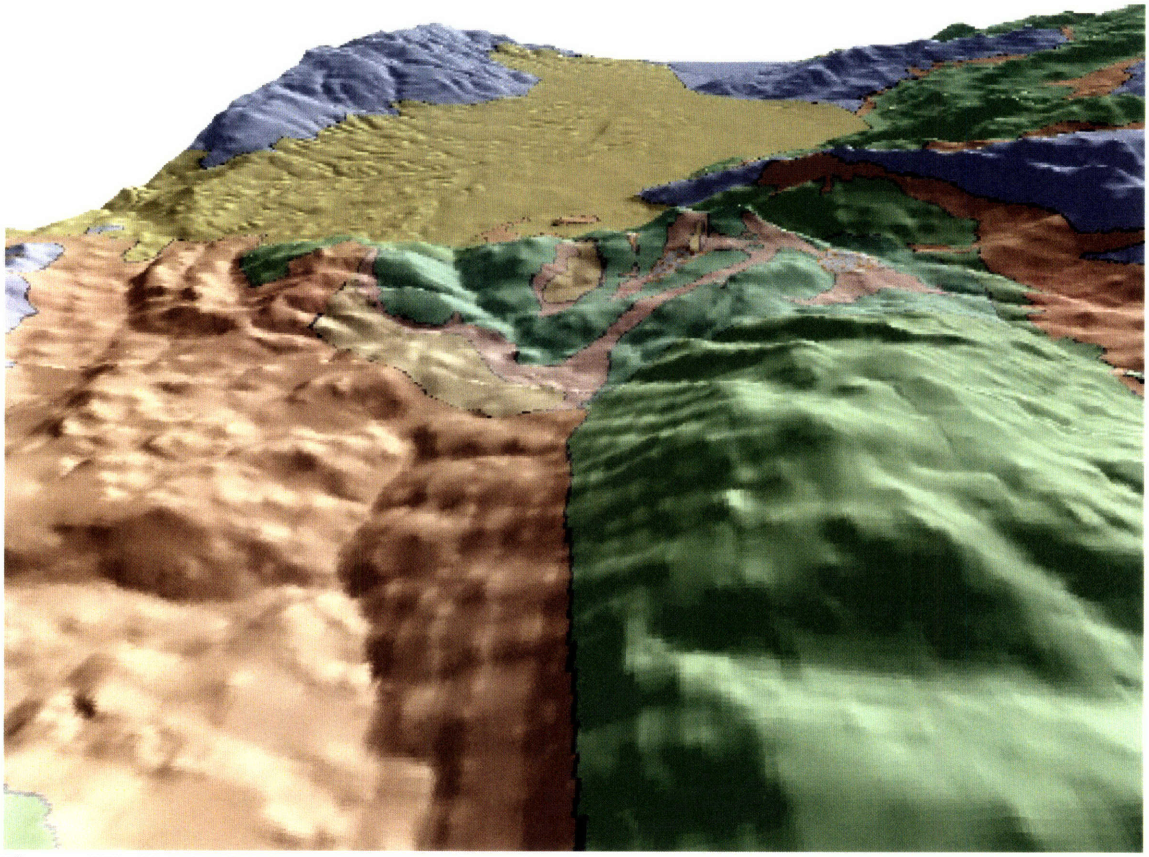

Figure 12: Geological structures projected onto topography, looking east down the North Giona fault. The valleys containing flysch appear to splay away from the end of the North Giona fault. Colors the same as in Figure 4.


Figure 13: sub-horizontal foliation in the transitional limestone.

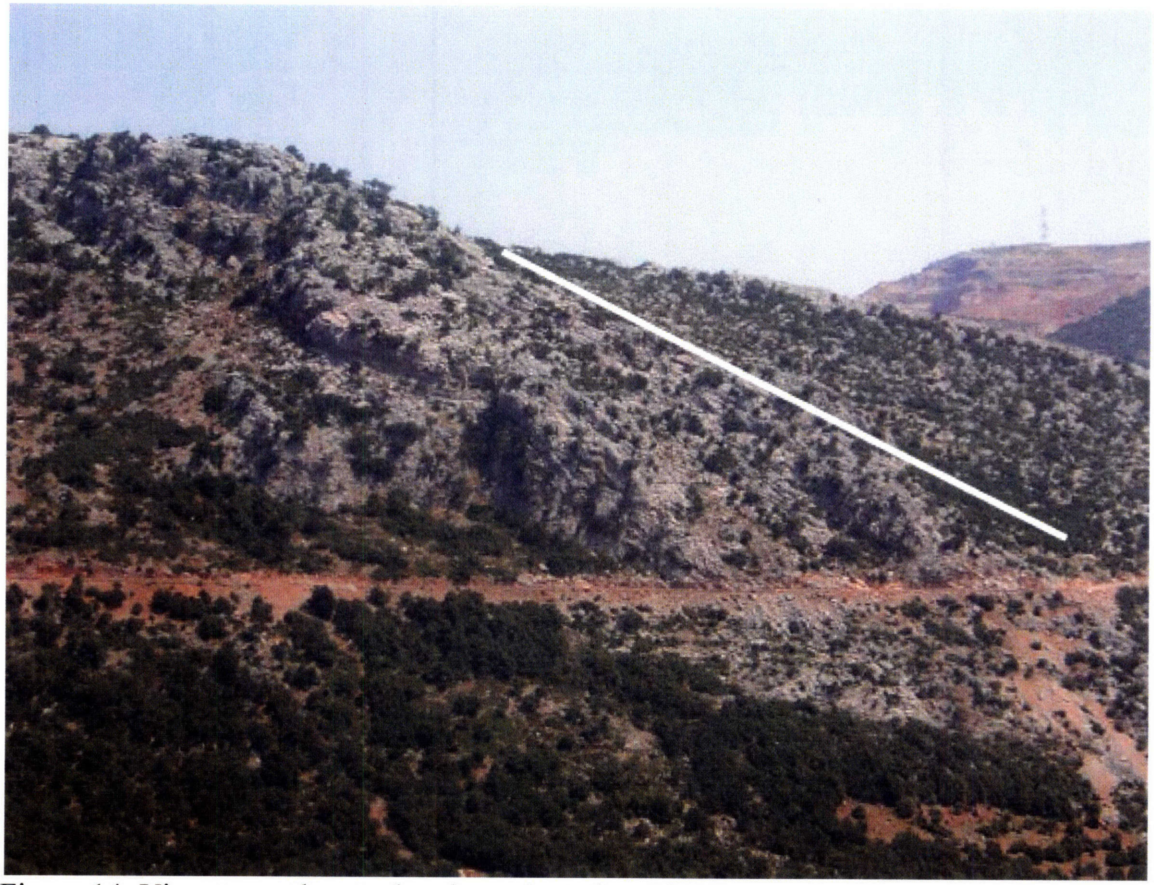

Figure 14: View to northeast, showing orientation of limestone bedding (white line) at nose of anticline.

Figure 15: minor fault surface near the nose of a northwest-southeast trending anticline


Figure 16: minor outcrop of flysch within limestone. Photo taken near Figure 15.

Figure 17: steeply dipping normal fault with corrugation axes plunging 45° towards 4°. View towards the south.


Figure 18: North-south orientated fault placing bauxite-rich limestone over red flysch.


Figure 19: Multicolored bands of altered flysch near north-south oriented fault.

Figure 20: A steeply-dipping fault oriented 288°/76°, displays corrugations and mineral lineations plunging 71° towards 27°. View towards the south.


Figure 21: Faulted contact between bauxite-rich limestone and red flysch. View towards the southwest.


Figure 22: Red flysch over transitional limestone north of the syncline by area F.


Figure 23: Transitional unit with hammer in the same position as in Figure 22.

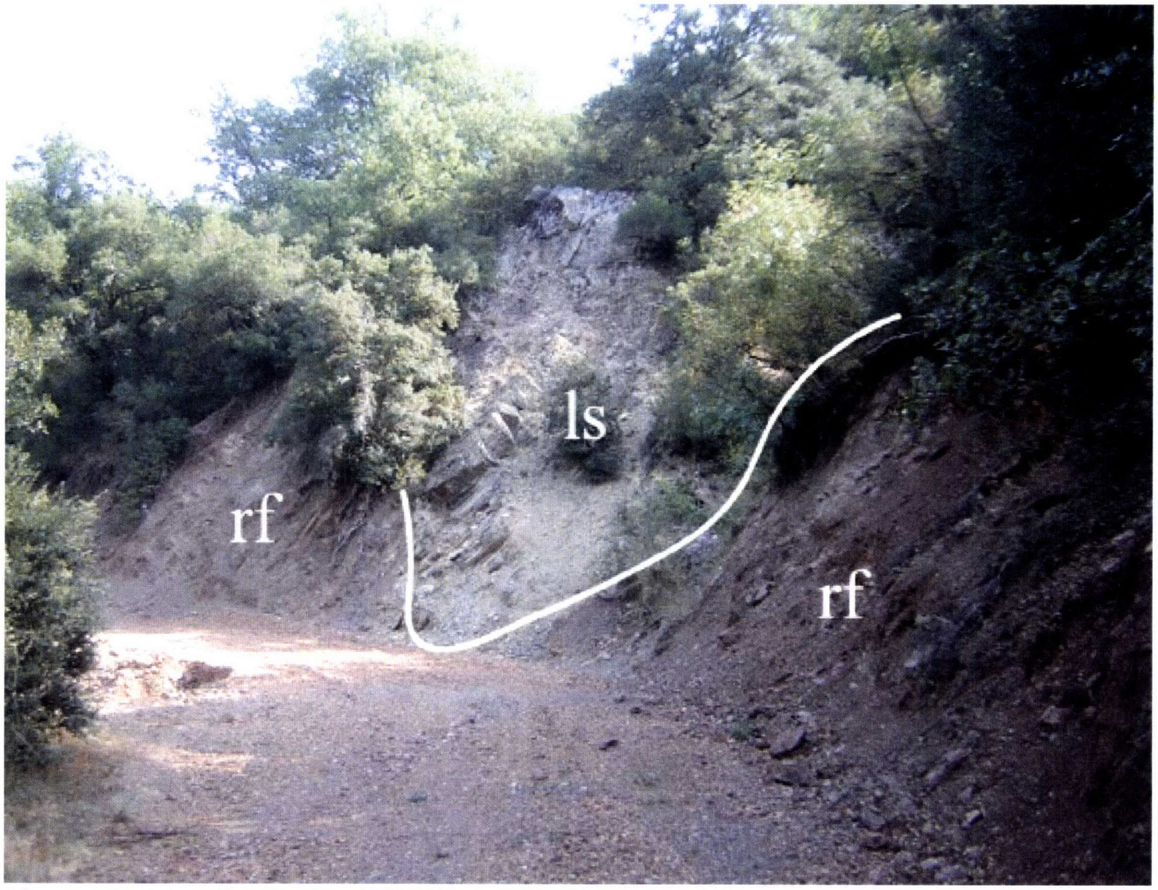

Figure 24: Steeply dipping (85°) limestone-flysch contact near area G. rf- red flysch, ls- limestone, white line- approximate limestone-red flysch contact . Flysch clearly lies above limestone elsewhere along this contact.


Figure 25: Highly folded flysch cleavage in area A

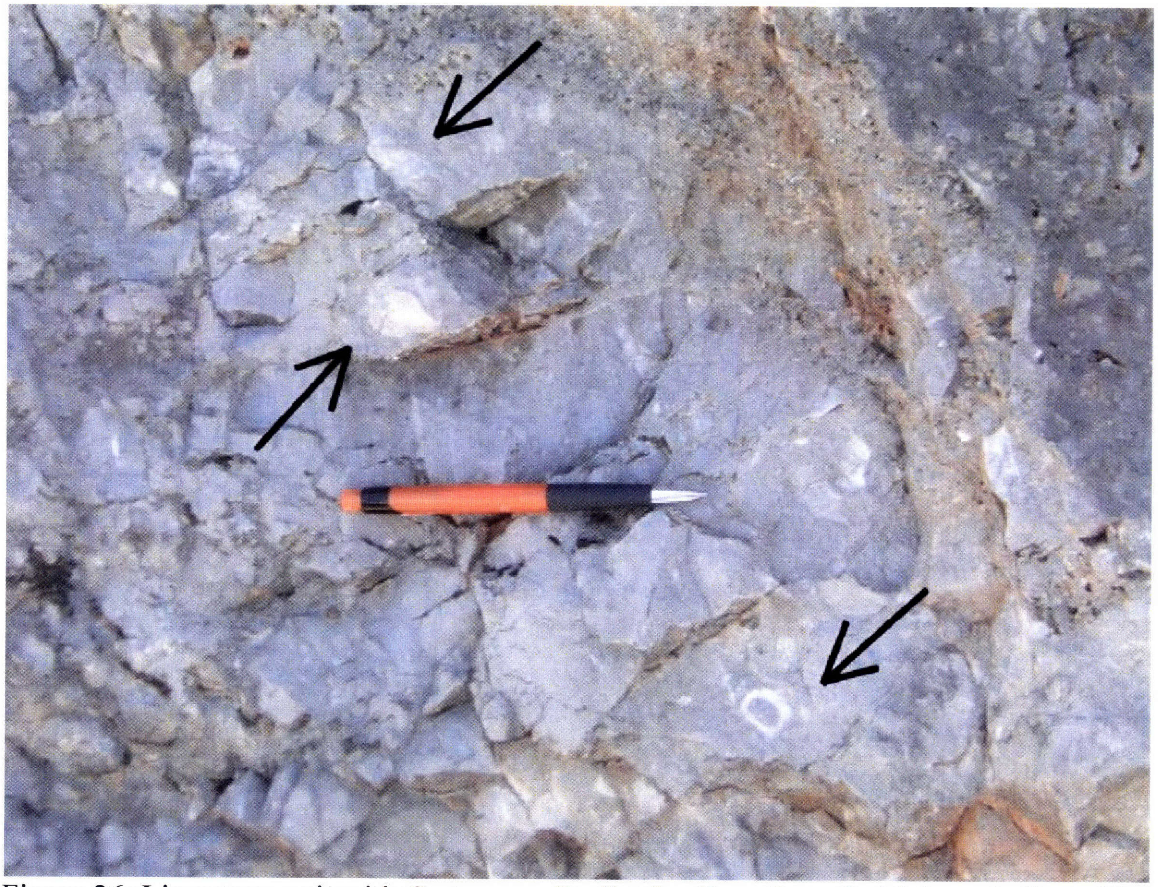

Figure 26: Limestone unit with Cretaceous Rudist fossils, a few of which are indicated by arrows.

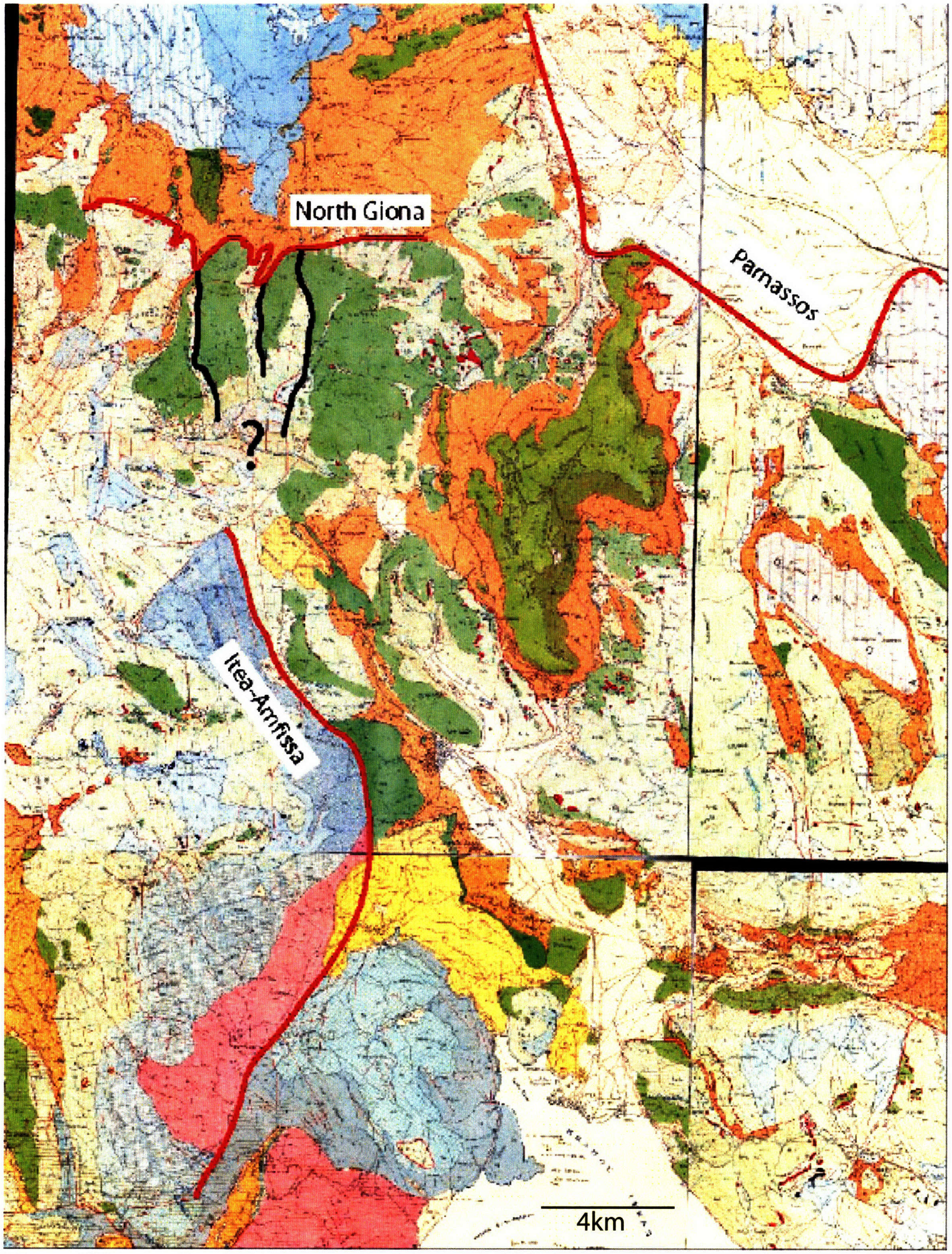

Figure 27: map showing the Itea-Amfissa, North Giona, and Parnassos faults in red. Three minor faults are shown in black, parallel to the Itea-Amfissa detachment, and may be splays of this fault (discussed in text). From Papastamatiou 1960, 1967 and Marinos 1967.