Universitetet
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FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme/specialisation: Petroleum Geosciences Engineering	Spring / Autumn semester, 20...... Open/Confidential
Author: Asbjørn Veiteberg	……………………………………… (signature of author)

Programme coordinator:

Supervisor(s):

Chris Townsend

Title of master's thesis:

Geologic Mapping and investigation into tectonic control on deposition . A case study of the Doumena Fault Block, Greece.

Credits: 30 Stp

Keywords:
Half graben
Sedimentation
Alluvial fan formation
Corinth rift
'

Number of pages: …………………

+ supplemental material/other: …………

Stavanger,……………………
date/year

Title page for Master's Thesis
Faculty of Science and Technology

Geological Mapping and Investigation into tectonic control on deposition. A case study of the Doumena Fault Block, Greece.

By

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Master Thesis
Presented to the Faculty of Science and Technology
University of Stavanger

University of Stavanger

June 2017

Abstract

Geologic Mapping and Investigation into Tectonic Control on Deposition. A case study of the Doumena Fault Block, Greece.

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The Doumena Fault Block is located onshore in the southern part of the Gulf of Corinth Rift system. The rift system consists of several east – west oriented half grabens that offers an excellent opportunity to study rotated fault blocks and the various syn-depositional sedimentary environments that form within them. The Doumena fault Block is one of the southernmost half grabens within the northern Peloponnese that is suggested to be the southern extent of a larger alluvial – fluvial drainage system. The stratigraphic framework of the Doumena Fault Block is complex with several different stratigraphic units that show several different depositional environments, and the main objective of this thesis was to differentiate the different units in the Doumena Fault Block, and establish the relative age of the different units. Additionally, two of the stratigraphic units located in the middle of the Doumena Fault Block were studied in greater detail, as these stratigraphic units were previously suggested to be internal alluvial fans within the Doumena Fault Block. In order to achieve a full understanding of the Doumena Fault Block and the evolution of the Doumena Fault Block, faults and other stratigraphic units within the Doumena Fault Block and selected features of the Kerpini Fault Block, had to be mapped and described along with detailed outcrop descriptions and the aid of photogrammetry.

Six different lithologies have been identified in the Doumena Fault Block, in addition to six stratigraphic units. The Doumena Fault Block is composed of both pre and syn-fault strata, and the relative age of the different units were determined from the angular relationship between the stratigraphic units and the immediate hanging wall of the Doumena Fault, facies characteristics and abrupt changes in facies. It is suggested that the pre – Doumena Fault strata consists of alluvial conglomerates originating from the Kalavryta Fault, while the syn-fault strata consists of localized alluvial fan deposits limited to the Doumena Fault Block.

Acknowledgment

I would like to thank my supervisor Chris Townsend for his support and guidance in writing this thesis. His knowledge and experience regarding geological structures proved very helpful during the fieldtrips. I would also thank Alejandro Escalona for his feedback in the process of writing this thesis, along with the discussions and ideas during the fieldwork.

I would also like to thank my colleagues Herman Birkeland and Eirik Oppedal that I could discuss and share ideas with. They have contributed to greater knowledge and a better thesis.

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Chapter 1: Introduction

1.1 Background

The Gulf of Corinth is located north of the Peloponnese Peninsula, Greece. It has formed as a response to back arc extension from the subduction at the Hellenic trench. The Corinth rift initiated between 4 - 5 Ma (Leeder et al., 2008; Ori, 1989) and is one of the fastest opening rifts in the world where the highest geodetic north- south extension rates (15-16 mm A^{-1}) have been recorded in the western part of the rift over the last two decades (Avallone et al., 2004). The extension resulted in a series of north dipping ESE-WNW striking normal faults within a 30 km wide area north on the Peloponnese Peninsula. The faults formed a series of asymmetric half-grabens from Mount Chelmos in the South toward the Gulf in the North. A large drainage network of antecedent rivers (Demoulin et al., 2015) cutting perpendicular to the faults have later filled most of these half grabens, and created excellent exposures of pre, syn and post rift sedimentation. The stratigraphic configuration of the rift system is mainly terrestrial alluvial – fluvial sediments with a carbonate basement in the southern part of the area, before it transitions to marine, brackish, deltaic and turbiditic deposits in the north. The focus of this study is the Doumena Fault Block, which is located in the greater Kalavryta – Diakofto area on the northern Peloponnese (Figure 1).

For this study the Doumena Fault Block is bounded to the north and south by the Mamoussia – Pirgaki Fault and Doumena Fault, while to the east and west it is bounded by the Klokos mountains and Vouraikos river. It is a sediment filled half-graben in relation to the larger Corinth rift system, and it is the northernmost tilted fault block with terrigenous syn rift alluvial – fluvial deposits. The Doumena Fault Block is one of several fault blocks with similar characteristics (Kerpini, Kalavryta) which is situated between the Vouraikos and Seliounas rivers in the same inactive rift system on the Peloponnese Peninsula. This study will attempt to better understand the Doumena Fault Block and how it fits into the general structural and sedimentary evolution of the rift system.

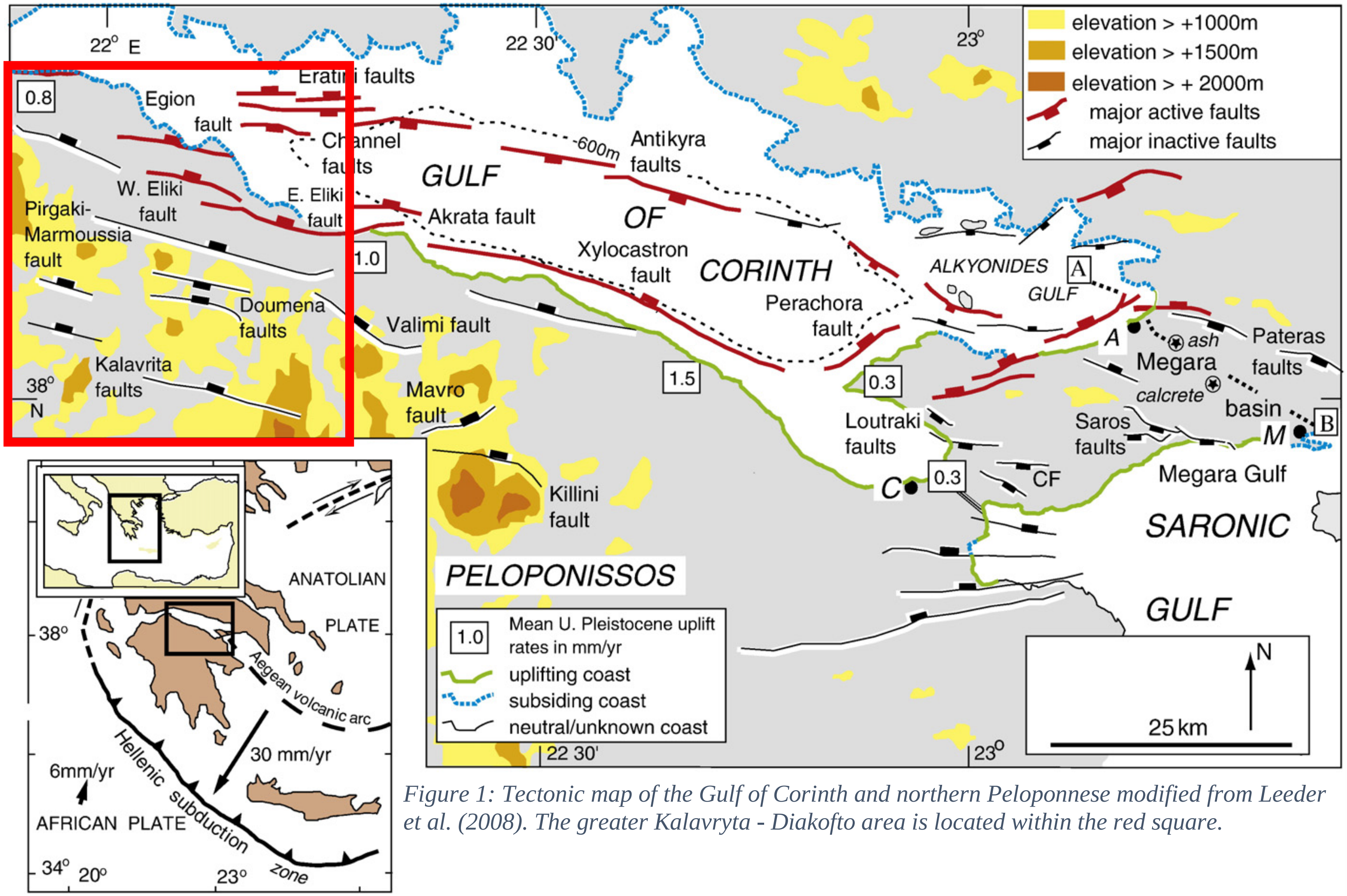


Figure 1: Tectonic map of the Gulf of Corinth and northern Peloponnese modified from Leeder et al. (2008). The greater Kalavryta - Diakofto area is located within the red square.

1.2 Geological problem and rationale

The Doumena Fault Block is suggested to be the distal part of a larger alluvial – fluvial system trending north (Ford et al., 2013; Sorel, 2000). And over the last four years, several students at the University of Stavanger have done geologic field work and investigated the structural and sedimentological development and framework of the Kalavryta (proximal) and Kerpini (medial) Fault Blocks, in addition to the marine deltas north of the Doumena Fault Block (Dahman, 2015; Finnesand, 2013; Hadland, 2016; Kolbeinsen, 2013; Lopes, 2015; Rhodes, 2015; Rognmo, 2015; Sigmundstad, 2016; Stuvland, 2015). The work in the Doumena Fault Block will be a continuation of the research into this alluvial – fluvial system in order to better understand the sedimentation and development of the greater rift system.

Previously, the Doumena Fault Block has mostly been studied on a basin scale. However, some detailed work has been done on a high angle colluvial fan in the Eastern section of the Doumena Fault Block, and on the fault plane itself with regard to fault facies and age dating (Bastesen et al., 2009; Causse et al., 2004; Kolbeinsen, 2013). Most of the regional studies were focused north of the Doumena Fault Block whereas the studies undergone previously by students from the University of Stavanger (Hadland, 2016; Sigmundstad, 2016; Syahrul, 2014) based to the south. The studies done show that N-S cross-faults, smaller alluvial fan deposits, intra basin faults and geological units within the different fault blocks can be subdivided, mapped and more accurately defined.

Several geological problems exist regarding; i) the basin infill, ii) the development of the Doumena Fault (Ford et al., 2013; Syahrul, 2014; Wood, 2013), iii) the extent and timing of deposition of the basal alluvial pre rift deposits. A recent study by Hadland (2016) have suggested that the alluvial fans found in the Doumena Fault Block could be related to the footwall derived fans in the Kerpini Fault Block, since the footwall derived fans in the Kerpini Fault Block show features that indicate the they were deposited close to the horizontal with.

This thesis will investigate the basin infill of the Doumena Fault Block, and try to establish the relative age of the different units. The aims are:

1. Identify and distinguish the different sedimentary units in the Doumena Fault Block.
2. Determine the relative age of the different units in the Doumena Fault Block.
3. Determine how the Doumena Fault has influenced sedimentation.
4. Confirm the presence of the fans identified by Ford et al. (2013) and Kolbeinsen (2013).
5. Compare structural and stratigraphic features between the adjacent fault blocks.
6. Develop a tectono- sedimentary evolutionary model for the Doumena Fault Block.
7. Determine if the crossfaults seen in the Kerpini Fault Block continue into the Doumena Fault Block.

1.3 Objectives

The main objective of this study is to map and describe the basin infill of the Doumena Fault Block. A second objective is to use outcrop data to establish relative age of the different units and create evolutionary models. The goal of the evolutionary model will be to tie the deposition of the alluvial fans with the other stratigraphic units in the Doumena Fault Block and the development of the Doumena Fault.

The results of mapping, descriptions and figures will be used to get a better understanding of the Doumena Fault Block and its role with regard to the larger rift system in terms of alluvial fans facies and facies distribution, interaction between faulting and sedimentation and the overall evolution.

1.4 Data and methodology

The methodology is divided into three sections.

1.4.1 Pre field Work

First, one had to do a literature review. There are many different theories about the evolution of the Gulf of Corinth rift system, and it was necessary to get a good overview of the work, which had been done previously while having a critical state of mind. One also had to read up on sedimentological structures in addition to fluvial, lacustrine and alluvial modes of deposition. A schematic six-step approach to field work by Tucker (2011) was studied in order to avoid bias when in the field, maps and remotely sensed data was used to create effective day to day plans and pinpoint outcrops.

1.4.2 Fieldwork

Fieldwork was completed during two separate fieldtrips, with a total length of four weeks. Data such as fault dip, dip direction, grain size and paleoflow directions were collected. Most of the time in the field was spent on mapping stratigraphic units and outcrop studies, where detailed descriptions were made and a number of photographs were taken. The outcrop data were mainly collected for studying alluvial, fluvial and lacustrine facies and their distribution. Faults were mapped and measured, and the best way of mapping faults proved to be mapping fault planes and lithological contacts.

1.4.3 Post-field Work

At this stage, all the data were synthesized, studied and interpreted. Field data such as dip, dip direction and paleocurrents were categorized and plotted in ArcGIS. Photographs were studied and figures created. All of these steps were performed in order to supply the findings, interpretation and analyses presented in this thesis.

1.5 Previous Work

The study of the northern parts of the Peloponnese peninsula started with Phillipson (1892) who was the first to propose a polyphase evolutionary model for the Gulf of Corinth rift system. Several authors have since done numerous studies and proposed highly debated theories regarding the number and style of the rift phases, geomorphology and fault evolution. The most important ones regarding the regional geology and the evolution of the Corinth rift are (Collier and Jones, 2004; Demoulin et al., 2015; Doutsos et al., 1988; Flotté et al., 2005; Ford et al., 2013; Ghisetti and Vezzani, 2004, 2005; Ori, 1989; Rohais et al., 2007; Sorel, 2000) to mention some. However, most of the researchers have focused their efforts onshore in the southern coastal part of the rift system, which is still active today. Further south toward the southern extent of the rift system that is suggested to represent early syn rift sedimentation have not been studied to the same extent.

Ford et al. (2013) gave an overview of the Kalavryta – Diakofto area, which involved the Doumena Fault Block. They introduced a stratigraphic model for the tectono – sedimentary evolution of the rift system in the Northern Peloponnese and classified the stratigraphy into three major groups for the whole rift system. However, the broad rift system scale of the study implies that detailed intra-fault block scale features were overlooked. In the study of the Doumena Fault Block, they identified three different stratigraphic units (Figure 2): fluvial sandstones and conglomerate, coarse alluvial conglomerates and the Mesozoic basement. They also identified an alluvial fan structure, which they named Troulos (Ford et al., 2013). Kolbeinsen (2013) investigated and classified a additional colluvial fan in the easternmost part of the Doumena Fault Block, to have been deposited late in the evolution of the Doumena Fault. The grain size distribution was examined, and it suggested that there may have been several periods of deposition. This coincide well with the general theory for the area, which is that the Kalavryta, Kerpini and Doumena Fault Blocks are part of a larger alluvial – fluvial system (Collier and Jones, 2004; Ford et al., 2013; Sorel, 2000), which are controlled and sourced by large south - north oriented antecedent rivers (Demoulin et al., 2015; Syahrul, 2014). Studies in the adjacent Kerpini Fault Block (up dip relative to the Doumena Fault Block) show that the dip angle of the beds is not increasing up section (Syahrul, 2014), and it has also been suggested that the initial sediments were present before the initiation of the Kerpini Fault (Stuvland, 2015). This contradicts Ford et al. (2013) who suggested that the early syn rift deposits deposited on a flat surface with slight northward dip direction. Whether this is the case in the Doumena Fault Block is unknown.

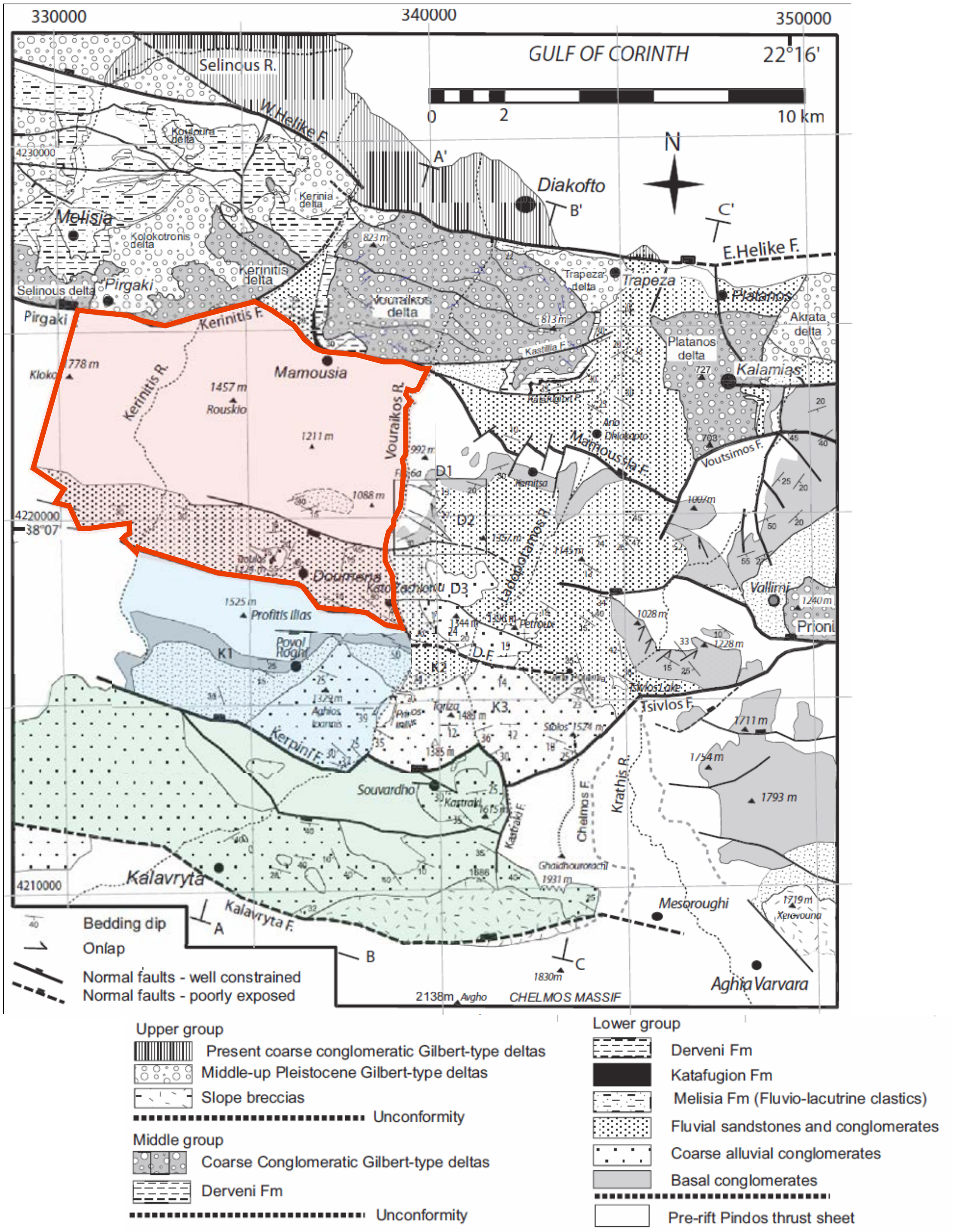


Figure 2: Structural and stratigraphic map showing the greater Kalavryta - Diakofto area. The red square show the extent of the Doumena Fault Block, while the light blue and green square show the Kerpini and Kalavryta Fault Blocks, respectivly. The stratigraphy in the Doumena Fault Block is divided into three distinct stratigraphic units; coarse alluvial conglomerates, fluvial sandstones and conglomerates and Pre rift pindos thrust sheet carbonates.

Chapter 2: Regional geology

2.1 Plate tectonics

In order to understand the complex tectonic setting in the Northern Peloponnese one need to understand the movement of the tectonic plates which is the main driving force in creating the present day structural configuration found on the Peloponnese Peninsula.

The pre rift basement was deposited as a carbonate platform during the Mesozoic. It was deformed during the Paleogene in the Alpine orogeny, where the African and Eurasian Plates converged and created mountain ranges along the Northern Mediterranean margin. Remnants after this event are visible as thrust sheets in mainland Greece and as thickened crust in the Aegean Sea (Taylor et al., 2011).

The Gulf of Corinth and the Peloponnese peninsula is located in the Northwestern part of the Aegean plate, which is a part of the greater Anatolian plate (Jackson, 1994). The configuration of the tectonic plates in the Eastern Mediterranean Sea involve the African, Arabian, Eurasian and Anatolian Plates (Figure 4). The Aegean plate is bounded by the Hellenic trench to the south and west, the Anatolian plate to the east and the right lateral North Anatolian Fault towards the north which separate it from the Eurasian plate. The boundary towards the Anatolian plate in the east have been widely discussed through time, and is currently not properly defined. (Taymaz et al., 2007).

The tectonic domain in the Aegean region have been dominated by two distinct events. First, the subduction of the African plate towards NNE below the Eurasian plate creating the Hellenic trench, and then the continental collision between the Arabian and Anatolian plates in the Eastern Turkey (Gautier et al., 1999; Jolivet et al., 1994). It started when the northward movement of the subducting African plate was significantly reduced around 30Ma. This resulted in rollback of the Tethyan slab and consequent back arc extension, which initiated the creation of the Aegean Sea (Armijo et al., 1996; Jolivet et al., 2010) and uplift in the Northern Peloponnese. The extension was accompanied by a clockwise rotation of about 40° – 50° (Burchfiel, 2008) at around 5 Ma due to the collison between the Arabian and Anatolian plates, which made the North Anatolian fault propagate towards the west-southwest into the Aegean Sea, and create a zone of transtension with deep isolated rift zones (Armijo et al., 1996).

The backarc extension in southern Greece is most likely a combined result from both the rollback of the slab and the rotational movement of the plates (Burchfiel, 2008; Flerit et al., 2004). The Corinth rift is suggested to have initiated approximately 5 Ma years ago, when the North Anatolian fault started to propagate. Today, deformation within the Aegean region is mainly controlled by the interplay between microplates within the Aegean plate (Bell et al., 2008; Taylor et al., 2011).

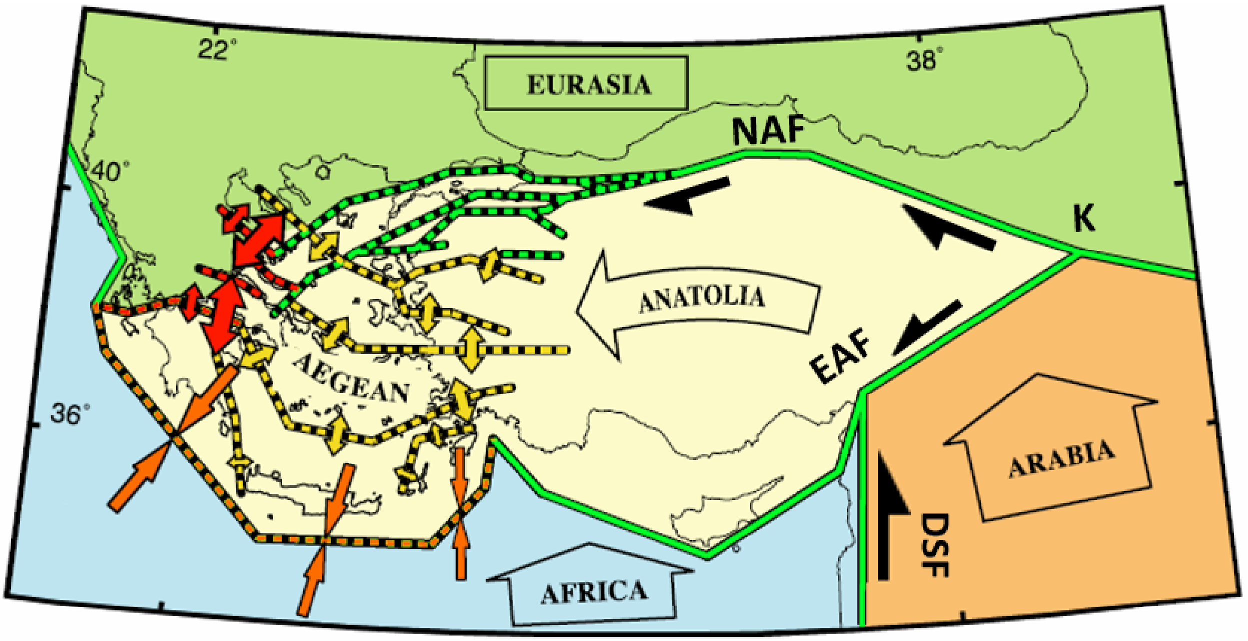


Figure 3: Tectonic setting of continental extrusion in the eastern Mediterranean with simplified boundary conditions. Hollow arrows show relative movement of the tectonic plates. The orange arrows show subduction of the African plate beneath the Eurasian plate. Yellow arrows show the direction of extension within the tectonic plates that are suggested to have initiated more than 15 MA ago. Recent extension (5 Ma) in the Gulf of Corinth and other areas further North is shown by red arrows. It is believed to have been influenced and acccelerated by the North Anatolian Fault. The western part of the NAF interacts with the back arc extension associated with the Hellenic subduction beneath the Corinth sea. EAF denotes the East Anatolian Fault; DSF the Dead Sea Fault; K the Karliova triple junction. Direction and size of arrows are not to scale. Modified from Flerit et al. (2004).

2.2 Structural Framework

The Gulf of Corinth is a 120 km long, asymmetric graben which narrows to the west (4km) at the Rion strait and broadens to the east (30km) towards the Saronicos Gulf (Figure 1). This is due to the Corinth Rift which have created a fault system where the main faults both offshore and onshore are mainly right stepping en –echelon normal faults with an average strike of 105-110° along the south margin of the Gulf (Ford et al., 2013). The Corinth rift is obliquely superimposed across significant NNW-SSE oriented, W – WSW verging thrust sheets (Mesozoic basement) that were inherited from the Alpine orogeny (Jackson et al., 2006; Skourlis and Doutsos, 2003). The Northern Peloponnese is mostly underlain by the oceanic Pindos thrust sheet with part of the Parnassos sheet to the east, and the Gavrovo–Tripolitsa sheet to the west (Figure 4).

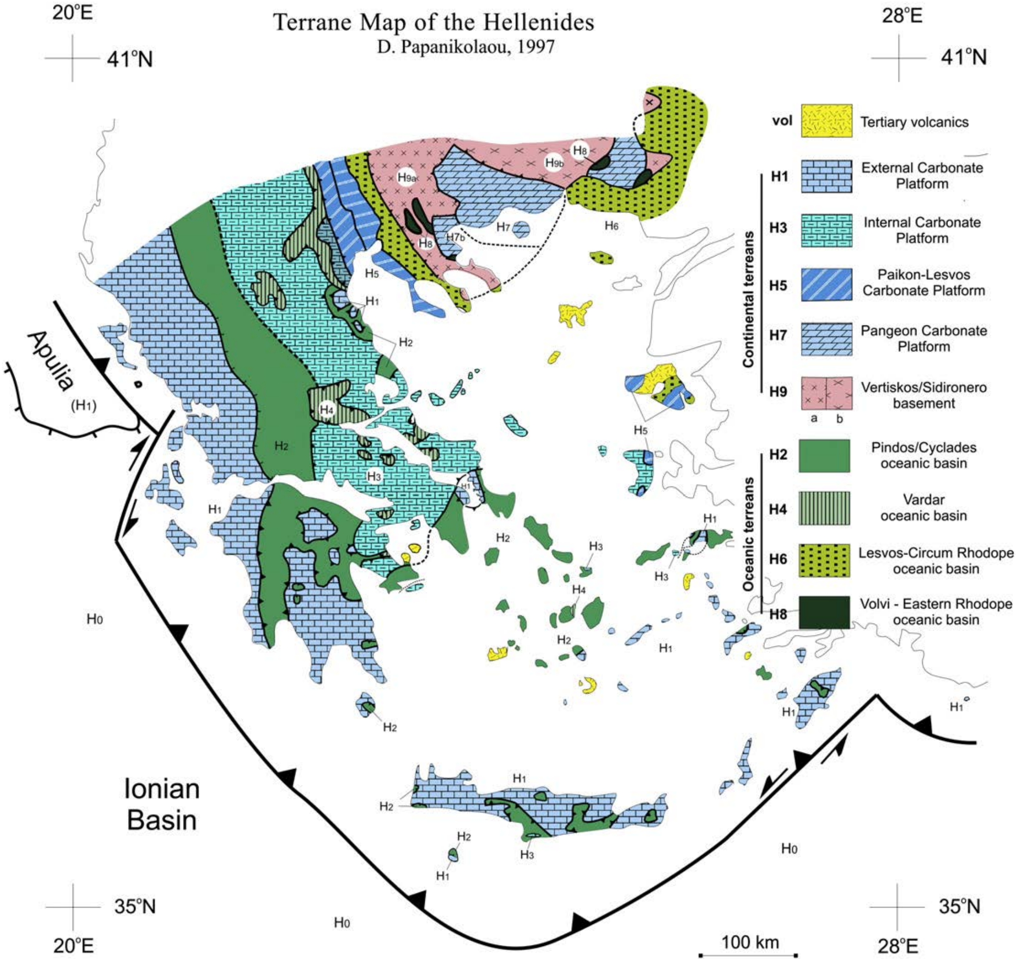


Figure 4 Terrane map of the Hellenides. Continental terranes H1, H3, H5, H7 and H9 are drifted Gondwana fragments with Mesozoic carbonate platforms whereas oceanic terranes H2, H4, H6 and H8 are Mesozoic oceanic basins with ophiolites. The Ionian Basin, being part of the East Mediterranean Basin, have subducted since late Miocene beneath the Southern Hellenides and represents the last future terrane H0. Modified from (Papanikolaou, 2013).

Sachpazi et al. (2007) researched the depth of the Moho, and found that the orientation of the depth contours reflect the crustal thinning and consequently the evolution of the Corinth rift. The research show that the depth of the Moho increase from 25-30 km in the Eastern part of the Corinth rift, to below 40 km in the western part. This suggest that the rift is less mature in the western part and less extended. This is supported by the fact that the depth contours show a Corinth Rift Trend (WNW – ESE) below the Eastern part of the Gulf, before it changes to a Hellenide trend (NNW-SSE) in the Western part. According to Nixon et al. (2016) the increased geodetic extension rates in the western part of the rift which one can observe today (Avallone et al., 2004) is suggested to be a direct result for that the locus of deformation having migrated toward the northwest along the axis of the Gulf with time.

Today, the faults in the Gulf represent the active part of the rift, while the inactive part is located south of the Gulf onshore. The inactive riftsection is characterised by several major north dipping faults. The faults have exposed and preserved sediments in ESE-WNW oriented half grabens across the northern Peloponnese (Ghisetti and Vezzani, 2004; Moretti et al., 2003). In the greater Kalavryta – Diakofto area the southern boundary of the fault system onshore is Mount Chelmos and the Kalavryta Fault. From Mount Chelmos and northwards there are five rotated and uplifted fault blocks that are bounded by major north dipping normal faults. This has created high topographic relief with altitudes up to 2300 m in the uplifted footwalls, which are directly related to extensional activity.

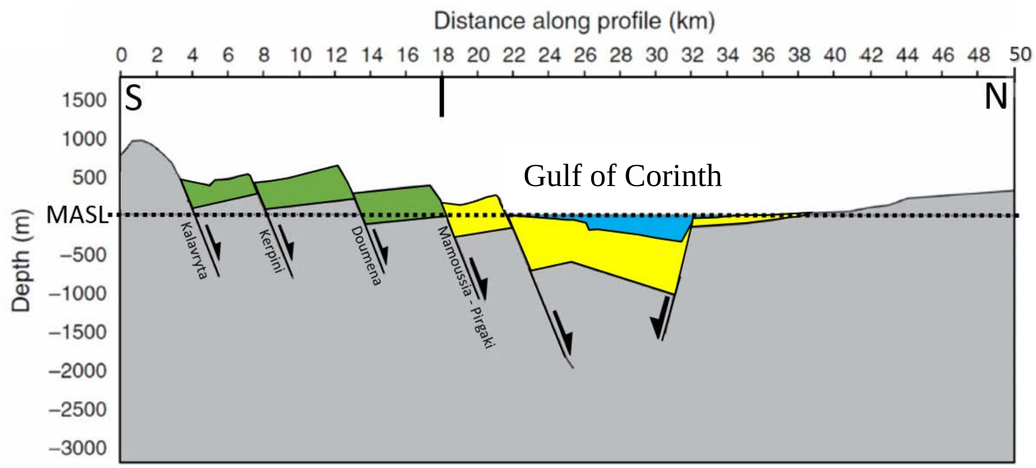


Figure 5: Cross section modified from Bell et al. (2009) showing the general structural setting of the onshore fault system in the Greater Kalavryta – Diakofto area. Green color represent the southern inactive fault system, while the yellow colour represent the current active fault system.

The evolution of the area is not well constrained and there are currently two main theories that exist. The first theory is that the faults and the syn rift sediments get progressively younger, northwards due to a moving regional detachment or low angle fault (angle < 30°) striking almost parallel to the Gulf of Corinth (Sorel, 2000). The second theory is that there is a single master fault that have the main structural control, and that there have been several rift phases of rapid extension and northward progression of the faults (Ford et al., 2013).

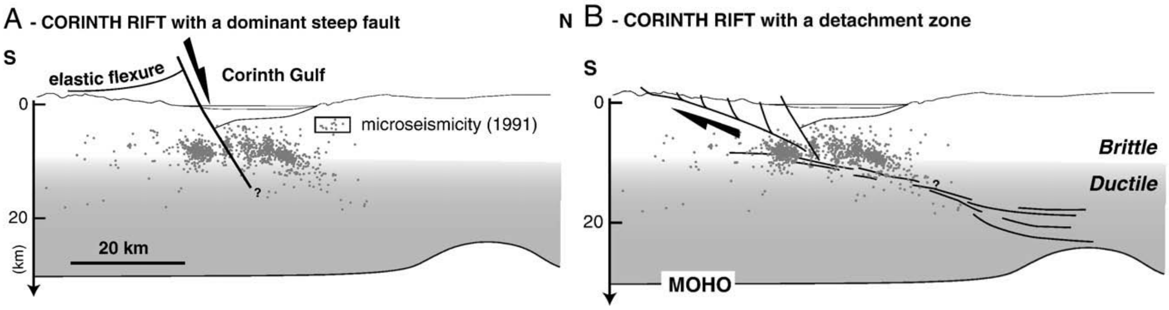


Figure 6: Conceptual models of two different extreme solutions regarding the evolution of the Corinth Rift (Jolivet et al., 2010). Figure A show the Kalavryta Fault as a large dominant steep fault, while Figure B show the Kalavryta Fault as a low angle detachment fault.

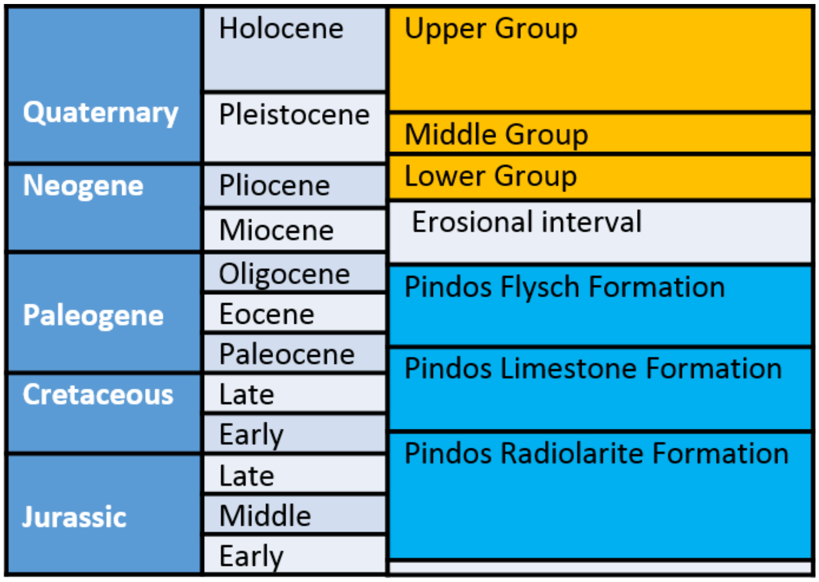
Both theories have in common that the half grabens can be visualised in a domino structural style, where rotation of the fault blocks have caused the footwall to be uplifted and the hanging wall to subside. Sediments deposited by alluvial and fluvial systems would then fill the accommodation space created during rifting, yielding the thick packages of sediments in close vicinity to the hanging wall of the faults. The area has experienced sedimentation over geological times scales and it is suggested that the half grabens onshore have a maximum estimated thickness of 2.8 km (Ford et al., 2013), which is more than the 2.5 km of syn rift stratigraphy calculated to underlie the eastern and central Gulf offshore (Nixon et al., 2016).

2.3 Stratigraphic framework

2.3.1 The Gulf of Corinth Rift system

The Gulf of Corinth area has been subject of structural and sedimentological studies for over a century. Many researchers has focused on the seismology, geomorphology and structural evolution of the rift system, while others have focused on the younger Gilbert-type deltas, associated turbidites deposits and the Pindos Thrust sheets. According to the current stratigraphic model the syn rift strata is proposed to have recorded several periods of rapid extension and fault migration, where the major antecedent river system controlled sediment supply and pre-existing relief influenced sediment routing early syn rift (Ford et al., 2013; Rohais et al., 2007). The stratigraphy of the southern part of the rift system, is early syn rift and have not been studied as detailed as the younger marine to brackish deposits to the north. However, Ford et al. (2013) published a paper where they classified the onshore syn rift deposits in the greater Kalavryta – Diakofto area into three informal groups, which all overlie the older carbonate basement.

Table 1: Stratigraphical overview of the different formations and groups situated in the Northern Peloponnese. This table combine previous work by Degnan and Robertson (1998); Ford et al. (2013) on the Northern Peloponnese. Basement units are marked in blue. Corinth rift associated units are marked in orange.



Quaternary	Holocene	Upper Group
	Pleistocene	Middle Group
Neogene	Pliocene	Lower Group
	Miocene	Erosional interval
Paleogene	Oligocene	Pindos Flysch Formation
	Eocene	
	Paleocene	Pindos Limestone Formation
Cretaceous	Late	
	Early	Pindos Radiolarite Formation
Jurassic	Late	
	Middle	
	Early	

Pre rift strata

The area of this study is situated on the Pindos thrust sheet. It is comprised of an approximately 1300 m thick succession of hemipelagic carbonates in addition to minor red and green radiolarites and sandy turbidites (Degnan and Robertson, 1998; Skourlis and Doutsos, 2003).

Syn – rift Strata

The syn rift deposits are divided into the Lower, Middle and Upper group after Ford et al. (2013).

Lower group

The Lower group is only found south part of the area, stretching from the Kalavryta Fault Block in the south to the Pirgaki-Mamoussia Fault Block in the north. It can generally be characterized as coarse grained alluvial to fine-grained lacustrine successions, which show local variations (Ford et al., 2013).

Middle group

The Middle group is characterised by marine to brackish ancient Gilbert-type deltas building northward. The ancient Gilbert type deltas are mainly comprised of eroded and reworked carbonate and Cretaceous to Paleogene flysch. Turbidites and hemipelagic conglomerate deposits can be found laterally alongside the gilbert type deltas. The Middle group is separated from the Lower group by an erosional unconformity, where approximately 0,3 Ma of the stratigraphy is missing (Ford et al., 2013).

Upper group

The Upper group was mainly deposited offshore in the active parts of the Corinth rift system. It consists of present day Gilbert-type delta conglomerates, distal turbidites and hemipelagic deposits. It is found in the Helike Fault Block and records onshore of the Upper group shows progressive uplift (Ford et al., 2013).

2.3.2 The Kalavryta depositional system

The Kalavryta depositional system is a larger alluvial – fluvial depositional system comprised of the Kalavryta, Kerpini and Doumena Fault Blocks. The Doumena Fault Block could be the distal part of this system, and the stratigraphy have not been properly studied before in this fault block. A general description of the current stratigraphic knowledge about the fault blocks in this system is described below. This information is based on regional surveys and local research done by previous students from the University of Stavanger.

2.3.2.1 Kalavryta Fault Block

The Kalavryta Fault Block is dominated by coarse alluvial conglomerates overlain by red shales (Rognmo, 2015). Sediments in the Kalavryta Fault Block are laterally extensive and stretch several kilometers northward from the town of Kalavryta in the south to Skepasto Mountain in the north. The thickness of the Kalavryta conglomerates have been estimated to be 1000m thick by Ford et al. (2013), while the red shales have an estimated thickness of 50 - 70m (Rognmo, 2015).

2.3.2.2 Kerpini Fault Block

According to Ford et al. (2013) the Kerpini Fault Block contains basal conglomerates, overlain by fluvial sandstone and conglomerates in addition to several internal alluvial units (Hadland, 2016; Sigmundstad, 2016; Syahrul, 2014). However, the existence of the fluvial sandstone and conglomerate is currently disputed by Hadland (2016), who characterised the same deposits to be part of the alluvial basal conglomerates.

The basal conglomerates is the dominant lithology in the Kerpini Fault Block, and it have been estimated to have a maximum thickness of 1300m. The eastern part of the Kerpini Fault Block is characterised by massive coarse alluvial deposits (Hadland, 2016; Sigmundstad, 2016; Syahrul, 2014).

2.3.2.3 Doumena Fault Block

The Doumena Fault Block contains basal conglomerates which onlap the paleoslope towards the north in the fault block. Fluvial conglomerate and sandstones in addition to coarse alluvial conglomerate overlie these. The fluvial unit consist of orange to red siltstones, pebbly sandstones and thick conglomerate beds, while the coarse alluvial unit consist of massive, cobble and clast-supported conglomerates (Ford et al., 2013).

2.3.2.4 Mamoussia - Pirgaki Fault Block

The Mamoussia – Pirgaki Fault Block is characterised by Gilbert Deltas and their associated conglomerates that are overlying older fluvial and fluvio-lacustrine deposits of the Lower Group that consist of interbedded conglomerate, pebbly sandstone bodies and minor red siltstones. The fluvio-lacustrine deposits have an estimated maximum thickness of 250- 500 m, and they are overlain by micritic limestone and an interbedded conglomerate and sandstone. estimated thicknesses of 10 and 18m, respectively (Ford et al., 2013).

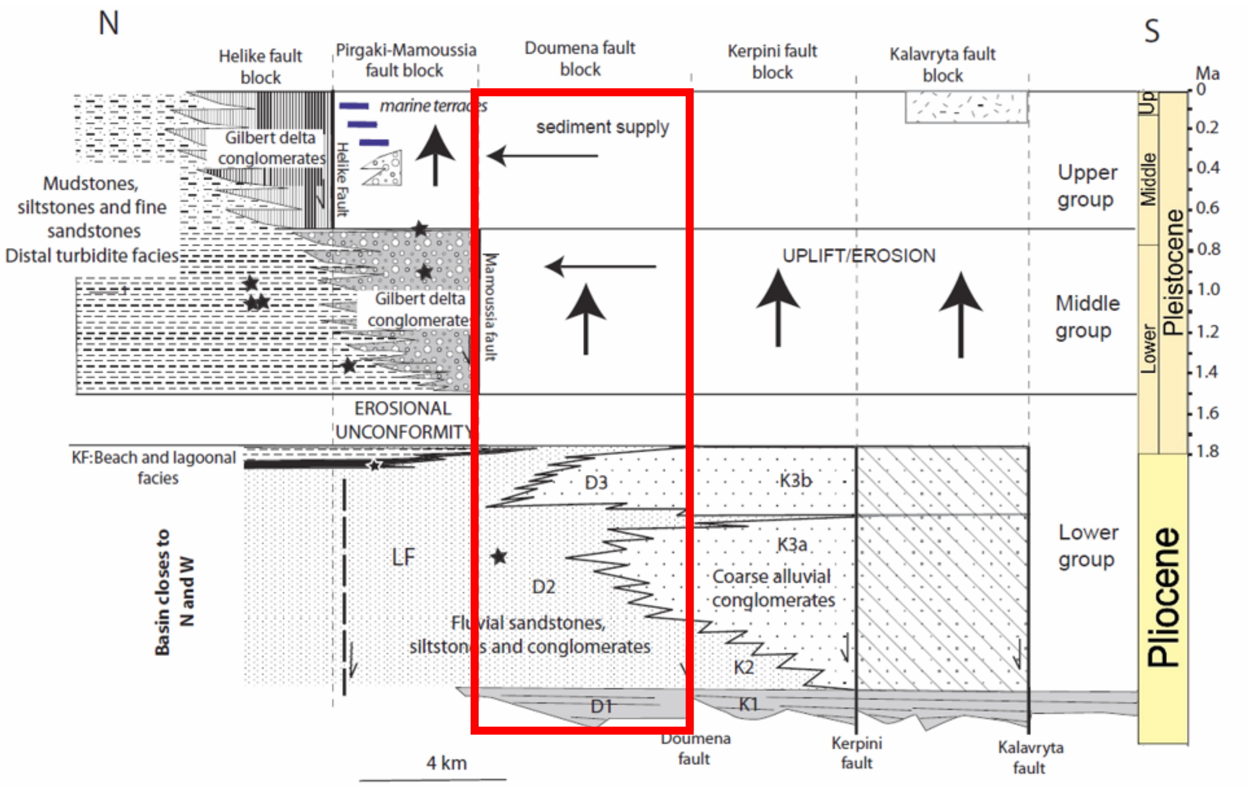


Figure 7: The syn-rift stratigraphy classification modified from Ford et al. (2013) resulted in the above wheeler diagram. The Doumena fault block is highlighted within the red square.

2.4 Rift basin and half graben formation

Rift basins are generally considered a response to divergent movement of two tectonic plates, where brittle failure of the crust have led to normal faults (Twiss and Moores, 2007). These normal faults often create geologic structures such as grabens, half grabens and horsts. Half grabens such as the Doumena Fault Block can generally be compared to a triangular geometry where the fault, the rift onset unconformity, and the post rift unconformity generally make up the bounding structures (Schlische, 1991) and the width of the half grabens are controlled by the length of the basin bounding fault (Cowie, 1998).

A feature of major importance for the Northern Peloponnese is the abandonment of faults within half graben systems due to dynamic basin evolution. The progressive abandonment of old faults and development of new faults in the hanging wall side of the extinct fault lead to gradual uplift in the footwall of the new fault (Leeder and Gawthorpe, 1987). Formation of rift basins occur by normal fault growth, linkage of fault segments and accumulation of displacement on the basin bounding faults. The main controlling factors for the development of the faults are lateral and vertical heterogeneities in the lithology and rock strength (Ghisetti and Vezzani, 2005). This include inherited structures such as folding due to the Hellenic fold and thrust belt. Ideally, normal faults will strike perpendicular to the principal direction of stress. However, a landscape with inherited structures can alter fault strike and their corresponding kinematics segmenting the rift basins (Ghisetti and Vezzani, 2004). Segmentation within half grabens depend on the basin architecture, and segment boundaries within basins are often marked by local highs and lows in the hanging wall and increased density of small displacement faults toward the fault tips of the main fault. Footwall elevations usually regarded as persistent barriers to fault rupture (Gawthorpe and Leeder, 2000).

Other types of segmentation can happen in overlap zones between en-echelon faults. Depending on the style of fault linkage one may get a transfer fault or an oblique monoclinal downbend, which develop at an high angle to the normal fault trend (gibbs 1984). Transfer faults is suggested to separate basins into different deformation styles and one believe that they can change the polarity of tilting in an halfgraben, in addition to accommodate the creation of extra large depocenters (Leeder and Gawthorpe, 1987).

Conventional fault growth models can be divided into three phases; initiation, interaction and linkage and a fully linked fault system (Figure 8). The initial phase is recognized by isolated and small displacement normal faults. The second phase happen when the faults start to link to each other and structures such as breached relay ramps develop. The final phase is defined to start when faults are fully linked together as one big fault or fault zone because the faults have grown and propagated towards a particular direction (Gawthorpe and Leeder, 2000).

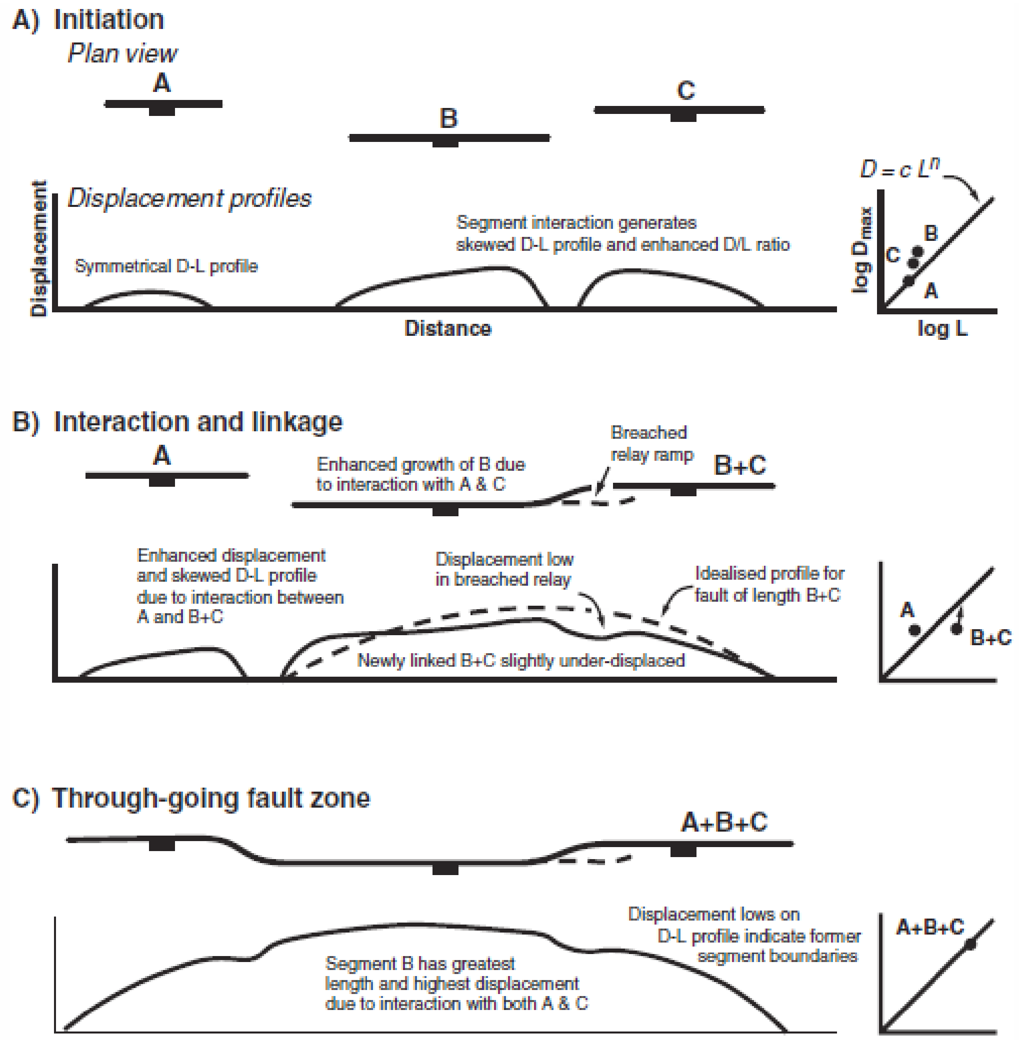


Figure 8: Schematic evolution of three fault segments that produce a major basin bounding fault, as illustrated by the evolution of segments A (Fault initiation stage), B (Interaction and linkage stage) and C (Fully linked fault stage). Observe how the displacement (D) and length (L) evolve so that the through-going fault zone has similar characteristics to those of an symmetrical isolated fault segment (Segment A in A). Note that the displacement profiles shown are for hard linked faults. This have produced skewed displacement profiles around the segments boundaries. Segments separated by transfer faults would have different displacement profiles. From Gawthorpe and Leeder (2000).

Folding is an important element in the development of normal fault zones. Transverse folds at high angle to fault strike are often associated with along strike displacement gradients, where transverse synclines defines displacement maxima (Schlische, 1995). Another type of extensional folds lie parallel to the fault zone and form due to ductile deformation in front of the propagating fault tip. These folds are classified as fault propagation folds, and they are commonly preserved as monoclines in the footwall of normal faults and as hanging wall synclines (Gawthorpe et al., 1997; Schlische, 1995). Folds are however often complex and the growth history of the fault can only be viewed if the fault tip can be reconstructed from basin stratigraphy (Gawthorpe and Leeder, 2000; Gawthorpe et al., 1997; Schlische, 1994). This often complicate the interpretation of folds in extensional settings which are suggested to have been created early syn rift, and experienced substantial erosion post deformation.

2.4.2 General sedimentary framework in rift basins

The main control on geomorphologic and sedimentary patterns in half grabens are the tectonic slopes, asymmetrical subsidence, lateral and axial transportation systems in addition to progressive fault rotation where one have nucleation of higher angle second and third generation normal faults (Leeder and Gawthorpe, 1987). Together, these factors exert large control on facies distribution in addition to creating uplift and accommodation space. Sedimentary infill in the form of hanging wall or footwall derived fans in rift basins are mainly influenced by the displacement geometry of the basin bounding normal faults. These faults can generally be viewed as linear features, and each fans catchment evolve with regard to the position of their fault. Footwall relief adjacent to main basin bounding faults increase as fault slip accumulates, and the abrupt decrease in gradient from the footwall to the hanging wall depositional basin can cause rapid deposition and the construction of alluvial fans and fan deltas. The size of the catchment is mainly controlled by the length of the tectonic slope produced during extension and the principal stream, which relate directly to the size of the drainage basin area. For any given climate and bedrock lithology, drainage basins controls the discharge of water and sediments, and thus the magnitude of alluvial fans and fan deltas along the basin margin (Gawthorpe and Leeder, 2000). Hanging wall catchments are initially much longer than those that gradually propagate into the footwall and they have gentler slopes. Hanging wall sourced fans are in other words larger than typical footwall derived fans and coalescence of hanging wall fans can create prominent low angle bajadas. Progressive rotation of the hanging wall dip slope toward the fault can result in fan surface incision and lobe offlap (Allen and Densmore, 2000; Gawthorpe and Leeder, 2000).

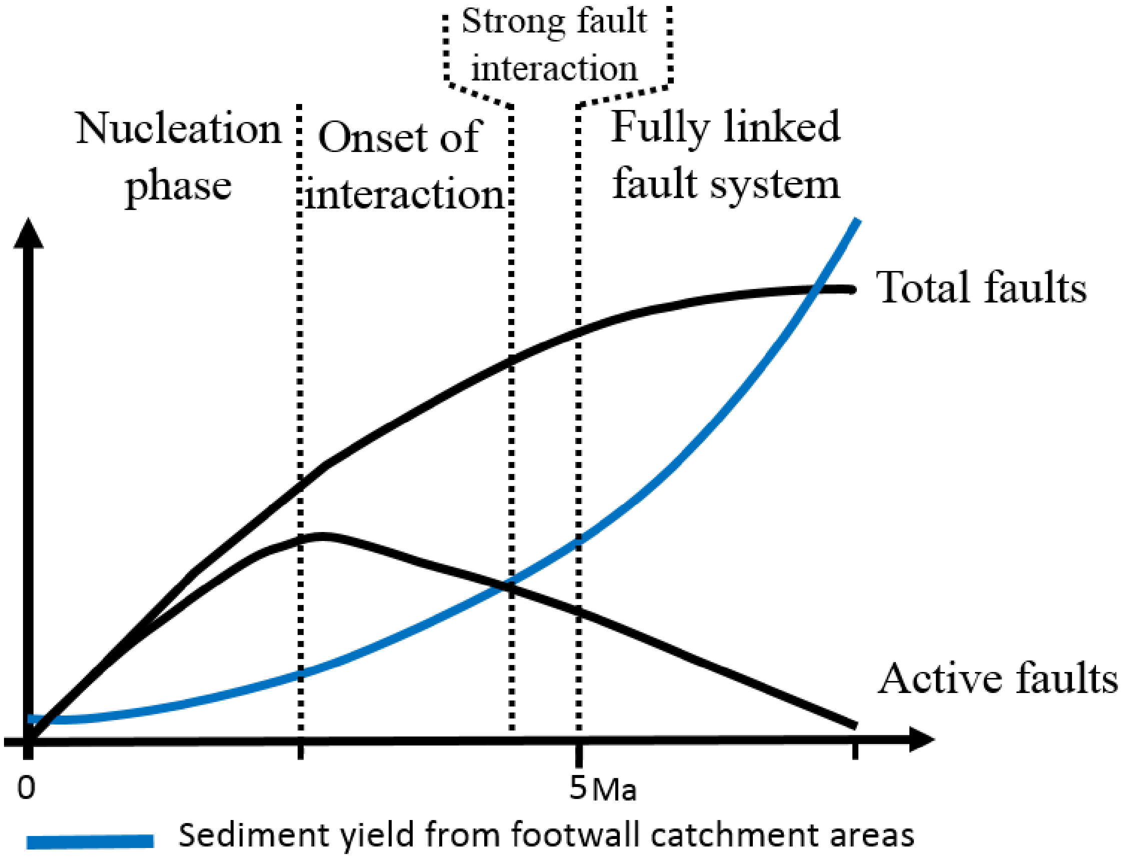


Figure 9: Sediment yield model for footwall catchment areas, where synrift sedimentation is a direct response to the different stages of fault evolution (A-C in Figure 8) of tectonic activity. The role of inherited drainage systems is not considered. Modified from (Cowie et al., 2006).

Fluvial systems running through open basins will interact with transverse fans and drainages as a response to fault induced tilting. Because there must be equilibrium between the fans, the axial and lateral rivers and the sediment influx. Together, these factors exert large control on facies distribution in addition to creating uplift and accommodation space (Gawthorpe and Leeder, 2000; Leeder and Gawthorpe, 1987). Fan interaction with fluvial systems generally result in incision or toe cutting of the fan.

2.5 Tectono-sedimentary models for continental terrigenous basins

In subchapter 2.4 and 2.5, one went through the main controls for half graben formation and the evolution of the sedimentary framework. Gawthorpe and Leeder (2000) have combined the theory into a tectono-sedimentary model for continental extensional rift basins, from rift initiation to the fully linked fault stage and fault death. One can use this model as an analouge for the evolution of the Corinth rift. The block models show terrigenous sedimentation in an evolving rift system and the following figures will explain how rift systems generally evolve through time.

2.5.1 Stage 1: Initiation stage

During the initation stage one get several isolated normal faults with small displacement. During this stage footwall derived sedimentation is very limited (Cowie et al., 2006), and fans derived from antecedent fluvial systems are much larger. Stratigraphic variability between the local depocenters is high, due to difference in sediment supply and routing of sediments early syn rift where fluvial system can incise into the uplifting footwalls or migrate around the fault tips. Local lacustrine basins in the hanging wall of the propagating normal fault segments can also be formed, yielding significantly different facies characteristics. (Gawthorpe and Leeder, 2000).

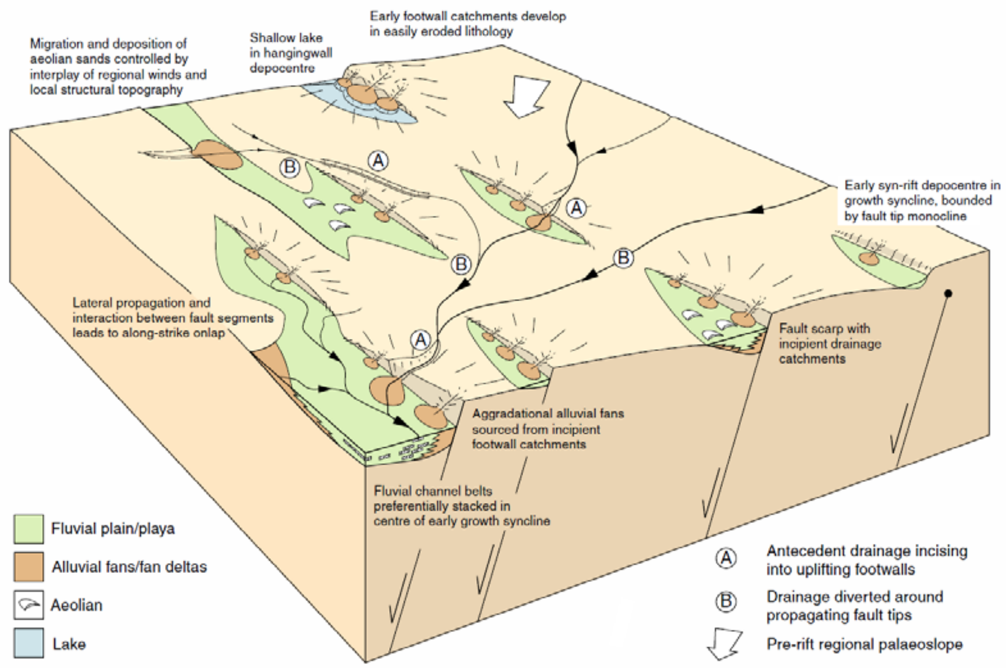


Figure 10: This figure display several different kinds of fans during early rift intiation. Note that the fans sourced from the antecedent fluvial drainage system and the uplifted hangingwall are larger than fans sourced from the smaller drainage catchment of the footwalls. Fans deposited in lacustrine settings will show significant different charactertistcs than fans deposited in nonmarine settings. Modified from Gawthorpe and Leeder (2000).

2.5.2 Stage 2: Interaction and linkage stage

During the second stage of rift evolution, the smaller faults which one could observe in figure XX have interacted and linked into two large continuous fault. The small segmented basins have linked together and the fluvial antecedent drainage system changed course due to the tectonic evolution, and is now located at the boundary between the segments (weak zone that is easier to erode). The dimension of the catchments have increased in size proportional to the displacement, and yield higher footwall and hanging wall derived sedimentation. Smaller consequent drainage catchments have matured and yielded large alluvial fans. Asymmetric subsidence or differential displacement have led to the formation of larger lacustrine basins and alluvial fans with a significant axial trend relative to the fault (Cowie et al., 2006; Gawthorpe and Leeder, 2000).

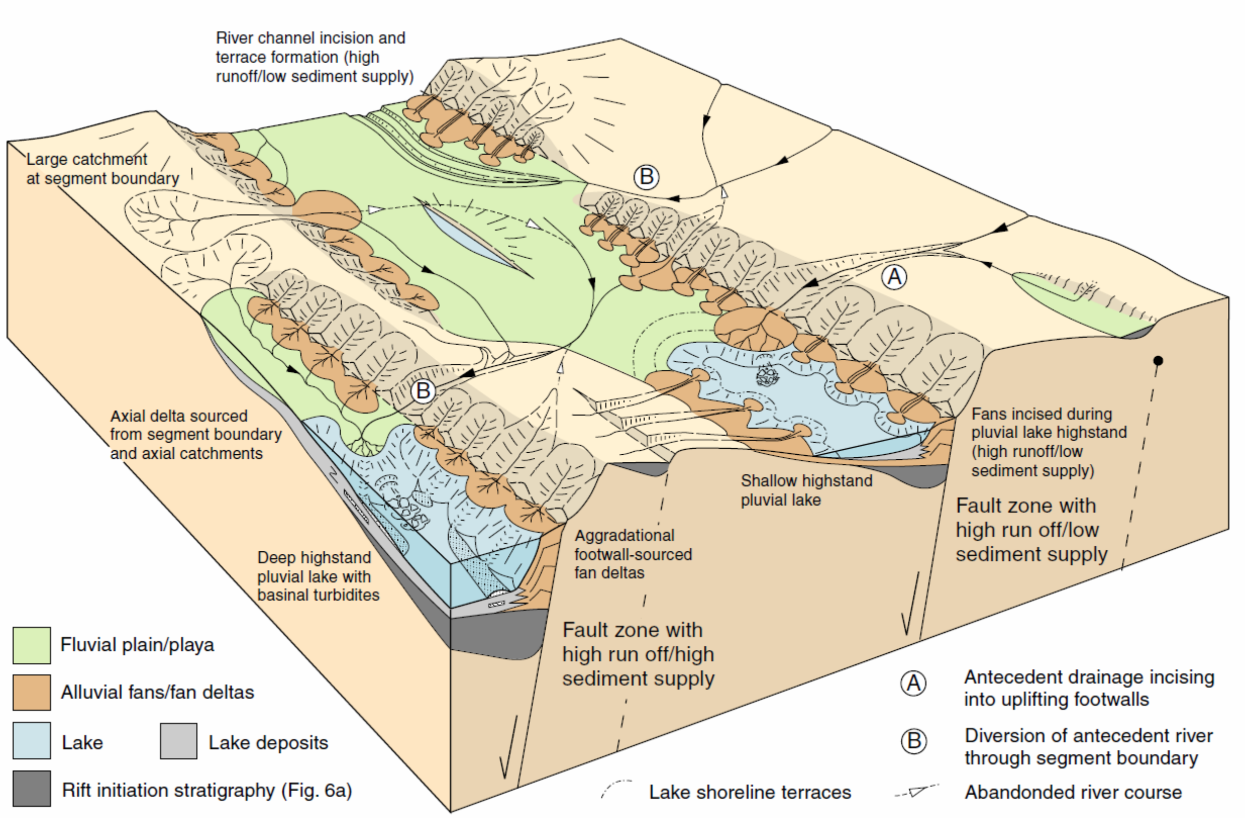


Figure 11: Display the second stage of rift evolution. The small segmented basins have linked into larger basins by either relay ramps or transfer faults. Modified from Gawthorpe and Leeder (2000).

2.5.3 Stage 3 and 4: Fully linked fault system stage and fault death

During the third and fourth stage of rift evolution the linkage of adjacent fault segments have created major basin bounding faults which typically define most major half grabens (Schlische, 1991). Uplift of footwall and erosion from the fluvial antecedent system have allowed axial rivers systems to reach previously isolated basin segments. The uplift caused the fluvial river system to meander and it can be observed as an asymmetric meander belt, which have incised some of the alluvial fans and lead to reworking. At the start of the fault death stage, displacement shift toward parallel synthetic fault in the hanging wall of the older basin bounding faults. This force the river system to migrate laterally and can in some cases lead to increased uplift and erosion of hanging wall derived fans (Gawthorpe and Leeder, 2000).

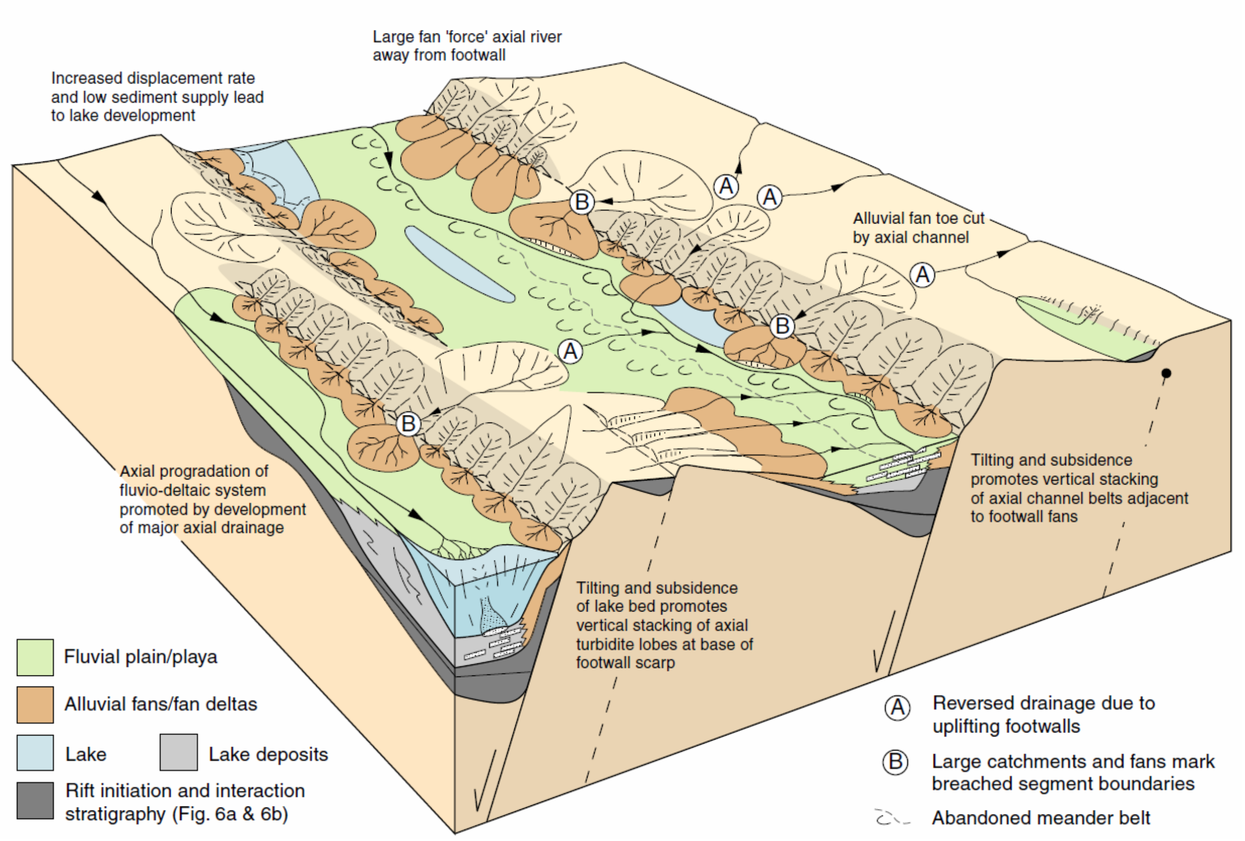


Figure 12: Display the third and fourth stage of rift evolution. Faults have been abandoned and new fault have been initiated in the hanging wall of the now extinct fault. Modified from Gawthorpe and Leeder (2000).

Chapter 3: Methodology

This study is enabling both fieldwork and digital elevation models in Petrel E&P in order to investigate the Doumena Fault Block. The aim of this chapter is to provide an overview of the methods applied during fieldwork and interpretation of outcrop data. The majority of the data were collected in the field, while processing and interpretation of the data were completed during and after the field trips.

3.1 Pre-Fieldwork - Planning

The Doumena Fault Block (60km2) in addition to selected areas and features of the Kerpini Fault Block was investigated in order to fulfil the objectives set for this study. The size of the study area meant that a comprehensive literature review of the regional geology was important in order to cover the whole area within the estimated timeframe. In order to do so, hardcover maps, previous interpretations, in addition to satellite imagery (Google Earth) were studied to find possible outcrops and the most efficient driving routes. Hardcover maps and digital elevation maps (DEM) enabled one to view the area in detail.

3.2 Fieldwork

Fieldwork was conducted during two field sessions with a total of three weeks in the field. Standard field equipment such as a digital camera, ruler, binoculars and a GPS was utilized in the field. The purpose of the fieldwork was to determine the stratigraphy of the Doumena Fault Block and establish the relative age of the different units in the Doumena Fault Block. This includes geologic mapping of faults, contacts and facies.

The collected field data can be divided into two sections; stratigraphic and structural data.

Stratigraphic data:

- Outcrop descriptions
- Facies
- Dip angle and dip direction
- Paleoflow directions
- Clast \ Grain size measurements

Structural data:

- Fault dip angle and dip direction
- Mapping contact

A schematic approach by Tucker (2011) to fieldwork was followed in order to avoid bias when in the field. The following six steps were applied to describe the outcrops:

1. Lithology
2. Texture
3. Sedimentary structures
4. Colour
5. Geometry and relationships
6. Fossils

Each outcrop were recorded by a GPS waypoint. Measurements such as grain size (Figure Xx), sorting, matrix content, sphericity and roundness of clasts (Figure XX) were noted and applied when describing lateral and vertical facies variability. Clast size where determined and classified by taking the average of the ten largest clasts within an area of 1x1m (Figure XX). Paleoflow data were collected by searching for imbricated discs and tabular shaped clasts.

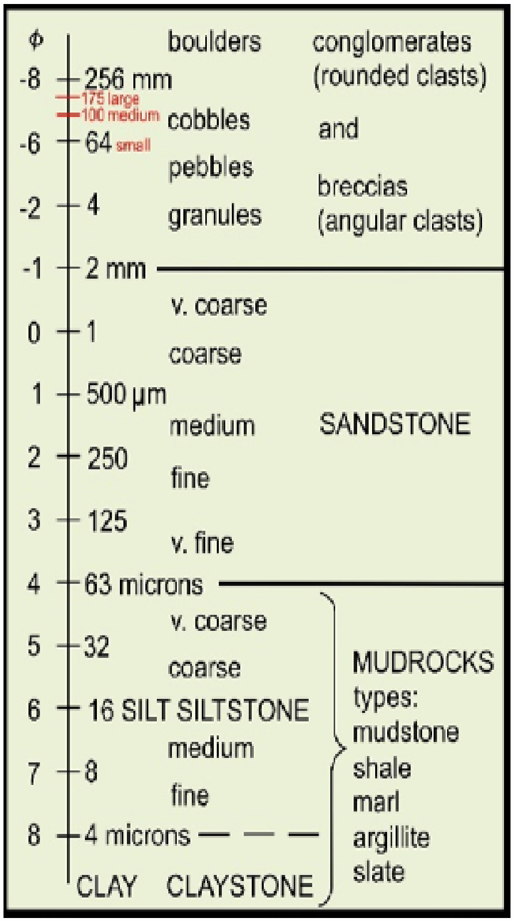


Figure 13 Grain and clast size classification by Tucker (2011).

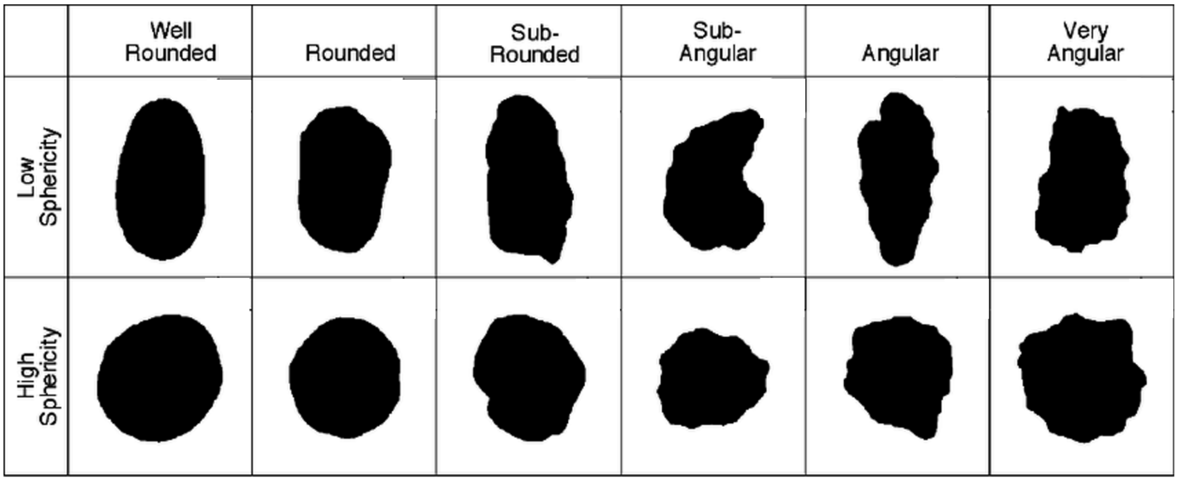


Figure 14: Display how one differentiate clasts based on roundness and sphericity. Rounding and angularity was determined based on the overall impression of the outcrops.

The direction of a paleocurrents is difficult to measure accurately, however a general trend can often be obtained. Strike and dip angles were measured by using a Silva Sighting Compass, and in areas where one were unable to measure the dip of bedding planes directly one used the Silva Sighting Compass with Mirror. This enabled one to measure strike and dip angles from a distance by sighting. The measurements on exposed bedding or fault planes from a distance are not very accurate, but yield a representative measurement.

Figure 15: Example of how the average clast size of an outcrop is measured. The ten largest conglomerate clasts within an area of 1x1 m is measured and averaged according to Tucker (2011).

The alluvial and colluvial fan deposits encountered in this thesis was classified according to the classification scheme by Blikra and Nemec (1998). Alluvial fans can generally be defined as a coarsening upward fan shaped mass of sediments deposited by permanent or temporary channelized streams from a point source on the mountain scarp. Whereas, colluvial fan deposits are dominated by sediment gravity processes which yield coarse grained and texturally immature slope-waste material deposited in the lower part of the mountain slope.

Table 2: Comparison of the distinctive features of colluvial and alluvial fans. This table is modified from Blikra and Nemec (1998).

Typical Characteristics	Colluvial fan	Alluvial fan
Geomorphic setting	Mountain slope and its base	Mountain foot plain or broad valley floor
Catchment	Mountain – slope ravine	Intramontane valley or canyon
Apex location	High on the mountain slope	At the base of the mountain slope
Depositional slope	35-45° near the apex to 15-20° near the toe	Seldom more than 10 -15° near the apex, often less than 1-5 near the toe.
Plan –view radius	Less than 0.5 km, rarely up to 1-1.5km	Commonly up to 10 km, occasionally more than 100km
Sediment	Mainly gravel, typically very immature	Gravel and\or sand, immature to mature.
Grain size trend	Coarsest debris in the lower zone	Coarsest debris in the upper zone
Depositional process	Avalanches, including rockfall, debris flow, and snow flow; minor water flow, with streamflow chiefly in gullies	Debris flow and\or water flow (braided streams

3.3 Post-field Work – Processing and Interpretation of Data

After each fieldtrip, all the data were synthesized and categorized. Geological maps, paleoflow directions in addition to dip and dip direction were georeferenced by using ArcGIS. Cross-sections created in the field were digitized without vertical exaggeration in CorelDRAW by using an elevation profile from a DEM. In addition to creating the cross-sections, CorelDraw were used to modify figures and pictures taken in the field.

Chapter 4: Field observations - Stratigraphic units

4.1.1 Introduction

Based on the observations made in the field, a number of stratigraphic units have been identified, and a map depicting the different units have been created. This section will present a description of the each of the stratigraphic units within the Doumena Fault Block, which can be differentiated on either facies, texture, geometry and extent, in addition to classifying them. The main focus of this study will be to give a general description of each unit in the Doumena Fault Block, whereby the Trouloz member will receive special attention.

A dominating feature that can be observed in the Doumena Fault Block is the paleoslope of the immediate uplifted hanging wall of the Doumena Fault. It can generally be viewed as a south dipping planar surface with dip angle that range from 25 – 30 ° and a mean dip direction toward the southwest. A large part of this area show a very low angle contact between the sediments and the basement which can be viewed as a plane stretching across the entire Doumena Fault Block. The plane make up the plane of the basal unconformity, where syn rift sediments lie subparallel to the paleo slope. The elevation of the basal unconformity change from west to east across the entire basin, and north of the basal unconformity, everything is basement, until the Mamoussia – Pirgaki Fault (Figure 16).

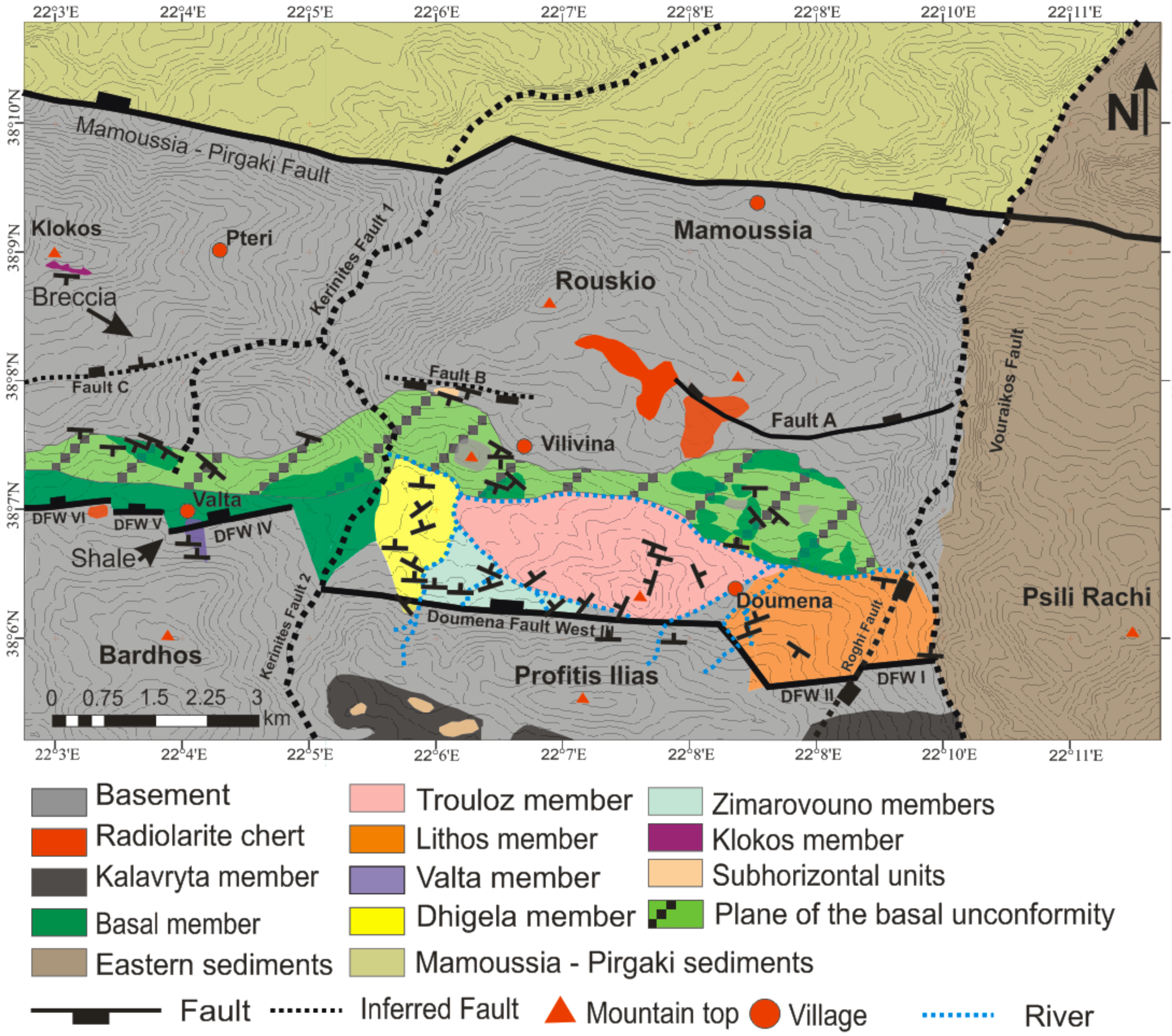


Figure 16: Structural and geologic map of the study area with all the faults and strtigraphic units marked. The legend below the map show the colour coding of the different stratigraphic units and the certainty of the faults. The Trouloz member is marked with the pink colour is situated in the middle of the fault block.

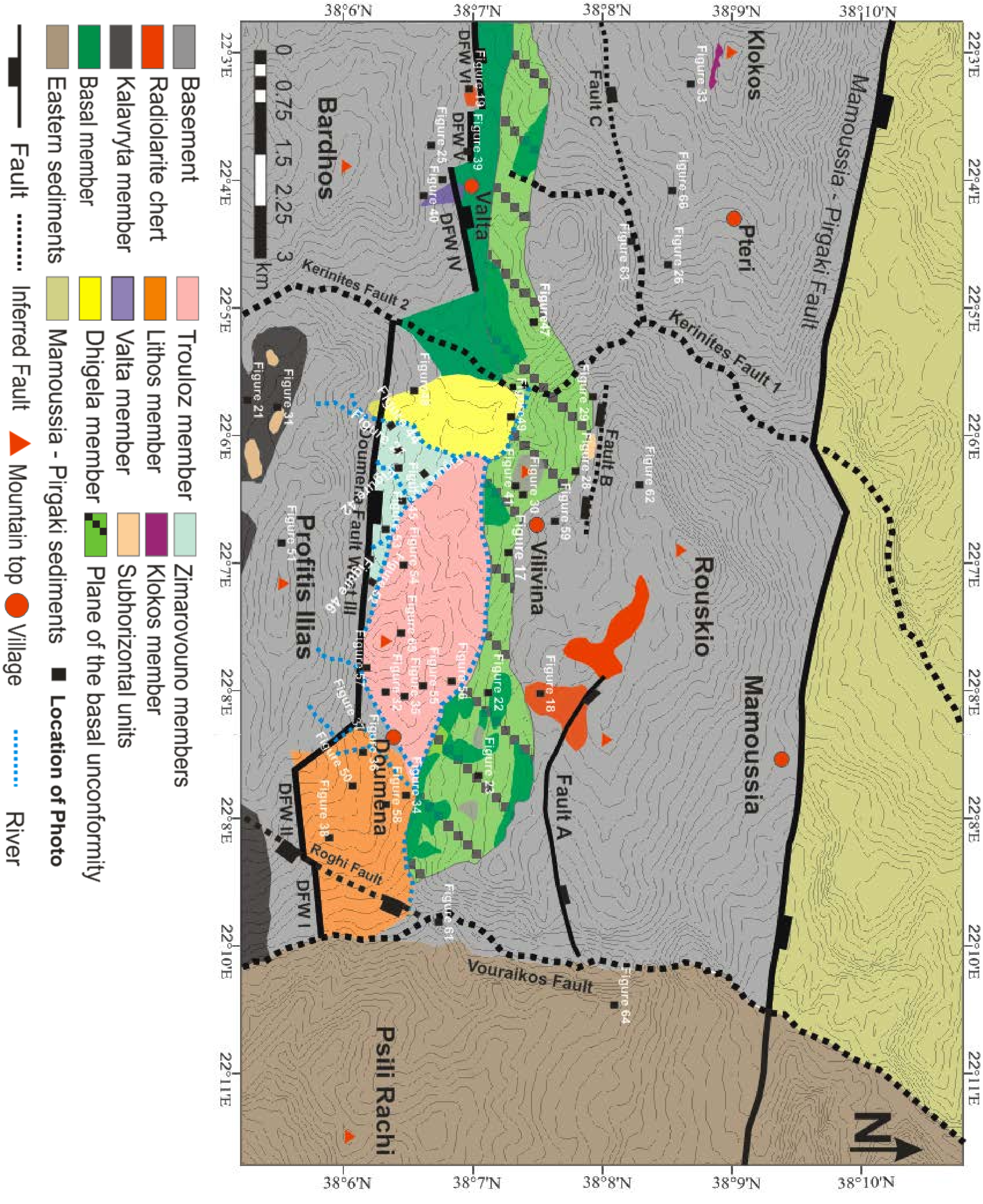


Figure 17: Showing the location of the figures in the following chapters and subsections.

4.1 Pre rift units

4.1.1 Basement lithologies – Pindos Carbonate and radiolarite

Figure 18: Light grey to brown limestone outcrop East of Vilivina village, in the hanging wall of the Doumena Fault Block. The outcrop display the chaotic nature of the basement, that show linear features and some very gentle folds.

The basement in the Northern Peloponnese have previously been described in detail by (Degnan, 1992; Degnan and Robertson, 1998; Skourlis and Doutsos, 2003). Two different types of basement lithologies have been found in the Doumena Fault Block, light grey to brown limestone (Figure 18) and light red to indigo banded radiolarite chert (Figure 19). The limestone is the main lithology in the Doumena Fault Block, whereas the radiolarite is only found at three different locations. The contact between the basement units is sharp, and it can be observed across large distances. Debris from weathered or eroded radiolarite chert can conceal the contact at certain locations, thus making it harder to determine the contact. Nonetheless, a general trend for the contact can often be found. According to Degnan (1992) the radiolarite chert is older than the limestone. It is assumed to be unconformably overlying the younger limestone in the Doumena Fault Block due to thrusting during the Alpine Orogeny (Cretaceous – Miocene), which severely deformed the basement units, in addition to later erosion and weathering.

Deformation is visible as fractures and folds, and it have made it difficult to do any measurements on the units. The degree of deformation varies a lot throughout the study area, and one can observe that some outcrops show linear features while others have been folded more than 90° (Figure 20). The radiolarite chert does not fiz when one apply Hydrochloric acid 15%, it is not possible to scratch with a nail (Ohm's hardness > 4) and clasts in the sediments often appear as sub angular in outcrops throughout the Doumena Fault Block. This agrees with previous work by Degnan and Robertson (1998), which have interpreted that the radiolarite chert represent a silica rich deep water depositional environment below the CCD (Carbonate Compensation Depth). Both the radiolarite and the limestone represent deep water facies formed in the Pindos Ocean, which later have been uplifted up to 1700m above MASL (Mean average sea level) during the Alpine orogeny

Figure 19: Banded red radiolarite interbedded with minor silt and claystones.

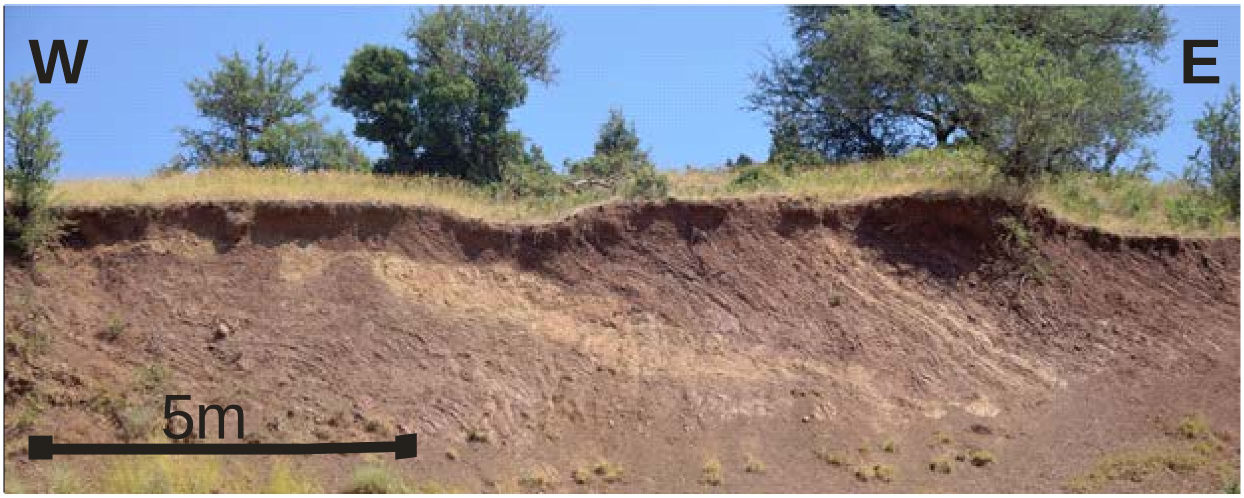


Figure 20: Finer sediments trapped within thrusted and deformed finely layered radiolarite chert.

Basement is exposed at many locations in the Doumena Fault Block. Basement outcrops described below are marked on the map with their corresponding number to show their location (Figure 21). From this point and forward basement will be used as a general term for Pindos carbonate, while it will be specified when one describe the red radiolarite chert.

1. Sediments truncate against basement highs at several localities. The basement highs can generally be described as subtle features on the topographic slope. However, the basement high located west of Vilivina village is much larger and represent a pronounced change in the topography with almost 40 m higher altitude compared to the nearby topography.
2. Klokos mountain is mainly composed of basement, and it's highest peak mark the westernmost extent of the Doumena Fault Block in this thesis. Klokos mountain stands out with more than 500m of relief compared to the west of the study area, and it act partly as a wind gap preventing sediments in the Seliounas river from reaching the Doumena Fault Block.
3. Most of the basement close to the Doumena Fault is covered by alluvial or colluvial fans. However, basement outcrops can be located close to Doumena, Platinotissa and Valta village in the form of recent avalanches. The sediment cover provided by the fans decrease gradually from East to West, and one can notice a significant reduction in sediment cover across the Kerinites river (proportional increase in basement outcrops).
4. Red radiolarite chert can be observed at three different locations. The two largest outcrops of red radiolarite is located East of Vilivina village, while a smaller outcrop is located West of Valta village close to the Doumena Fault.

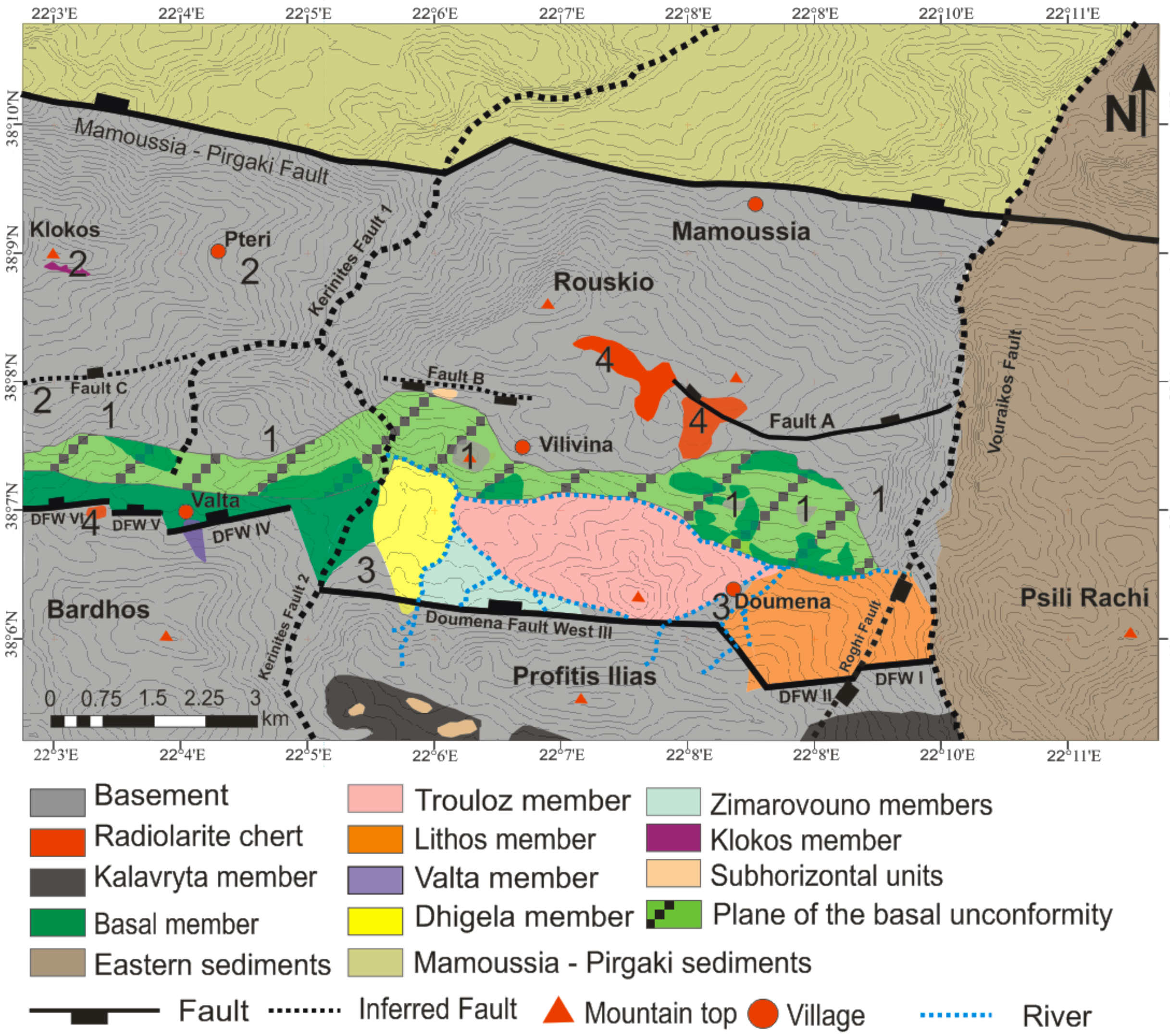


Figure 21: Map of the Doumena Fault Block. The locations of the different basement outccrops described on this and the previous page are marked on the map. Nr 1. Basement highs on the uplifted hanging wall of the Doumena Fault Block. 2. Klokos Mountain. 3. Avalanche deposits. 4. Location of radiolarite chert.

4.2 Syn rift deposits

4.2.1 Kalavryta member - Kalavryta and Kerpini Fault Block

Figure 22: Showing the subangular clasts and the chaotic nature of the Kalavryta member.

The Kalavryta member lie unconformably above the basement in both the Kalavryta and Kerpini Fault Blocks (black unit in Figure 16) . Several outcrops in close vicinity to the Kerpini and Doumena Fault in the Kerpini Fault Block were studied in order to understand the evolution of the Kerpini Fault Block. This unit is important for this study since it could extend into the Doumena Fault Block.

The Kalavryta member studied in the Kerpini Fault Block consist of polymictic cobble sized conglomerates with occasional thin sandstone to pebble conglomerate lenses. Fine conglomerate beds show channel like characteristics, and display coarse to pebbly grains. The conglomerate clasts generally fine northwards from the Kerpini Fault toward Profitis Ilias, with clasts sizes that range from cobbles to boulders.

Bedding and bedding contacts are poorly defined, chaotic, and only a few outcrops show indications of bed boundaries made up by a trend of larger clasts. Sorting is poor and the clasts are sub rounded to sub angular. The conglomerate is clast supported to the south close to the Kerpini Fault, and more matrix supported to the north.

Limestone is the dominant clast type, in addition to sandstone and chert clasts. The limestone clasts are sub angular to sub rounded, and show both high and low sphericity, while sandstone clasts are abundant, highly spherical and rounded. Chert clasts are generally sub angular and show low sphericity.

Based on the poor sorting and the sandstone lenses this unit have been interpreted to be an alluvial fan with some interspersed braided fluvial deposits.

4.2.2 Basal member – Doumena Fault Block

Figure 23: Clast supported conglomerate overlying thinly bedded sandstone. The figure display the well bedded stratigraphic units which show a sharp boundary between different energy regimes.

The Basal member sits directly on top of the basement in the Doumena Fault Block, and is the oldest unit in the Doumena Fault Block. The unit is located on the immediate hanging wall of the Doumena Fault, and it is stretching from Vouraikos Valley in the East to Klokos Mountain in the west (green unit in Figure 16).

The fresh surface of the conglomerate appear to be light to dark grey, while the fresh surface of the sandstone is light beige to orange. The weathered surface of the unit is generally orange to grey. An average clast size is difficult to determine due to the nature of this unit. However, clasts size range from pebble to cobbles for the polymicitic conglomerates, while the sandstones are very coarse. Bedding and bedding contacts are well defined and the contact with the basement can be regarded as the plane of the basal unconformity that can be viewed over large distances. Thickness of the conglomerate beds range from 0.5 to 2 m and the thickness of the sandstone range from several centimetres to 30 cm. The conglomerate clasts are moderately to well sorted and are sub rounded to well rounded. The contact between the sandstones and the conglomerates is sharp, and internal boundaries within the clast-supported conglomerate that can be described as both gradual and sharp erosive, indicating deposition in a high energy environment.

Limestone is the dominant clast type with chert and occasional few sandstone clasts. The clasts generally display both low and high sphericity and are moderately to well sorted. A regional trend can be seen regarding the sphericity and sorting of the clasts that seem to increase from west (Klokos Mountain) to east (Vouraikos Valley). Based on the sorting, the morphology of the clasts and the sharp erosive contact this unit have been interpreted as deposits from an alluvial fan where a significant braided fluvial deposits can be found, probably originating from stream flows. where the sandstones have been interpreted as coarse grained fluvial channel fill.

Dip angle and dip direction measurements were made at exposed locations throughout the area. Nonetheless, the unit appear only in patches on the immediate uplifted hanging wall of the Doumena Fault Block. A general SW dip direction toward the Doumena Fault is measured, and the dip angles vary between 22° - 30° across the entire area. The unconformable contact between the basement and the unit can generally be viewed as a planar plane that make up the plane of the basal unconformity.

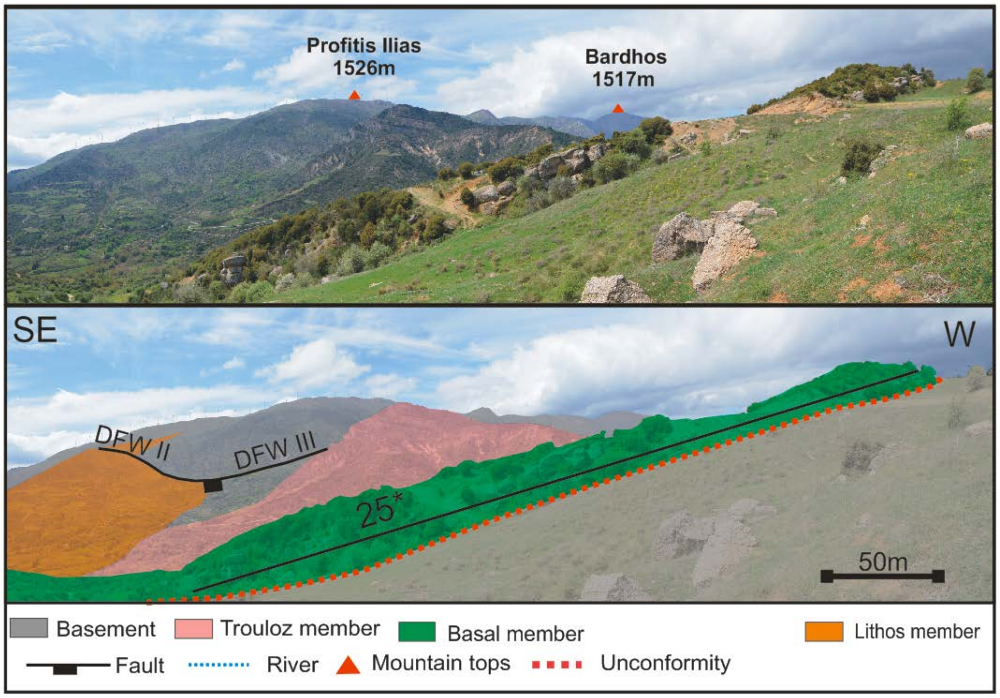


Figure 24: Display the sub parallel to parallel relationship the Basal member have with the basement. Abbreviations: DFW = Doumena Fault West.

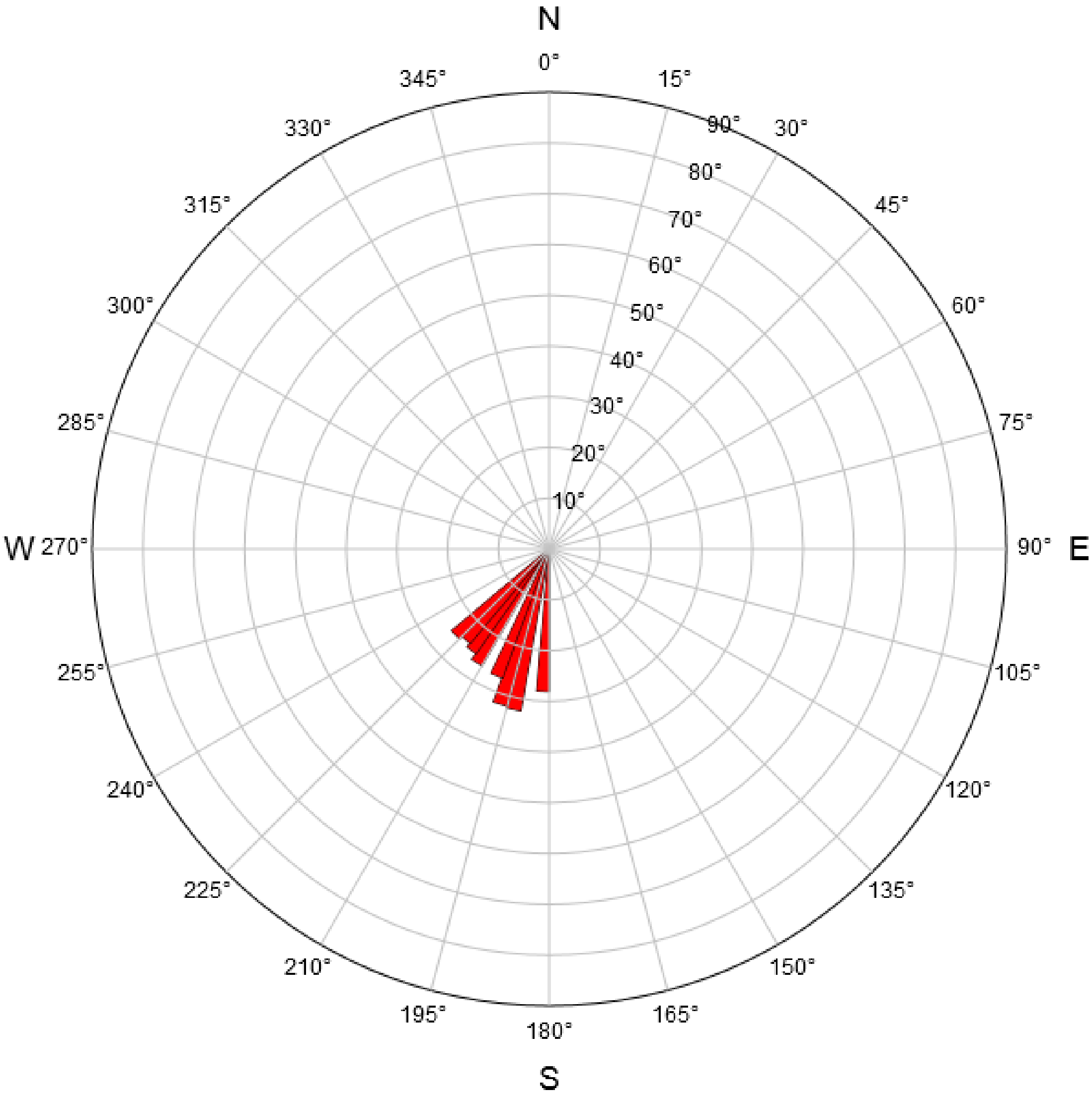


Figure 25: Showing the measured dip angle and dip directions for the Basal member.

4.2.3 Shale – Doumena Fault Block

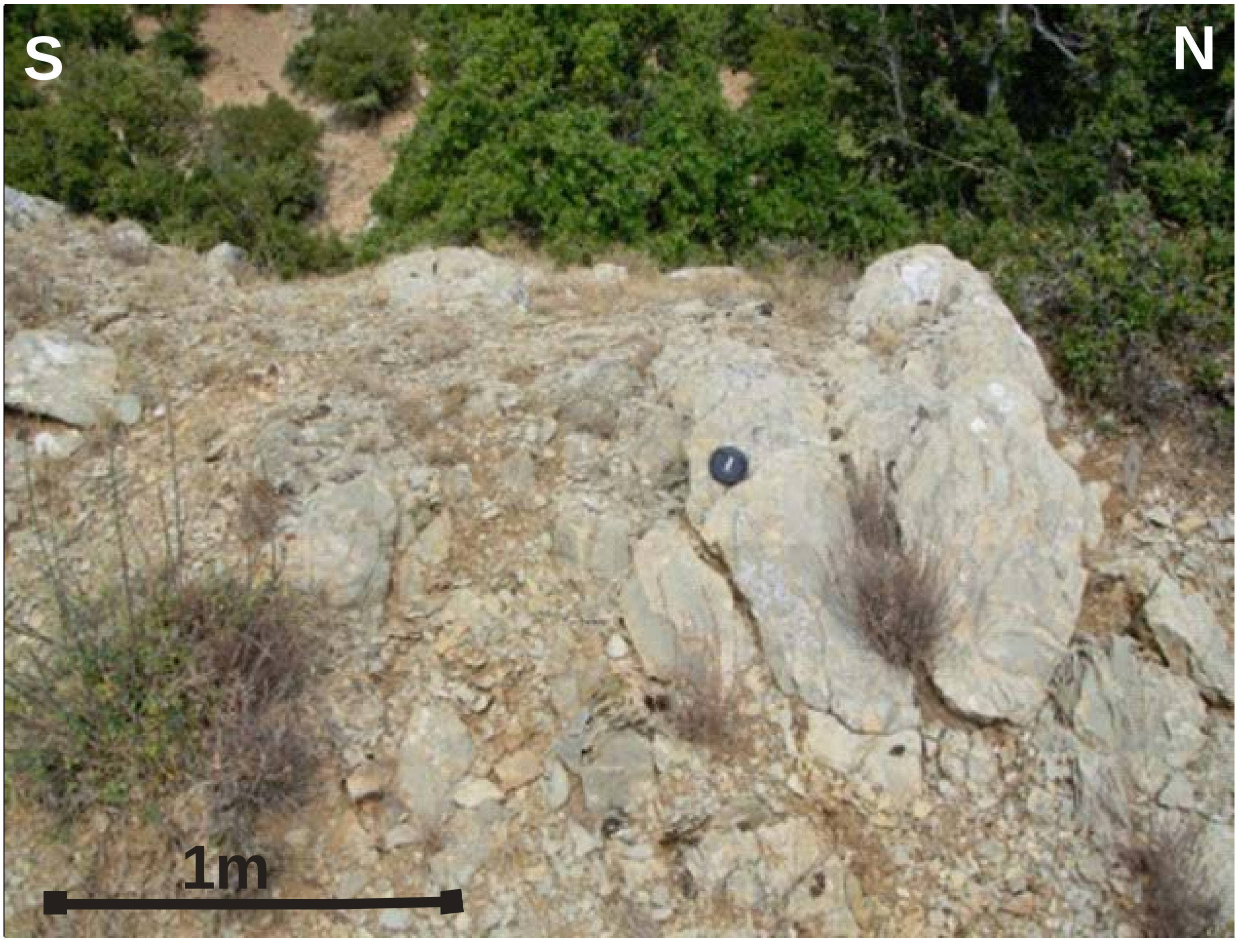


Figure 26: Grey shale located close to Valta village.

The Shale is located at the westernmost end of the Doumena Fault IV, south of Valta village in the Doumena Fault Block (location is shown with arrow in Figure 16). The outcrop is limited in extent, and it covers an area of 5 x 10 m. The fresh surface of the shale is light grey in colour. It consist of laminated planar beds that range from 0.5 - 2 cm in thickness with uniform\homogenous texture and composition. True thickness of the whole unit is estimated to approximately 6- 8m, and the contact between this unit and the basement is parallel and sharp. Bedding planes seem to contain a number of joints with unknown depth, and it was not possible to do any confident dip angle and dip direction measurements for this unit. It is uncertain whether the shale is derived from the basement or have been deposited as finer fluvial channel fill in the form of overbank and floodplain deposits. The location of the shale

4.2.4 Breccia - Doumena Fault Block

Figure 27: Breccia in situ. This outcrop is located in the Klokos Mountains.

The Breccia have been located within one outcrop in the Klokos Mountain close to the Western Boundary of the study area. The small outcrop is situated at an altitude of 1052m and covers an area if 6 x 6 m (location is shown with arrow in figure 16).

The fresh surface of this unit is light grey to grey, while the weathered surface of the unit is light brown to dark red in colour.

The average clast size fine upward from medium cobble to large pebbles. Bedding and bedding contacts are well defined, and the clasts are angular to very angular clasts. Sorting is poor, and the thickness of the planar beds range from 20 – 50 cm. The breccia is monomictic and contain only limestone clasts with low sphericity derived from the basement. Dip angle and dip direction was measured to 04° / 10° for this unit.

Other units situated in the Doumena Fault Block located close to the Doumena fault, display similar bedding and clast size. However, the clasts in those beds are less angular and have been interpreted as talus deposits related to distinct stratigraphic units.

4.2.5 Sub-horizontal units - Doumena Fault Block

Sub-horizontal units are defined as sediments that have a dip angle of 10° > X . Sub-horizontal units within the Kalavryta and Kerpini Fault blocks have previously been studied in detail by Stuvland (2015). The sub-horizontal units are important because they represent an anomaly with regard to timing of deposition and fault evolution. They are assumed to be syn rift and they are located high up on uplifted flanks of fault blocks throughout the Northern Peloponnese.

The two sub-horizontal units observed in the Doumena Fault Block have not been studied before and they will therefore be given a general description (Figure 28).

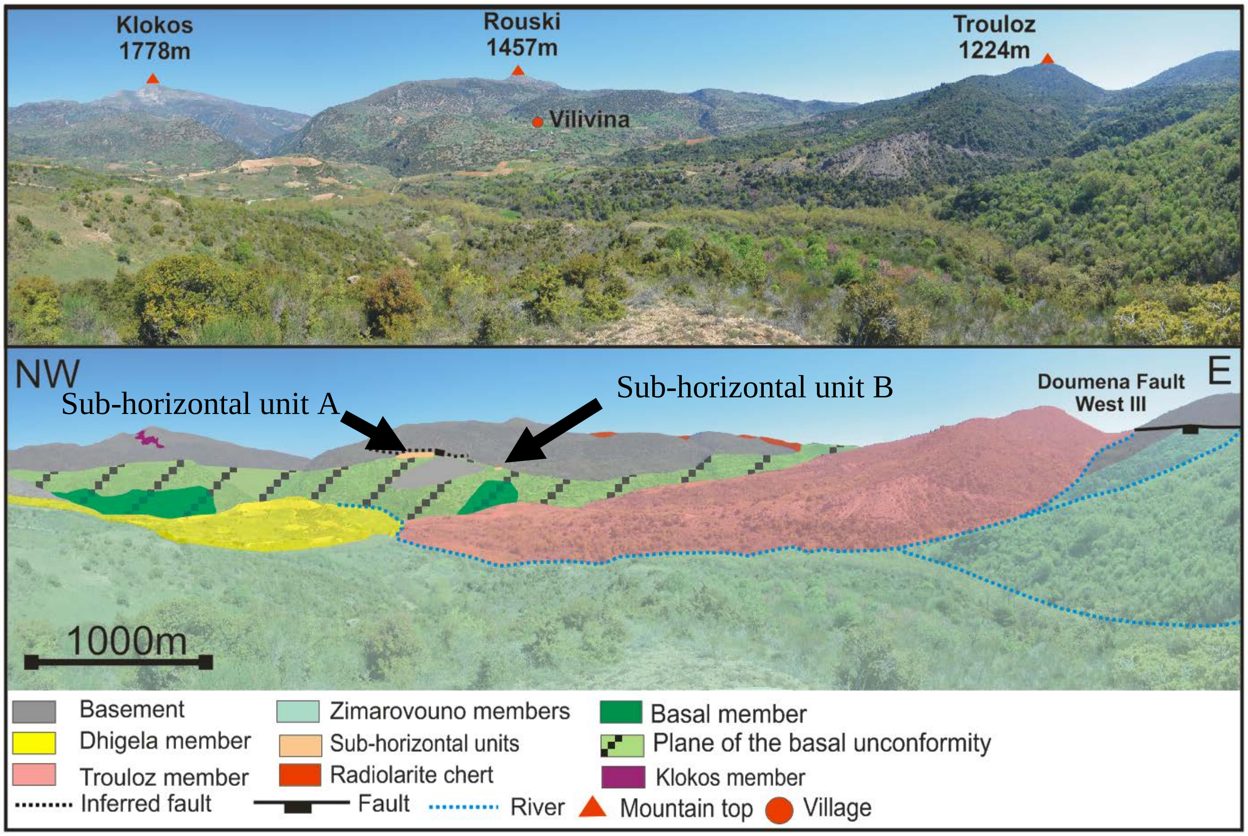


Figure 28: Showing the location of the sub-horizontal units. The large sub-horizontal unit located close to Fault C is sub horizontal unit A. Sub-horizontal unit B is located close Vilivina village.

4.2.6.1 Sub-horizontal unit A - Doumena Fault Block

Unit A is located approximately 1km NW of Vilivina village, at an altitude of ~990 MASL. The outcrop stretches 240m west – east and approximately 30-60m south -north. The thickness of the vertical section range from 1 - 4 m, increasing to northeast- East. The unit consists of interbedded conglomerate and sandstone that appear to onlap the basement.

The fresh surface of the conglomerate range from light grey to beige, while the fresh surface of the sandstone appear beige to light brown. The weathered surface of the conglomerate is grey to light brown (Figure 30) and the polymicitic conglomeratic clasts display a gentle normal grading from pebbles to medium cobbles, with an average size of small to medium cobbles.

Bedding and bedding contacts are well defined, with sharp erosive bases that can be traced tens of meters. The thickness of the conglomerate beds range from 10 cm to 1m, while the sandstone beds rarely become thicker than ~2-3 cm. The polymicitic conglomerate is clast supported, moderately to well sorted, and the clasts are sub angular to sub rounded.

Limestone is the dominant clast type, in addition to sandstones and radiolarite chert. Limestone clast display both high and low sphericity, and are sub rounded to rounded. Sandstones are also highly spherical and rounded, contrary to the radiolarite chert that have low sphericity and are sub angular.

Poor exposure due to vegetation observations to the exposed southern side of the outcrop, and to the top of bedding planes. Only a few dip angle and dip direction measurements was taken since this unit is not the focus of this thesis. Dip angle and dip direction was measured to 08°/210°.

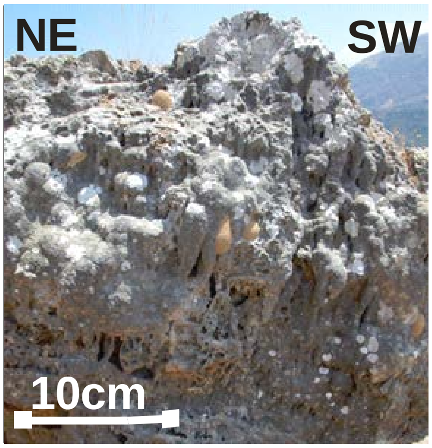


Figure 29: Cemented conglomerate located in sub-horizontal unit A. The cement observed here represent a very local feature within an 0.5 m X 0.5m area. The conglomerate at this exact location is interpreted to have a higher calcite content, which made it cement due to weathering.

Figure 30: Outcrop photo of Sub-horizontal unit A. The photograph is taken at the eastern edge of the unit with the erosive bases. The unit display the same characteristics as they appear in the figure.

4.2.6.2 Sub-horizontal unit B

Sub-horizontal unit B is located approximately 200m West of Vilivina village, at an altitude of 880 MASL (Figure 28). The outcrop is exposed within a 20m long section stretching SW-NE, where the thickness of the vertical section range from 5m - 7m. with and it can only be viewed from southeast towards northwest.

The fresh surface of the polymicitic conglomerate appear light brown and the conglomeratic clasts range from pebble to cobble in size. Bedding and bedding contacts are well defined, planar and the thickness of the conglomerate beds range from 2 - 3m in thickness. The polymicitic conglomerate is clast supported, well sorted and have sub angular to rounded clasts. Limestone is the dominant lithology, in addition to sandstone and chert. The limestone show highly spherical and sub rounded to rounded clasts, whereas the radiolarite chert clasts display low sphericity and are sub angular to sub rounded.

Only a few dip angle and dip directions of this unit was measured due to the size and state of the outcrop. The general area surrounding the outcrop is heavily eroded due to active farm work, and it is not possible to trace the conglomerate in the fields. However, a distinct basement high directly to the west of this outcrop imply that the conglomerate onlap or sit unconformably on the basement, even though the contact is not visible. Dip angle and dip direction was measured to 12°/224°.

Figure 31: Sub horizontal unit B with thick beds and dip toward the South West.

4.2.6.3 Sub-horizontal conglomerate of the Kerpini Fault Block

Most of the conglomerate in the Kerpini Fault Block are coarser than the ones found in the Doumena Fault Block (Sand unit in Figure 16). But, the sub horizontal units located by Stuvland (2015) to the North west in the Kerpini Fault Block contain a lot of fine sediments. According to Stuvland (2015), the sub horizontal units in the Kerpini Fault Block are deposits from fluvial incision by the Kerinites river which was deposited late or post Kerpini Fault. They represent the last phase of deposition from the fluvial drainage network. Therefore, sub horizontal units in the Kerpini Fault block had to be studied, since the sub-horizontal units could be the source of similar fine-grained deposits in the Doumena Fault Block. A general description for sub-horizontal units located toward the northwest in the Kerpini Fault Block is noted below .

The sub horizontal units consist of conglomerate interbedded with sandstone beds. These sandstone beds range from 50cm - 20cm in thickness, while the conglomeratic beds range from 1-2 m in thickness. The conglomerates are generally clast supported, and at certain locations imbricated. Clasts range from small cobbles to medium cobbles (64mm – 100mm) in size and they are generally sub angular to rounded, with the majority of the clasts being sub rounded to well rounded. Dip angle and dip direction measurements show a dip angle and dip direction of 07°/65°.

Figure 32: This display an outcrop of typical sub horizontal units of the Kerpini Fault Block. The photograph is taken toward the East close to the Western Flank of Profitis Ilias.

4.2.6 Eastern sediments - Eastern Doumena Fault Block

The Eastern sediments are located east of Vouraikos valley in the Eastern Doumena Fault Block, and outside the area of focus in this thesis. Nonetheless, they should be mentioned since the sediments are located in close proximity to the Doumena Fault Block (Western), and display sediments with significantly different thickness, facies, texture. The Eastern sediments display the three informal lithostratigraphic units that make up the Lower Group according to the stratigraphic defined by Ford et al. (2013) in Figure 2. It is important to understand the timing and depositional of the eastern sediments in order to get a good understanding of the general evolution of the area and how the depositional environment have changed over time.

The three lithostratigraphic units (Figure 7) have been deposited in three different sequences of deposition and can be described from old (1) to young (3).

1. Basal alluvial conglomerates with thick beds and coarse grains that have been tilted toward the south with a dip angle of ~12°. The unit onlap the paleoslope on the northern fault crest, and it make up the basal unconformity in the Eastern Doumena Fault Block.
2. Fluvial conglomerates characterized by orange to red siltstones, pebbly sandstones and thick, coarse conglomerate bodies with erosive bases up to 10m in thickness..
3. Alluvial conglomerates that are very thickly bedded, clast supported conglomerate that have little to no internal structure.

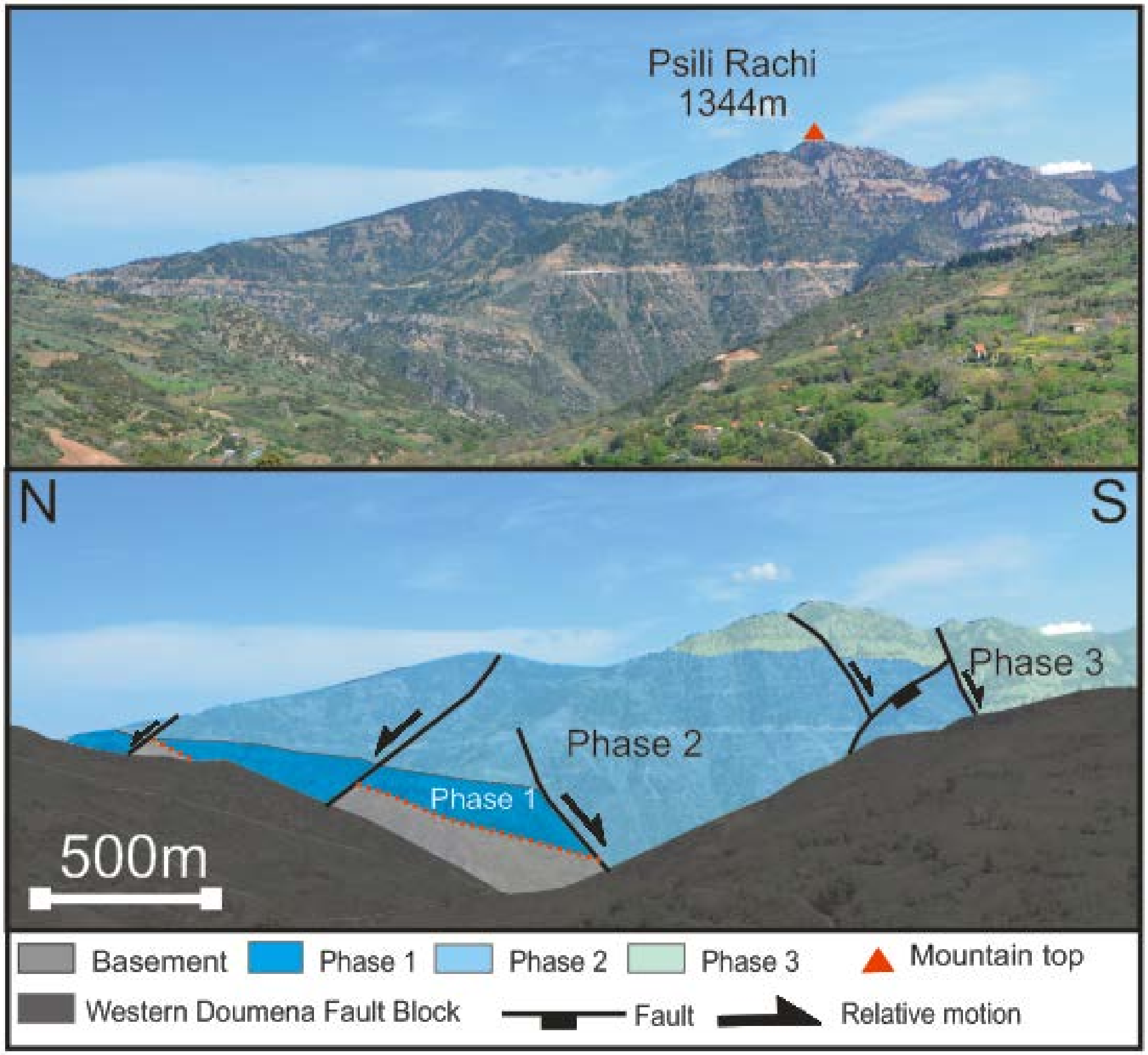


Figure 33: Display the three informal stratigraphic units across the Vouraikos Valley. Note the thick packages of sediments that reach up to 1344m.

Chapter 5: Alluvial and Colluvial fan units

The following stratigraphic units, have been interpreted to be either colluvial or alluvial fan units. They were named according to the nearest mountaintop, river or village.

5.1 Klokos member

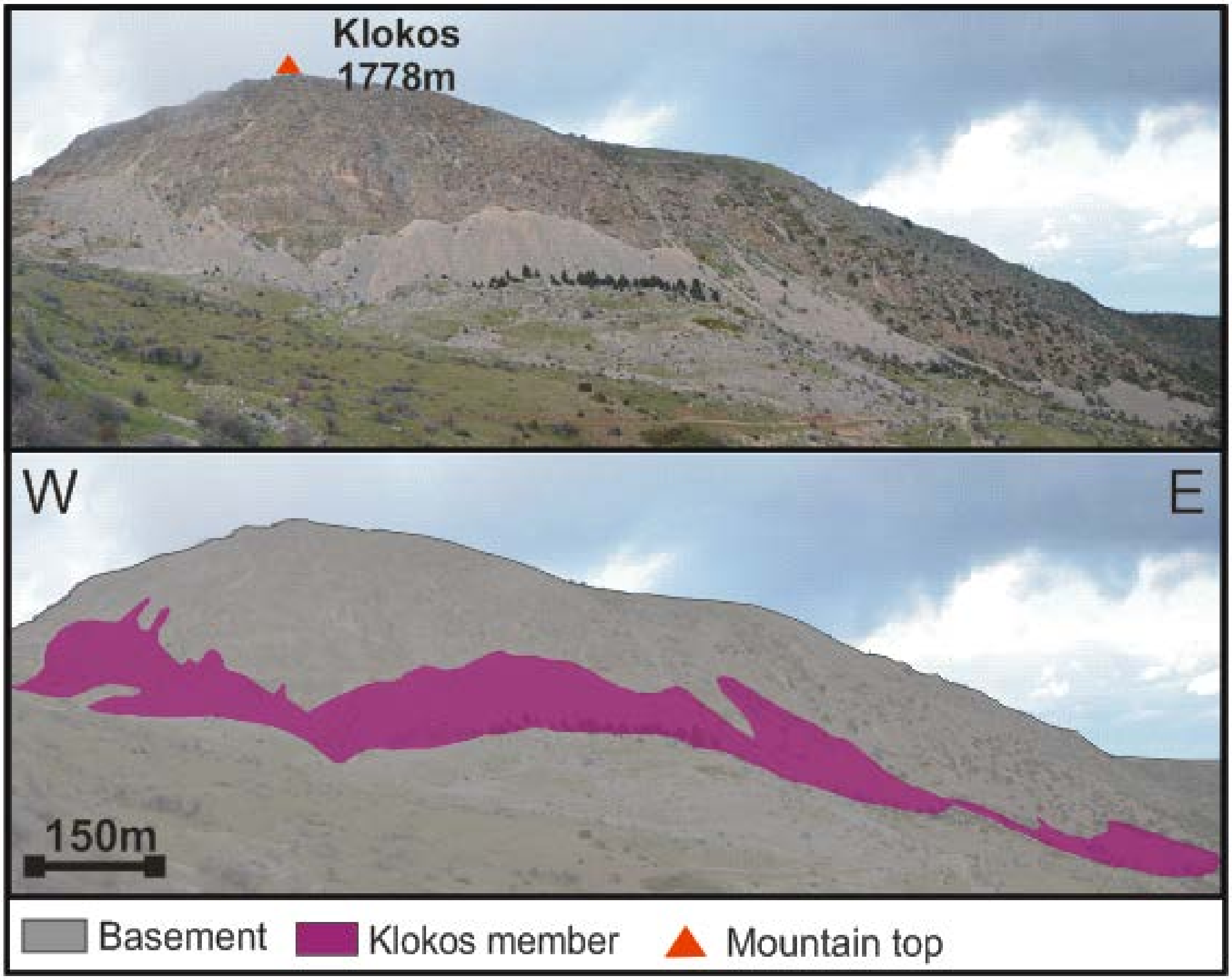


Figure 34: Showing the Klokos member directly below the Klokos mountaintop at 1778 m.

The Klokos member is located directly below the Klokos mountaintop (1778m) at an altitude of ~1670 - 1340m (highest apex to lowest toe). This is directly south of the westernmost and highest point of the study area. Klokos Mountain makes up a significant topographic horst structure together with Skepasto Mountain (Kerpini Fault Block) in the northwestern Peloponnese, and it is a feature that dominates the western part of the Doumena Fault Block.

The Klokos member covers an area of ~0.11km^2 that stretch approximately 1.2 - 1.5 km in length east-west and 50 - 150m south-north. It is made up of many small fan units, which have their individual apex located high up on the mountain slope. The measured dip angle of the depositonal slope of the fans range from 40 – 60°. Dip angle generally decrease from the apex of the fans (~ 50°) toward the toe, and the dip angle at the toe is approximately 25°-35°. Each of the fans generally have a cone shape, a plain view length of approximately 100-250m and a width of 50 - 100m.

The fresh surface of the unit is light grey to grey, and the unit is made up of clast supported breccia that have clasts which range from pebble to boulders in size. Several large boulders greater than 1m at the longest axis can be observed at the base of the fan, and the clasts fine north up the slope.

Bedding and bedding contacts are poorly defined, unlithified, and only linear trends are visible at a few locations where the bedding seem to have an openwork texture, and larger clasts are partly supported by finer sediments. Sorting is poor and the clasts are angular to very angular. The clasts are monomictic and are made up of limestone that is derived from the basement.

Based on the on the upslope fining nature of the clasts, the chaotic bedding, the steep depositional slope and the location of the fans the Klokos member have been classified as colluvial fan deposits. These are deposits that have been deposited primarily by gravitational processes. The topographic configuration of the Klokos Mountains in combination with weathering have formed an array of colluvial fans that have been coalescing into aprons. The morphology of the clasts (openwork texture) in the fans imply that the main depositional process where rockfall, with little to no water content.

5.2 Lithos member

The Lithos member is the easternmost unit in the Doumena Fault Block. It is located directly east of Doumena Village, and it is bounded by the Doumena Fault II to the South, the immediate uplifted hanging wall of the Doumena Fault to the north, the river Vouraikos to the east and the Trouloz member in combination with a basement high toward the west. The Lithos member has previously been studied by Kolbeinsen (2013). It will therefore only be given a short description in addition to some structural observations that were not mentioned in her master thesis. The Lithos member was interpreted to be a large debris and water flow dominated colluvial fan which is still active today (Figure 35).

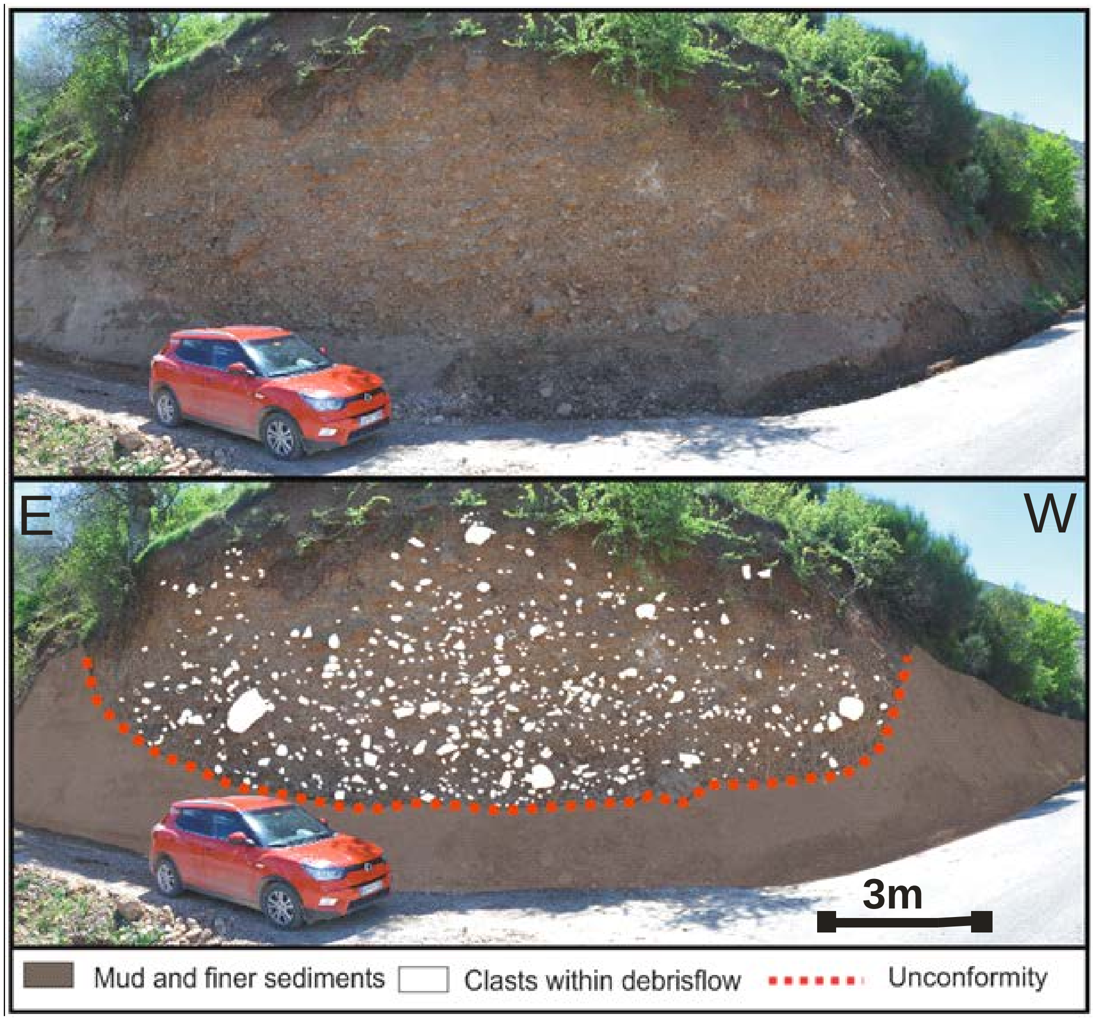


Figure 35: Display a debris flow of poorly sorted conglomerate, which have incised into finer facies in the Lithos member. The debris flow have clasts that contain blocks of conglomerate up to 50 cm in length.

The Lithos member is a cone shaped unit located high up on the mountain slope. The member covers an area of 3.2 km^2, and it extends in width and length from the apex beyond the immediate base of the mountain. The plain view radius is approximately 1.4 km measured from the apex toward the toe and the fan stretches at the most ~1.75 km Southwest - Northeast. The apex of the fan is located at approximately ~1200 m while the toe is located at ~ 600 m. Based on dip angle and dip direction measurements on stratified and cemented beds, one can measure that the dip angle of the depositional slope to the west of the apex range from 20 - 30°, while the depositional slope near the toe range from 10-15°.

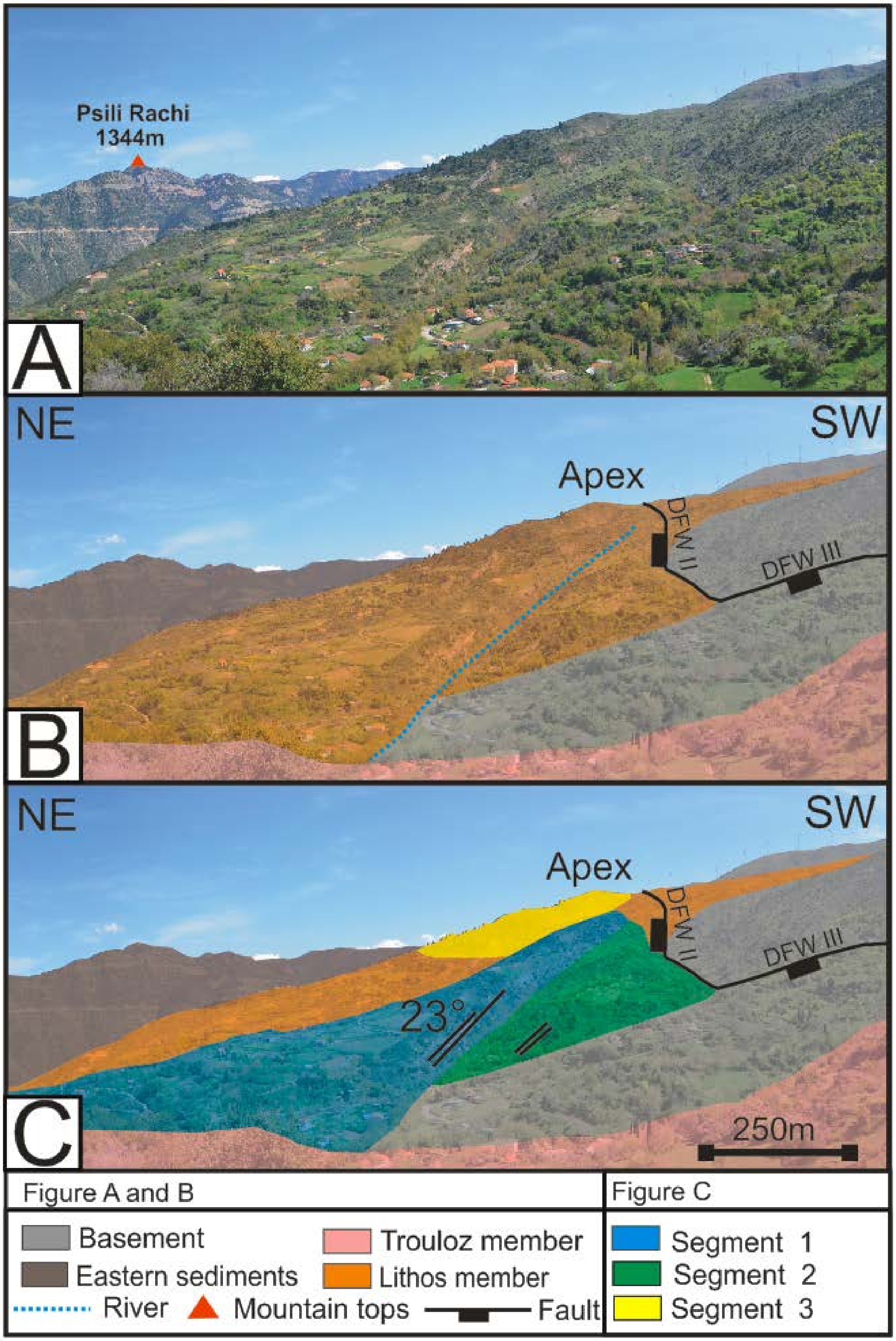


Figure 36: Figure A display an uniterprted image of the Lithos member. Figure B display an interpreted image of the Lithos member and the bounding units. Figure C highlight the three segments that was previousley undescribed within the Lithos member. DFW denote the Doumena Fault West.

5.2.1 Segment 1

Segment 1 (Green colour, Figure 36) is comprised of poorly consolidated to moderately sorted conglomerate interbedded with a few sandstone beds. Clasts range from pebble to cobble in size, and the clasts generally fine toward the northwest and west. The fresh surface of the conglomerate is light brown to dark brown, while the weathered surface of the conglomerate is dark brown to dark grey. Bedding and bedding contacts of both the conglomerate and the sandstones are well defined and planar. The thickness of the conglomerate range from 1 - 2 m in thickness, while the thickness of the sandstone range from 10-30cm. The conglomerate is poorly to moderately well sorted, and the clasts are sub angular to sub rounded. The contact between the sandstone and the conglomerate is sharp with lateral truncation of sandstone beds that indicate erosive surfaces. Imbrications are observed in some beds and the unit can be observed with an average dip angle of 23-25° toward northwest. The exposure of the outcrop is limited to the western and eastern side of this unit which stretch for over 600 m SE-NW.

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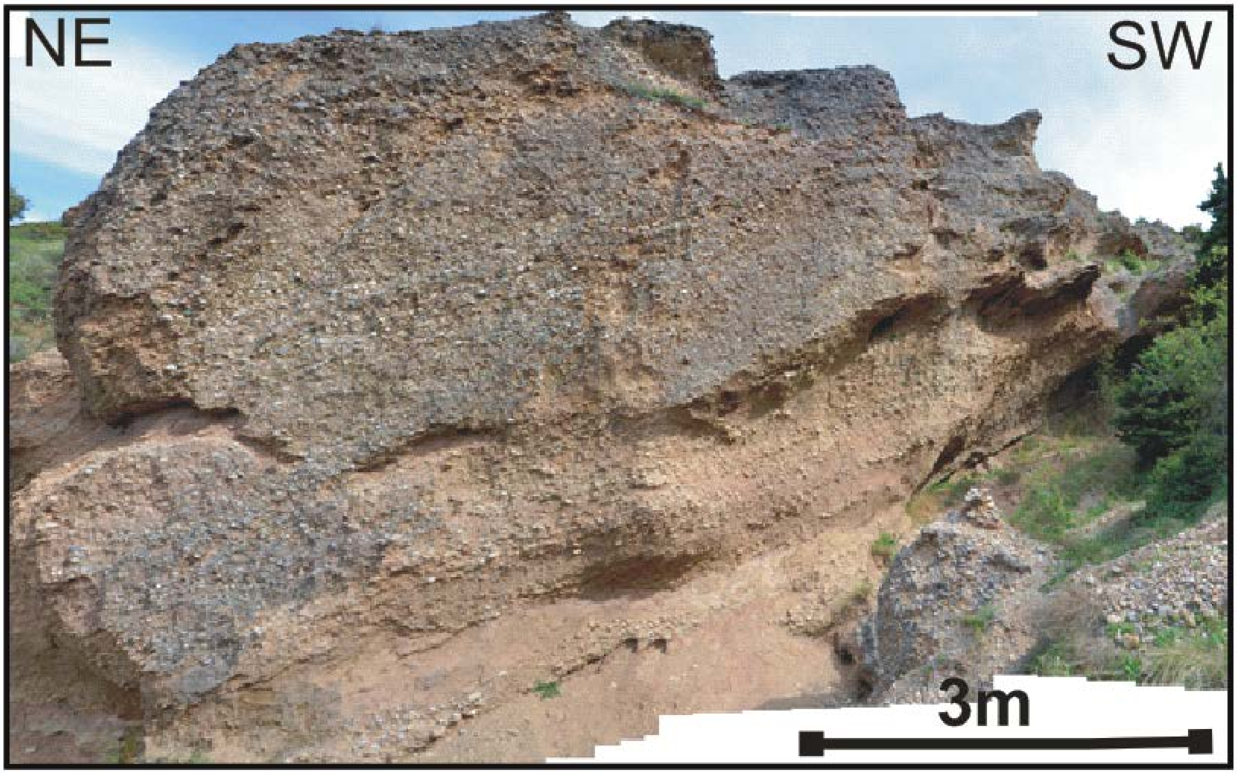


Figure 37: Showing the thick consolidated conglomerate, which are interbedded with sandstone beds.

5.2.2 Segment 2

Segment 2 (Blue colour, Figure 36) is comprised of consolidated, poorly to moderately sorted conglomerate interbedded with sandstone beds. The fresh surface of the conglomerate is grey to dark grey, while the weathered surface appear light brown to brown. Clasts range from pebbles to small cobble, and the clasts become smaller toward the northwest. Bedding and bedding contacts of the conglomerate is well defined, planar and range from 20cm – 40 cm in thickness. The unit has been measured to have a dip angle that ranges from 26 - 28° with dip directions toward the NW. Exposure of the outcrop is mainly limited to the western part of this unit in addition to a small part that can be observed from the east. The unit stretches for approximately 400 m southeast -northwest.

Figure 38: Showing the interbedded conglomerate and sandstones in segment B. Scale is relevant forleft part of the image.

5.2.3 Segment 3

Segment 3 (yellow colour, Figure 36) is located close to the apex of the Lithos). It is dipping southwest towards the fault with a dip of about 8-10°. It is grey, and it contain poorly sorted and sub angular to sub rounded conglomerates. Bedding and bedding contacts are well defined and one can trace the contacts throughout the outcrop. The conglomerates show a few interbedded sandstone layers up to 40 cm in thickness that show normal grading (Figure 39(B)). The sandstone beds suggest that it was deposited in a fluvial low energy environment, or alluvial with significant channels.

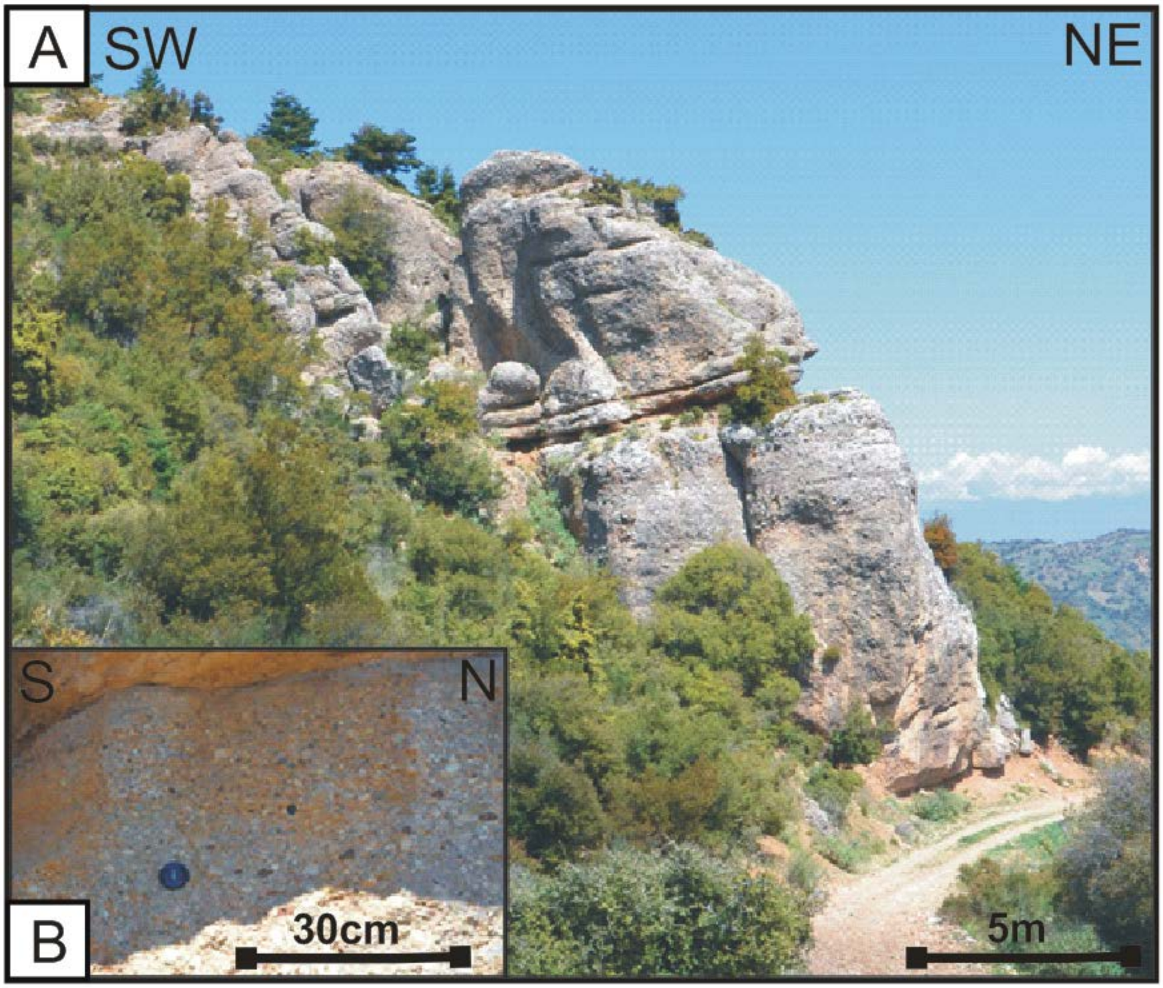


Figure 39: Figure A display the conglomerate structure that dip toward the fault. Figure B display the fining upward sequence of the sandstone.

5.2.4. Summary

Based on the observations above this member can generally be classified as a debrisflow dominated colluvial fan. This is based on the position of the apex high up on the mountain slope and the large immature clasts that can be observed near the toe at the fan. However, this unit has several indications of alluvial fan deposition close to the apex where thick sandstone beds with normal grading are up to 40 cm thick. The thick package of conglomerate and sandstone in segment 3 are inclined toward the fault and it represent a depositional system, that is not present today. It suggest that the colluvial fan might has been an alluvial fan prior to rotation with a stable sediment supply. Henceforth, the sediment supply might have been cut off due to faulting and uplift of the fault block, where the fan went from fluvial to gravitational control.

5.3 Valta Member

The Valta member is named due to its close proximity to Valta village. It covers approximately 0.2 km^2 and the fan stretches approximately 700m SSW-NNE from Bardhos Mountain toward Valta village. The fan has a lobate shape and the width of the fan rarely exceed 100m. The main outcrop of the fan is located on a small foot plain of the Bardhos mountain slope, close to the presumed apex at an altitude of 1060m.

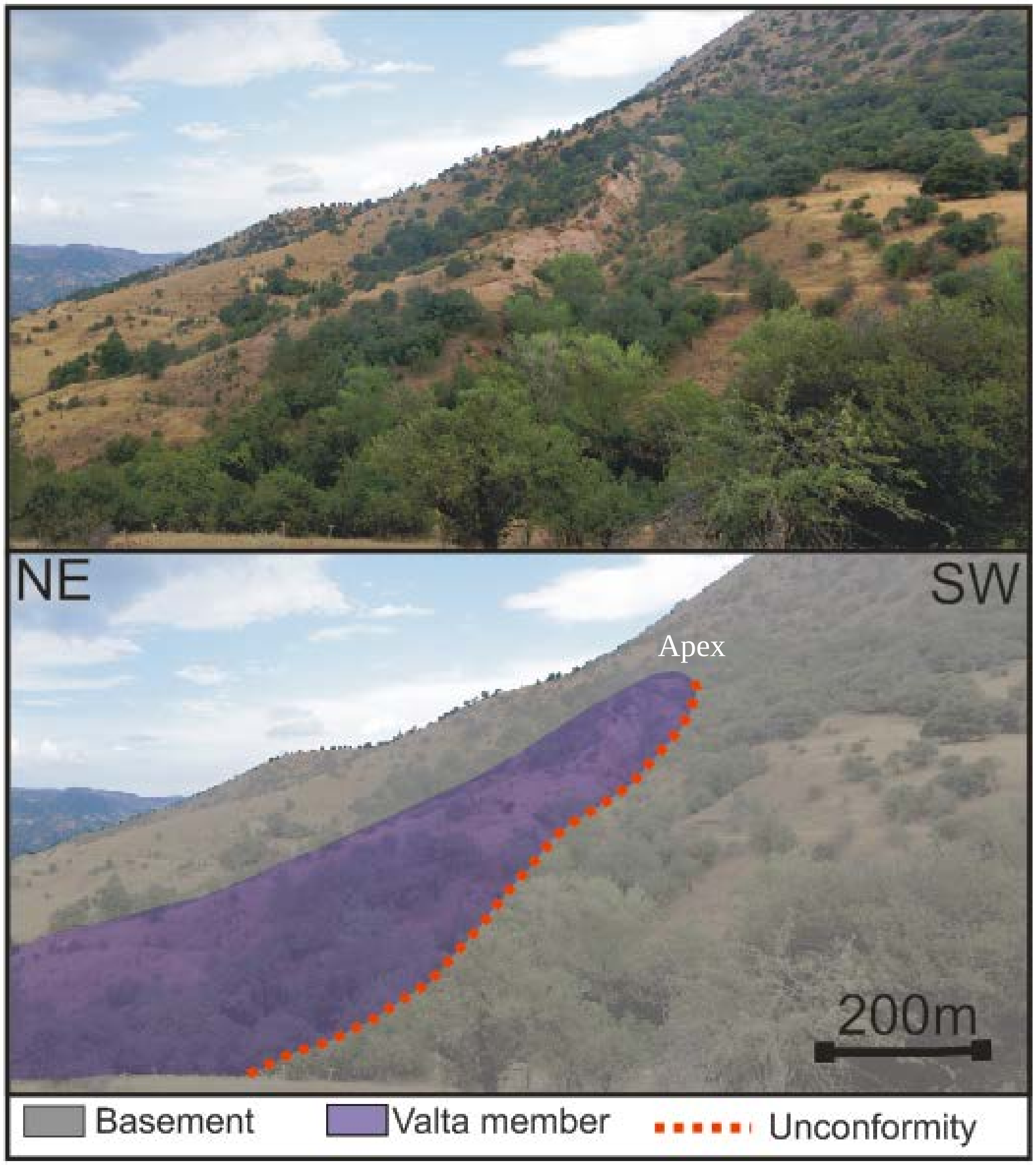


Figure 40: Showing the large outcrop of the lobate Valta member close to the apex.

The outcrop can only be viewed from west towards east, and it stretches approximately 210m North-South. The dip angle and dip direction at the apex range from 11-13°/164, whereas the depositional slope at the toe is not exposed. The fan is composed of sandstones and conglomerates that show a gentle inverse grading throughout the vertical succession. The conglomerate is poorly sorted, and the clasts are sub-angular to sub-rounded. Bedding and bedding contacts are well defined and they can be traced laterally across the outcrop. The conglomeratic beds range from 0.2 to 2m in thickness and clasts range from cobble to large pebbles in size. The maximum length of the longest axis of the clast is approximately 16 cm, with a mean length of about 10 cm. The conglomerate is clast supported most proximal and monomictic. Clasts seem to become finer distal, and it became matrix supported proportional with the increase in sand content. This can be seen from an outcrop above the apex, on the mountain slope or here interpreted as talus slope, where one can observe clast supported, angular and well stratified conglomerate. These deposits have been interpreted to represent talus slope deposits. This fan have been interpreted to be an alluvial fan. This is due to the coarsening upward sequence of the alluvial fan, the fining downslope nature of the sediments and it’s location where the main body of the fan is situated at a terrace\ foot plain.

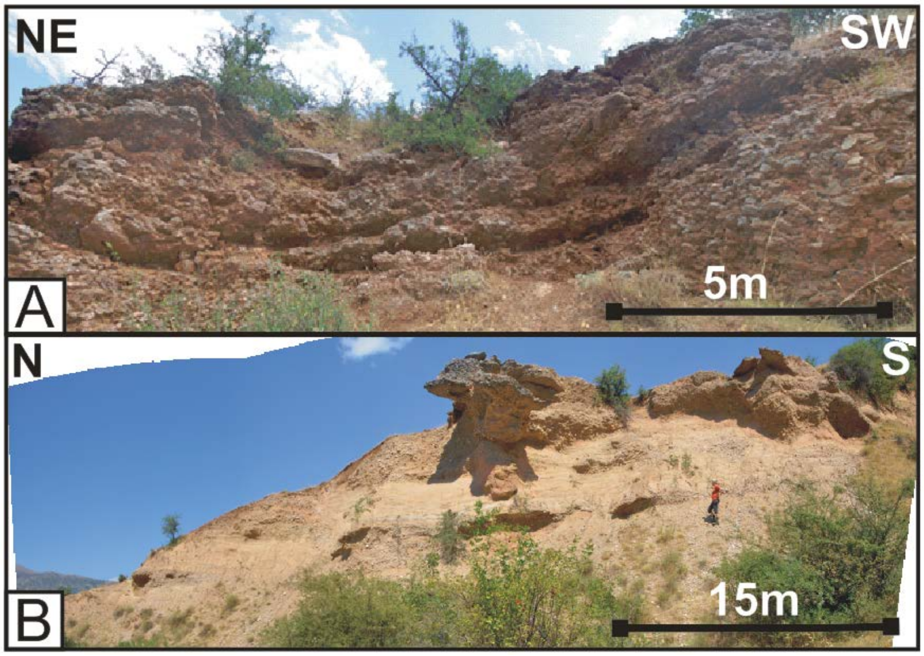


Figure 41: Figure A showing the interpreted talus slope deposits. Figure B show the large outcrop with interbedded conglomerate and sandstone.

5.4 Zimarovouno members

The Zimarovouno members are named after the closest mountain peak and it has three members that have very little outcrop exposure. This unit is characterised by the relatively fine grained nature of the sediments that has proven to be excellent soil for vegetation. These units infills the gap between the two main fans in this study the Trouloz and Dhigela members. The description for each of these three members are based on a very limmited number of outcrops, and one will therefore give a rough general description of the units.

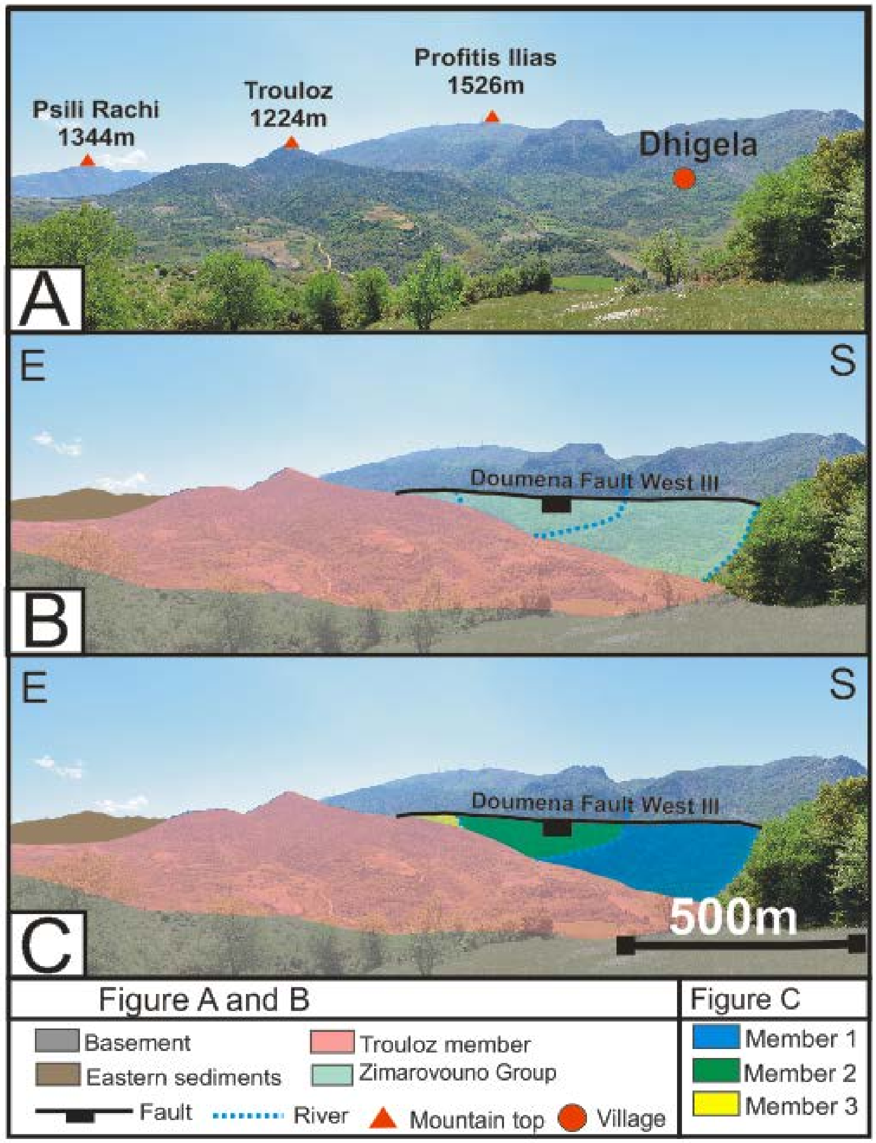


Figure 42: Showing the location of the zimarovouno members.

5.4.1 Zimarovouno member 1

Zimarovouno member 1 (Figure 42) covers an area of 0.5 km^2 and it stretches 961m m from SSW-NNE. The width of the unit range from 350 -550 m (south – north), and it is bounded by the Dhigela member to the west, the Trouloz member to the north, the Doumena Fault to the South, and the second Zimarovouno member to the east.

The unit dips toward the north - northeast, and the dip angle range change from 25° toward 18° utmost north in the unit. This unit has three different exposed outcrops, and it is the best exposed unit of the three members. Figure 43 show the outcrop located farthest to the south. It depicts the coarsest part of a vertical succession where the clast size ranges from 3 to 12 cm, with a mean clast size of 4 cm. The conglomerate fine rapidly towards the north, and this can be seen from Figure 43 were the conglomerate is clast supported.   100m west of this outcrop, recent erosion from a river have exposed a channel oriented east – west. Whether this correspond to a regional trend is unclear, however the position is noted in Figure 17.

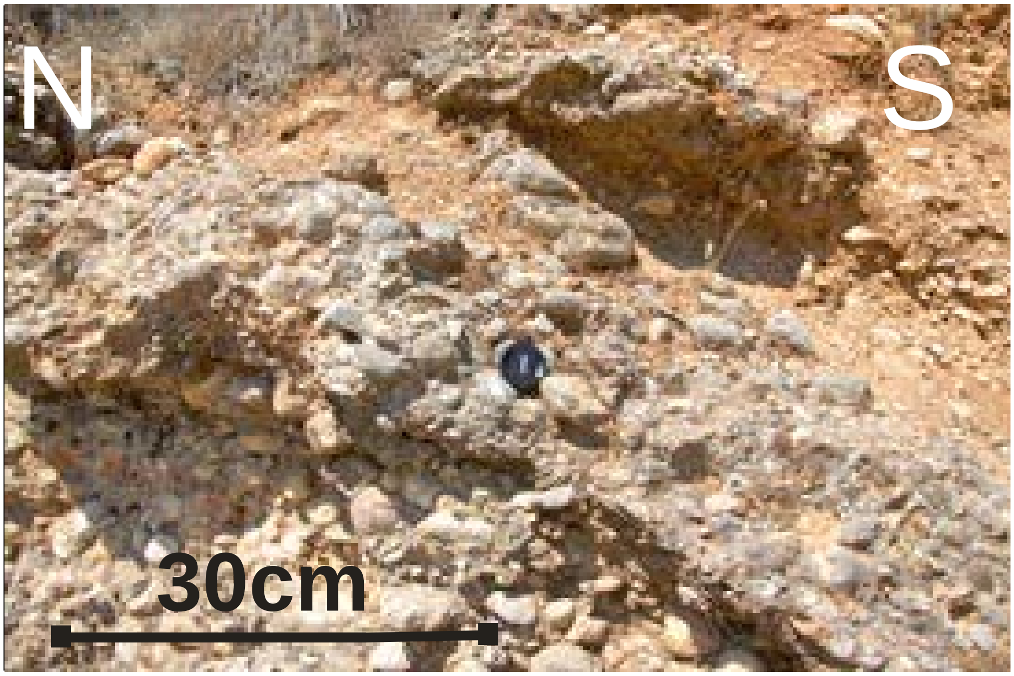


Figure 43: Show clast supported conglomerates. The conglomerate is clastsupported and the conglomerate range from 3 – 12 cm in length along the longest axis, and the dip angle and dip direction of this unit was recorded as ~25°\26°

Figure 44: Further NNE towards the distal part of this unit one can observe very fine layers of interbedded sandstone, clay and matrix dominated conglomerate. The unit show a dip angle of 18° to northeast.

Figure 45: Outcrop with a channel oriented east – west within Zimarovouno member 1.

5.4.2 Zimarovouno member 2

The second Zimarovouno unit covers an area of 0.5 km^2 and it stretches 600m m from SSE-NNW. It is bounded by Zimarovouno member 1 to the west, the Trouloz member to the north, the Doumena Fault III to the South, and the third Zimarovouno member to the east. The width of the unit ranges from 1150 -550 m (South – North), and it is controlled by two rivers that run between the different Zimarovouno members. The unit dips toward the NNW, and the dip angle is approximately 22°. Two outcrops represent this unit, where one is impossible to get an image of due to a very steep slope. The unit is comprised of clast supported conglomerate interbedded with sandstone, that seem to become finer toward the north and coarser toward the south toward the Doumena Fault. This is based on the relative increase in vegetation toward the north, and relative decrease in vegetation toward the south. Dip angle and dip direction measured on this unit was 22* toward NE.

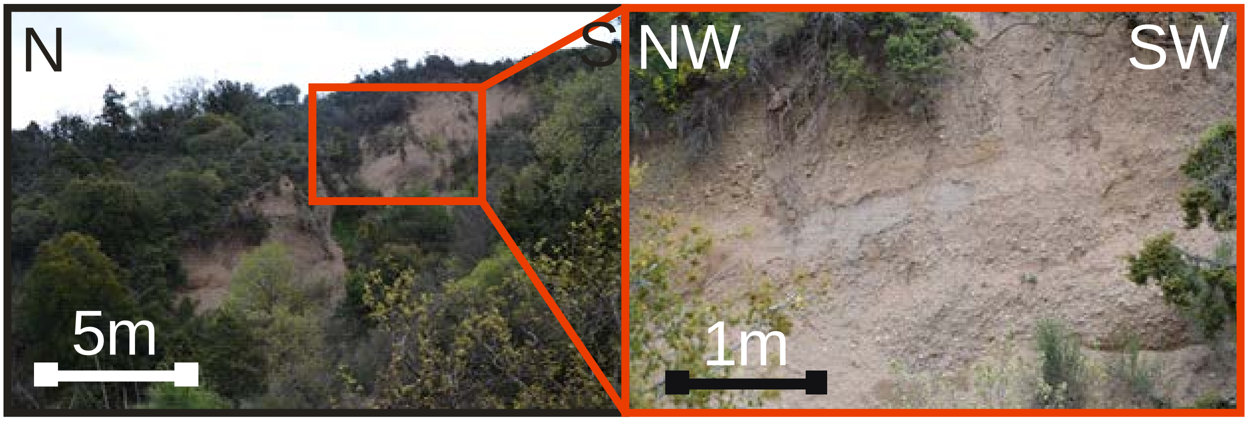


Figure 46: Showing the location of the finer deposits of Zimarovouno member 2.

5.4.3 Zimarovouno member 3

The third Zimarovouno unit covers an area of 0.27 km^2 and it stretches 650m m from SSE-NNW. It is bounded by the first Zimarovouno member to the west, the Trouloz member to the north, the Doumena Fault to the South, and the third Zimarovouno member to the east. The width of the unit range from 670 -580 m (South – North), and it is controlled by two rivers which run at each side of the member. The unit have been measured to have a dip angle of 12° and a dip direction toward the NW, This unit is only represented by two outcrops with uncertain relation. The most proximal outcrop represent clast supported conglomerate which range from pebble to cobble in size.

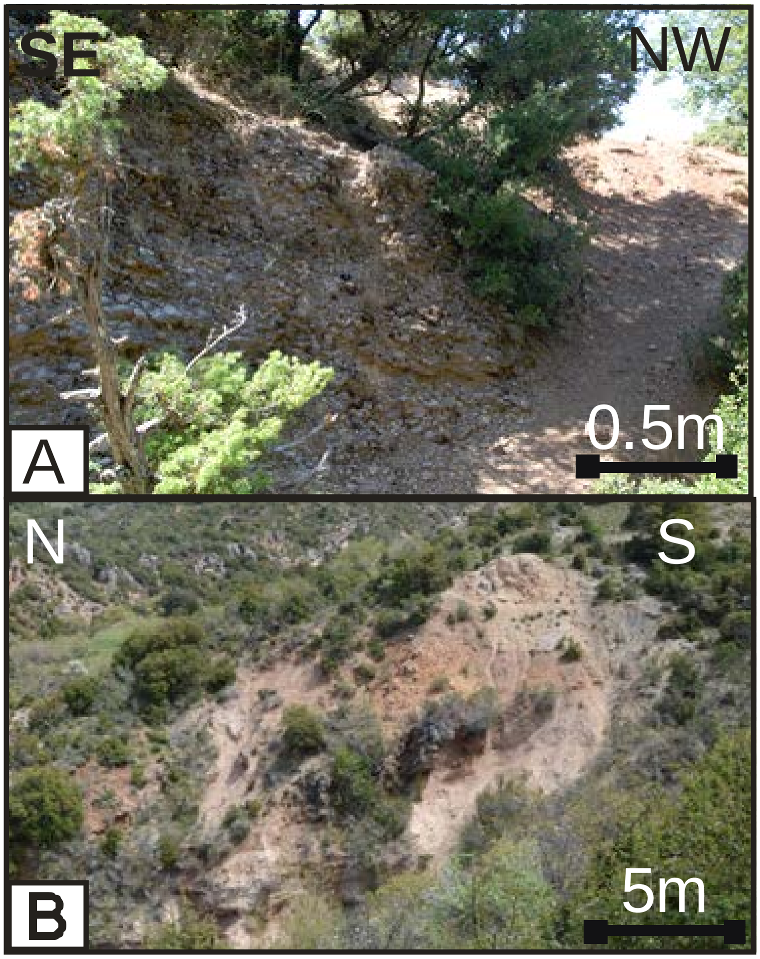


Figure 47: Figure A show the proximal clastsupported rocks of the Zimarouvouna member. Figure B show the distal part of the same member where one have interbedded sandstone and conglomerate.

5.5 Dhigela member

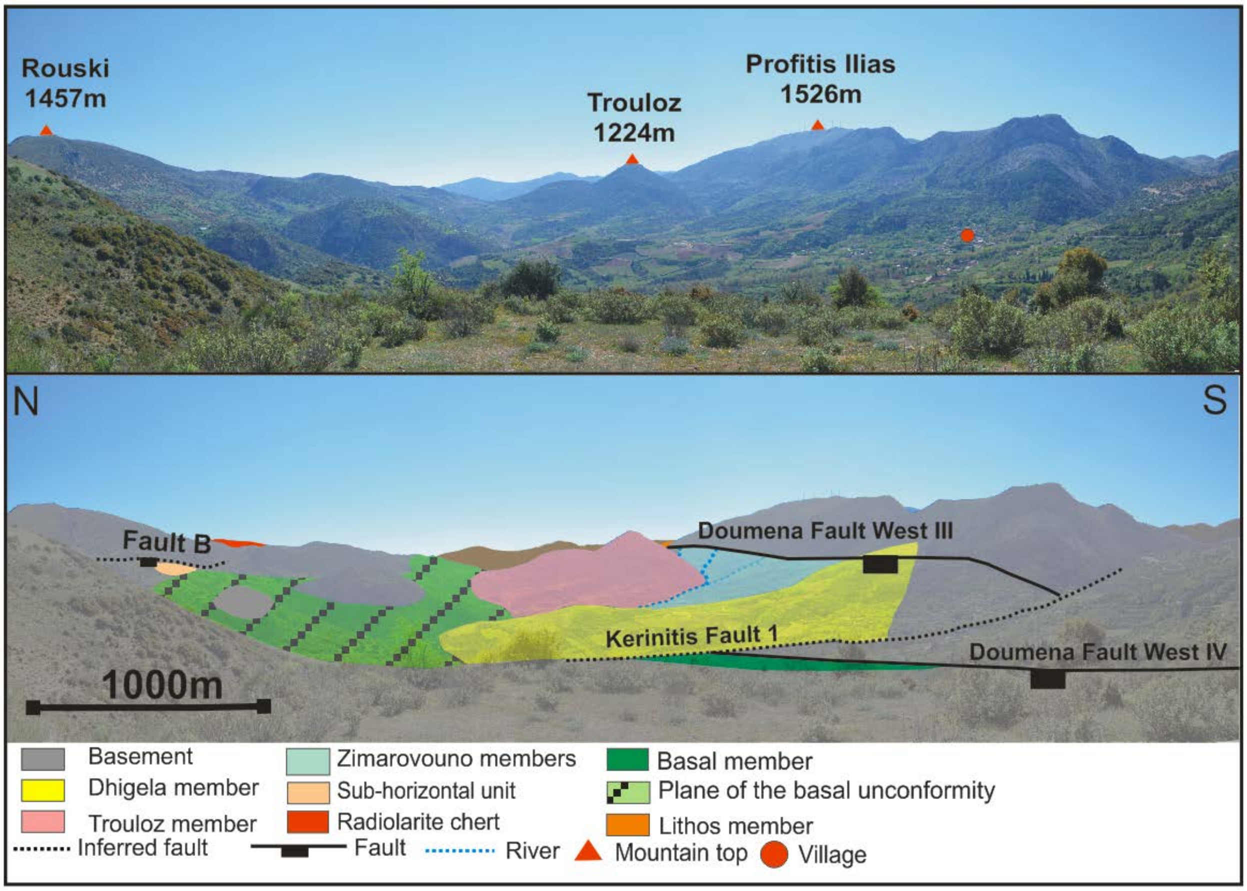


Figure 48: Showing the relationship between the Dhigela member(yellow) and the other units of the Doumena Fault Block.

The Dhigela member is bounded by the Kerinitis River (and the Basal member) to the west, the immediate hanging wall of the Doumena Fault III to the north, the Doumena Fault to the south, the Kerinites river to the West, and the Zimarovouno member 1 in addition to the Trouloz member to the East (Yellow unit, Figure 16). The Dhigela member is generally poorly exposed and the description given below are based on a limited number of outcrops.

The Dhigela member covers an area of ~ 1.21 km^2, and the fan has an elongate lobate form that stretches approximately 1.6 km South – North. The width of the fan generally increase in width from ~230 m at the inferred apex, to 680m at the toe (south to north). The Dhigela member is sourced orthogonal to the Doumena Fault West III, and the apex of the fan is located close to the base of the mountain at an altitude of approximately 900 m. From the highest point of the Dhigela member one can observe that topography indicate that the fan is comprised of a large structure that is suggested to contain a number of lobes. However, significant erosion in addition to vegetation and poorly exposed bedding have made correlation of individual beds very difficult from the upper to lower part of the fan. There is a drop in elevation of more than 230 m from the highest point of the fan to the toe. The elevation and thickness difference toward the southern part of the fault block suggest that there was significant accommodation space in place at the time of deposition and it is suggested here that is might have been attributed to the existence of the inferred Kerinitis Fault.

The outcrops of this unit is mostly located at two locations, a large outcrop at the upper section of the unit, and several small outcrops at the lowermost part of the fan. The description for the unit will be based on those outcrops.

The large outcrop is located close to the apex of the fan stretches for ~350m (south – north). It is only possible to view the outcrop from the west towards the east exhibiting a ~60m vertical succession of interbedded finer layers of conglomerates, siltstones and possibly mudstones. The large outcrop is very steep, and it is not possible to access more than the three first beds for clasts measurements. Therefore, the clasts size measurements and sorting is possibly non-representative for this unit. The unit consist of interbedded conglomerate and sandstone, and the fresh surface of the conglomerate and sandstone of the Dhigela member appear light beige to brown. Clasts range from large cobbles to pebbles and the unit thin toward the north. Several large channels trending NNE- NE can be observed in the large outcrop of the upper zone in the Dhigela member (Figure 49). Bedding and bedding contacts are well defined, tabular and they can be traced for 350m throughout the exposed outcrop. The conglomerate is mainly clast supported, while the sandstone is matrix supported. Sorting of the upper beds is unknown, but it seem from a distance to be moderately well sorted. The clasts at the bottom of the large outcrop are rounded, and highly spherical. Whether this is the case for the whole outcrop is unknown. Generally, bed thicknesses decrease up section and the clasts seem to become smaller.

Figure 49: Display the thick and laterally continuous beds of the Dhigela member.

The outcrops located at the toe are scarce, however due recent excavation some of the outcrops are available (Figure 50). The extent of the outcrops located at the toe rarely exceed 10 m in length and height. It consist of conglomerates that fine into conglomerates interbedded with sandstones at the highest point at the toe.

The fresh surface of the conglomerate is brown to beige, while the sandstone is light beige to yellow. The clasts of the conglomerate range from cobble to pebble, while the sandstone have coarse grains. The conglomerate is mainly clast supported at the lowermost part of the outcrop, but the conglomerate become more matrix supported towards the top where the interbedded conglomerate and sandstone is located.

Bedding and bedding contacts are well defined and tabular, and the conglomerate is poorly to moderately well sorted. The clasts are sub angular at the bottom of the toe, but the roundness generally increases upward along the section indicating increases fluvial energy.

Limited exposure of this unit limit dip and dip directions of this unit. The dip angles and dip directions for this unit is approximately 12 – 14° to the south in the upper zone, before the dip angle decrease to 3-4° in the lower zone.

Based on the, roundness, the moderately well sorted clasts, the location of the fan at the base of the mountain, the general fining upward sequence of the beds at the toe, and the long parallel bedding this fan has been interpreted to be of alluvial origin, with substantial fluvial input.

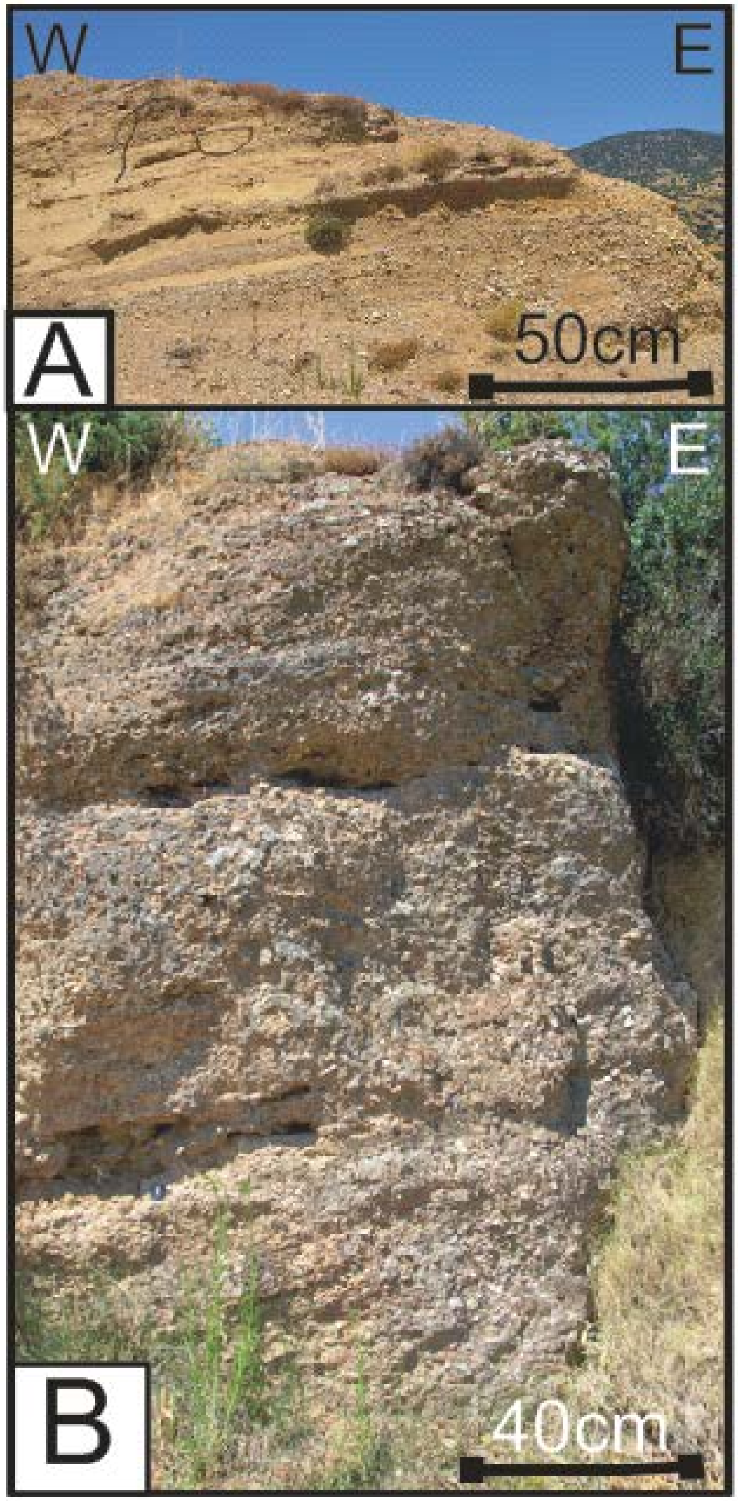


Figure 50: Display the upper (A) and lower (B) beds at the toe of the Dhigela Member. Note the decrease in thickness from the thin upper packages of unit A compared to the thicker and coarser basal beds in figure B.

5.6 Trouloz member

5.6.1 Introduction

The Trouloz member forms the main target of this study, therefore the field observations for this unit are detailed. Facies and facies distribution have been investigated in addition to general texture and grain size, sedimentary structures and paleo current directions. Lateral and vertical facies variations have been described in terms of facies, geometry and texture in addition to fan morphology that have been classified according to Blikra and Nemec (1998). The Trouloz member is located directly west of Doumena Village, in the middle of the Doumena Fault Block. The Doumena Fault and the Zimarovouna Group bound the unit to the south together with the Dhigela member to the West, The Basal member the north, and the Lithos member to the east. The Trouloz member covers an area of ~ 4.5 km^2, and it have a fan shaped form that generally increase in width from 630m to 3.2 km (south- north).

From the highest point of the Trouloz member (Figure 50 , Trouloz 1224 MASL), one can observe and divide the unit into three different lobes. The northern, western and eastern lobes. The plain view length of the fan is approximately 1.7 km from south – north and the length of the lobes varies considerably. The western lobe is much larger than the others stretching ~2.7km toward 305°. While the northern lobe stretches 1.6 km s-NWW and the eastern lobe stretches 1.2 km SW-NE. The fan is sourced orthogonal to the Doumena Fault West III, and it is situated at the base of the mountain. The apex of the fan is located at an altitude of 1224 MASL, where the main dip angle and dip direction of the structure is ~15 ° towards the northwest. The dip angle of the unit changes from north to south, and east to west. Each of the lobes show different dip angles and dip direction. Due to the fine nature of the sediments, vegetation and poor exposed bedding, correlations along individual beds are difficult in the northern and eastern lobe. However, the western lobe, which will be thoroughly investigated with shorter representative logs, have some exposed outcrops. The logs are based on observations and correlation between areas of good and poor rock exposure. There is a drop in elevation of more than 500 m from the presumed apex of the fan towards the lower areas northeast of Dhigela village at the toe of the western lobe. The elevation and thickness decreases towards the western part of the fault block suggest that the depocentre of the Doumena Fault Block is located to the northwest of the Trouloz member. In the following subchapters, the texture and geometry of the Trouloz member will be divided into the Western lobe, the Northern Lobe and the Eastern lobe.

Sedimentological logs

Three different sedimentological logs were made for the Trouloz member. A description regarding lateral and vertical facies changes follow each of the sections that were logged.

Log 1

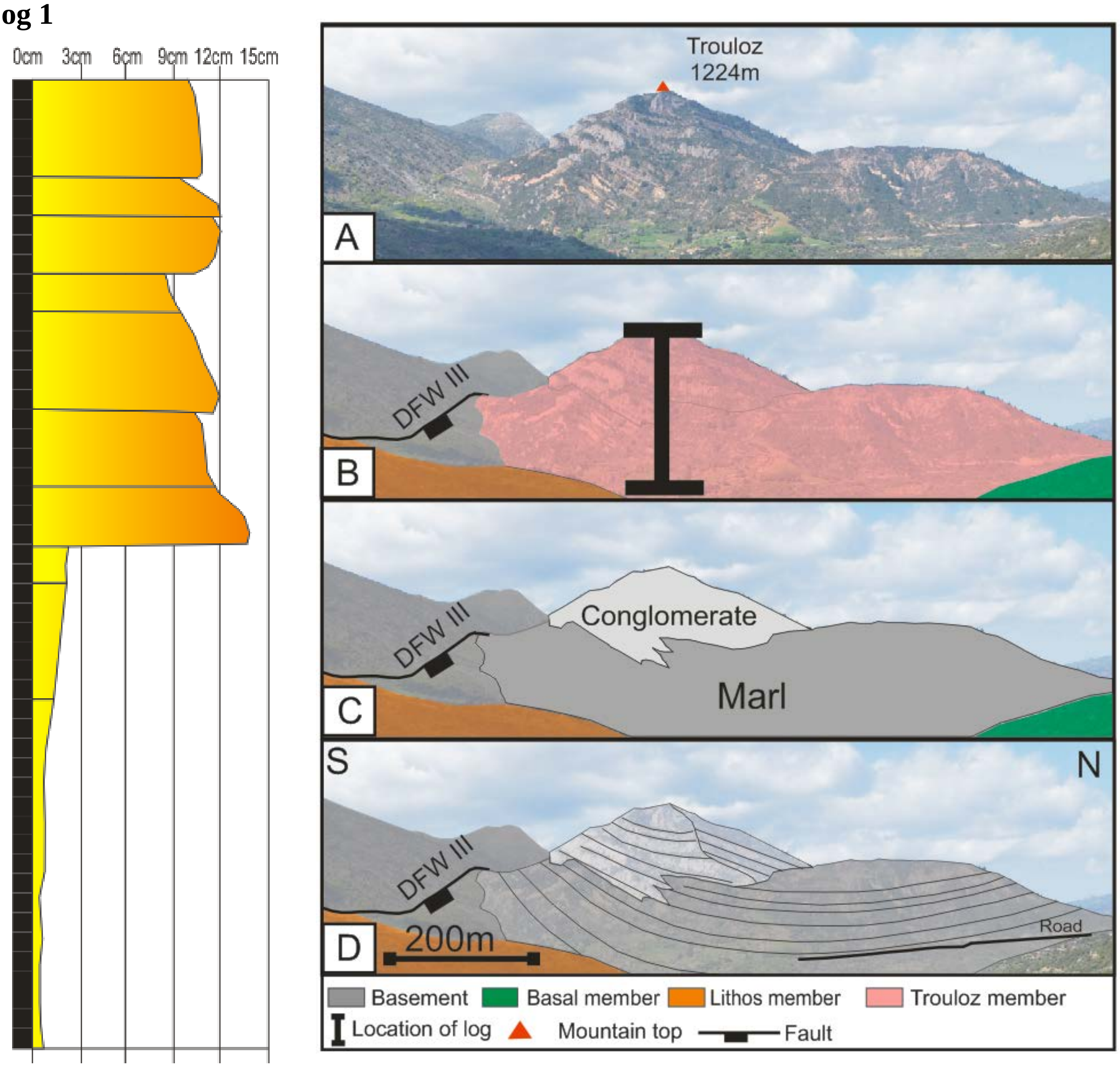


Figure 51: Section 1 display a synthethic lithological log for the entire Trouloz member, in addition to a structural and sedimentological interpretation. Clasts sizes for the conglomerate was measured on the southern side of the Trouloz member, whereas the marl was inspected on from the eastern side of the Trouloz member. Figure A show an uniterpreted image of the Trouloz member. Figure B show the interpreted iamge of the Trouloz member. Figure C display the facies interpretation of the Trouloz member. Figure D show the structural interpretation of the Trouloz member, The Trouloz member have been classified as a gentle monoclinal fold. The geologic log show the huge difference between the marl and the conglomerate-

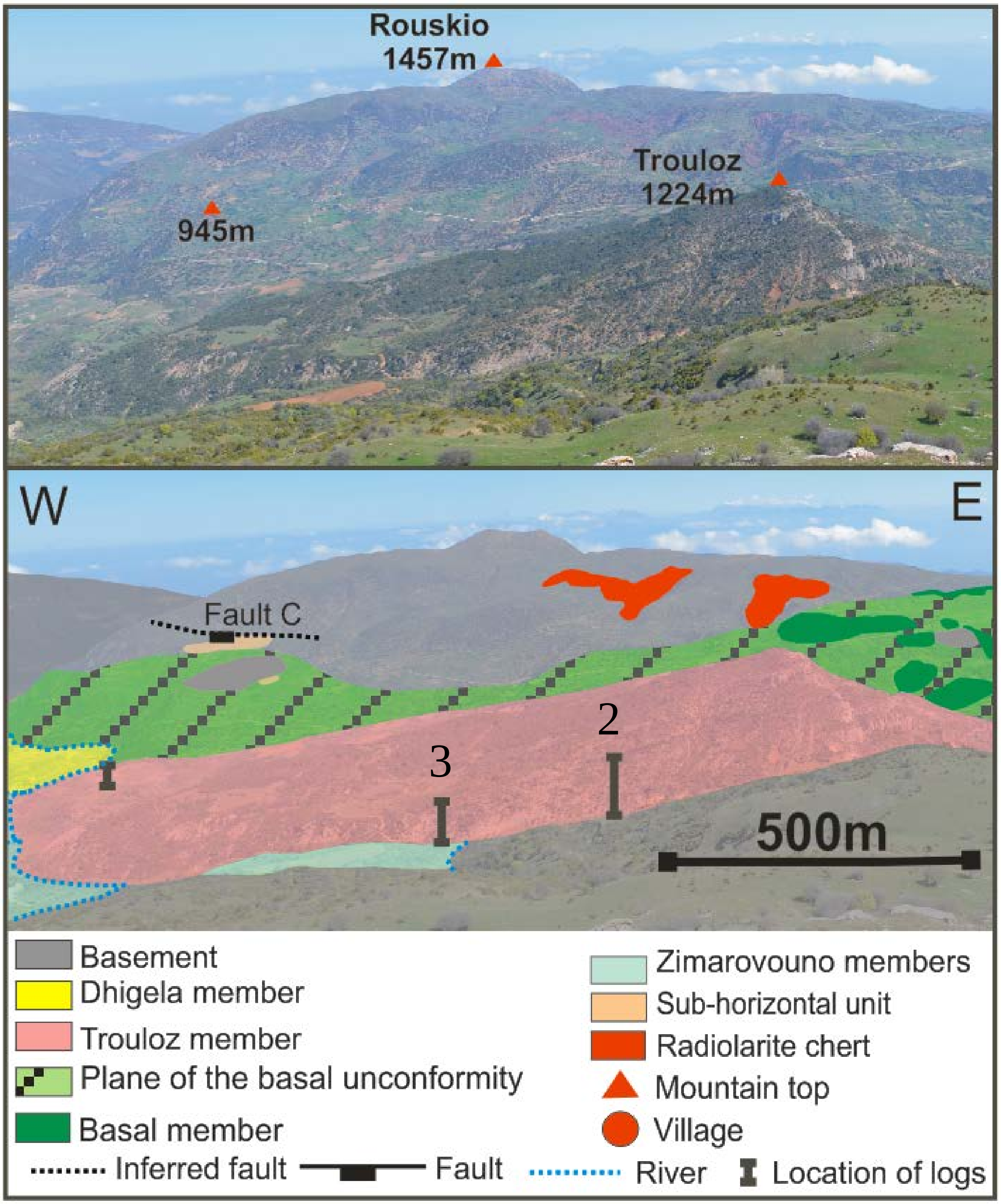


Figure 52: Display the Trouloz member and the location of log nr 2 and 3 that were made on the southern side of the Trouloz member.

Log 2

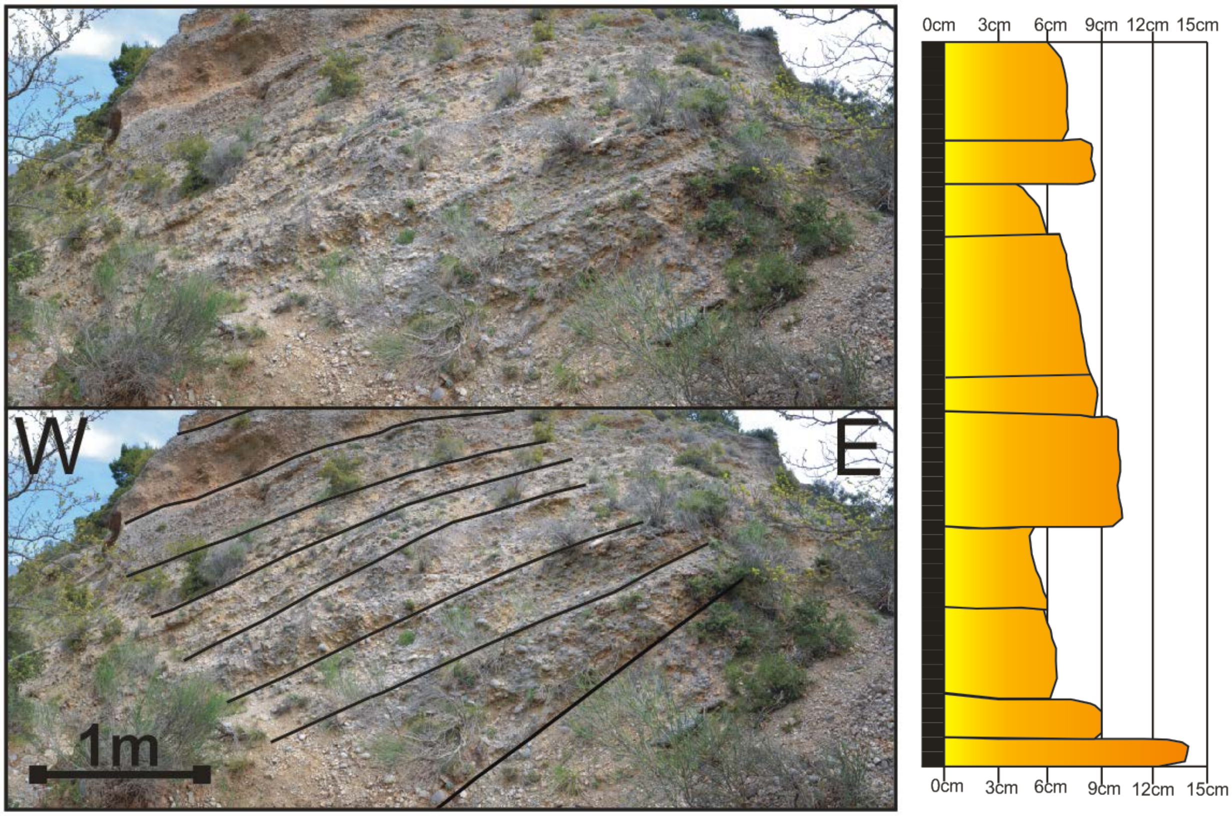


Figure 53: Display the outcrop of log 2.

Location 2:

This outcrop is situated 450m west of the Trouloz peak, on the southern side of the Trouloz member. It represent the first location where beds could be properly differentiated within the larger conglomeratic packages. The outcrop display clast supported beds, that show a rough fining upward sequence. The clasts are sub rounded to rounded and the beds have become more pronounced from East to west. Average clast size range from small to medium cobbles.

Log 3

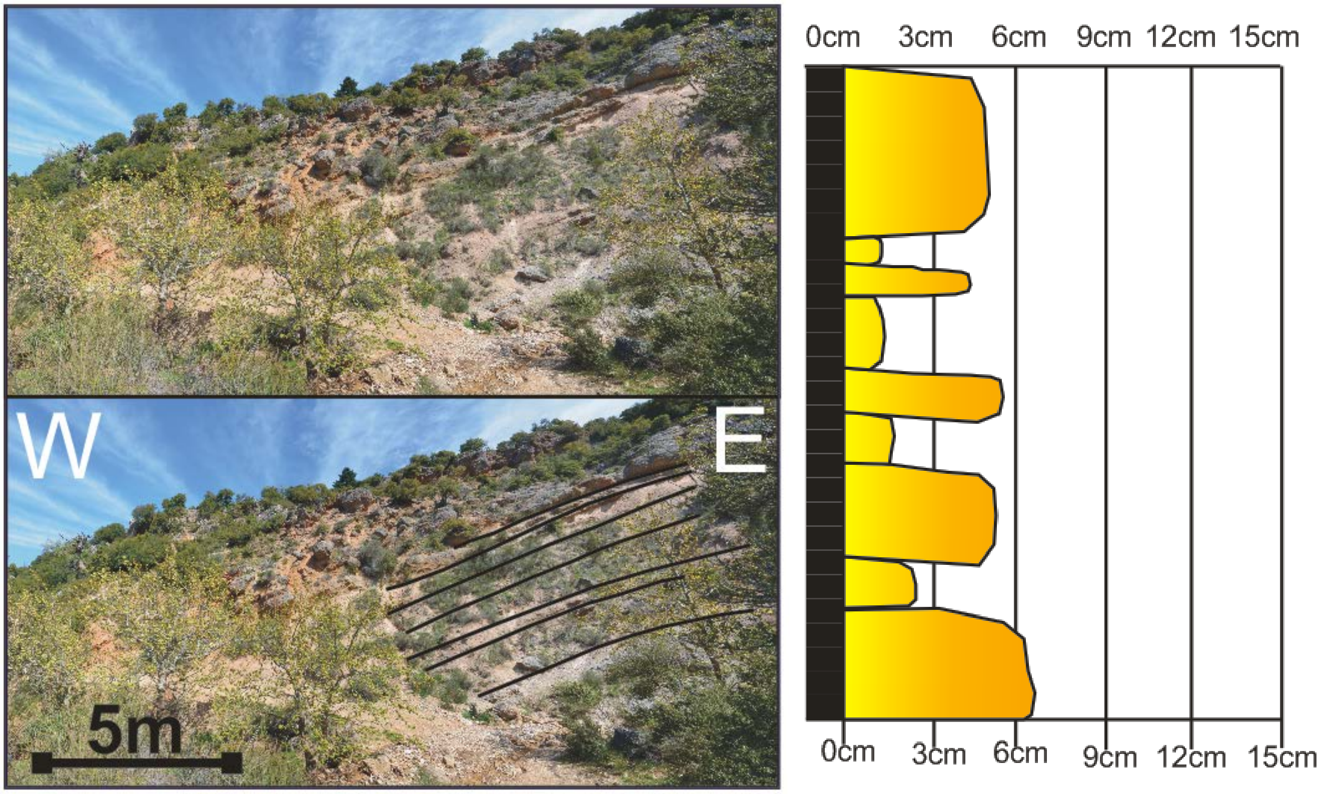


Figure 54: Display the outcrop of log 3

Location 3:

Section 3 is located close to approximately 1000m west of the Trouloz peak on the southern side of the Trouloz member. At this location the bedding show transitional characteristics with interbedded sandstones and conglomerate.

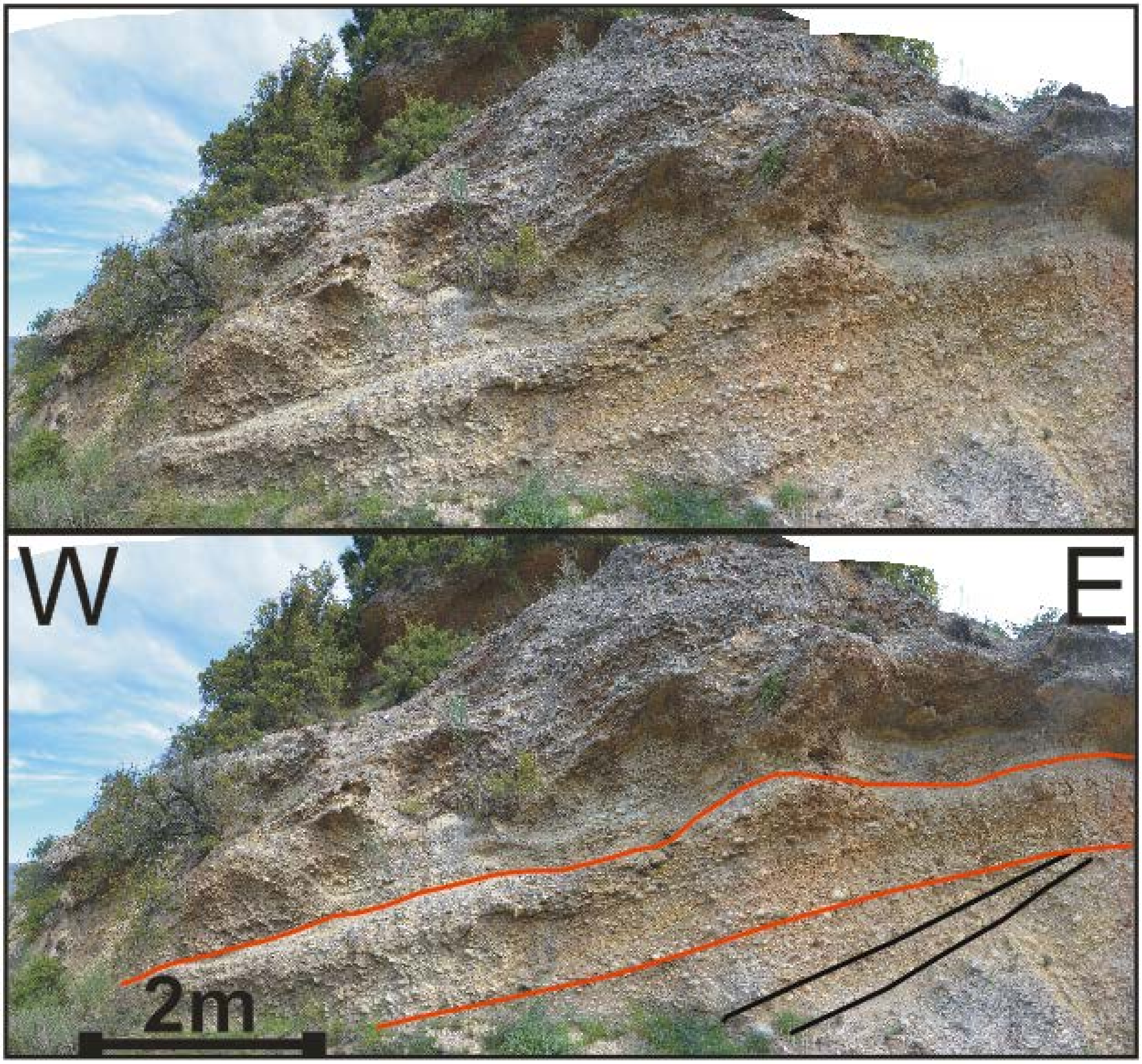


Figure 55: Erosional features of the Trouloz fan.

5.6.2 Facies

Based on the structural and stratigraphic interpretation it is possible to divide the Trouloz member into two different lithologies; coarse conglomerate and marl. Each of the units have been interpreted to represent a different time of deposition, and this is based on the onlapping nature of the coarse conglomerates, and the sharp change in lithology.

5.6.2.1
Marl

Figure 56: Display bedded marl in the northern lobe.

Figure 57: Display crossbedding in the Northern lobe of the Trouloz fan.

The marl represent one of the oldest deposit in the Doumena Fault Block. It is bounded by the immediate footwall of the Doumena Fault and the Zimarovouno Group to the south, the uplifted hanging wall of to the north, the Lithos member to the east and the Dhigela member to the west.

The fresh and weathered surface of the marl is light yellow to beige, and it seem monomictic. Bedding and bedding contacts are well defined most proximal, where one can differentiate packages of bedding up to 3m in thickness. To the north and west from this outcrop, it is not possible to differentiate packages of marl from a distance. Based on the dip angle and dip directions of the structure, it can concluded that the unit form a linear down plunging syncline toward the NWW.

5.6.2.2Coarse conglomerate

Figure 58: Displaying coarse conglomerate from a distance.

This unit is part of the upper section in the Trouloz member. It is bounded by the Doumena Fault to the south, and is situated ontop of the underlying marl to the East, west and north (Figure 50). It can be viewed as a wedge shaped geometry, that thin from east to west.

The fresh surface of this unit is light grey to dark grey to the east and, and grey to beige to the west. The conglomeratic clasts generally display a chaotic and ungraded nature, where the mean size of the clasts range from medium cobbles to pebbles (64 -100mm).

Bedding and bedding contacts are poorly defined at the eastern extent of the structure, before they become more pronounced and well defined toward west. From section 2 and toward the west individual bed sets within the large conglomeratic packages can be recognised. The contact between the sediments change from sharp planar to transitional in close proximity to section 3 at the western extent of the coarse conglomerate. Bed thickness generally decrease from several metres at the eastern extent to less than 0.5 metres in the western extent of the structure. The clast supported polymicitic conglomerates fine towards the NWW, from medium cobbles to more matrix supported and fine grained interbedded sandstones and conglomerate at the western extent. The conglomerate is poorly sorted and the clasts are generally sub rounded to rounded.

Limestone is the dominant lithology, in addition to sandstones, red radiolarite chert and green radiolarite chert. Limestone clasts show both low and highly spherical clasts, and they are sub rounded to rounded, while radiolarite chert appear as sub rounded. On the basis of clast origin one can classify limestone, sandstone and red chert as intra formational, since these can be found in outcrops in the Doumena Fault Block. However, the green radiolarite chert have not been identified in the Kalavryta, Kerpini and Doumena Fault Blocks, and it has therefore been defined as an extra formational clast type.

Limited exposure and poor accessibility limit the amount of dip and dip directions for this unit. The dip and dip directions measured on exposed units display a NWW direction with an average dip angle of 15-18° at the centre and a dip angle of ~4° at the westernmost part.

This unit has been interpreted to be of alluvial origin, with substantial fluvial input. This is based on the clast supported conglomerates that loose energy toward the west, and become more transitional facies. The change in colour is mostly attributed to the increased sandstone to conglomerate ratio and loss of depositional energy where the coarse conglomerates go from clast supported in the east toward matrix supported in the west.

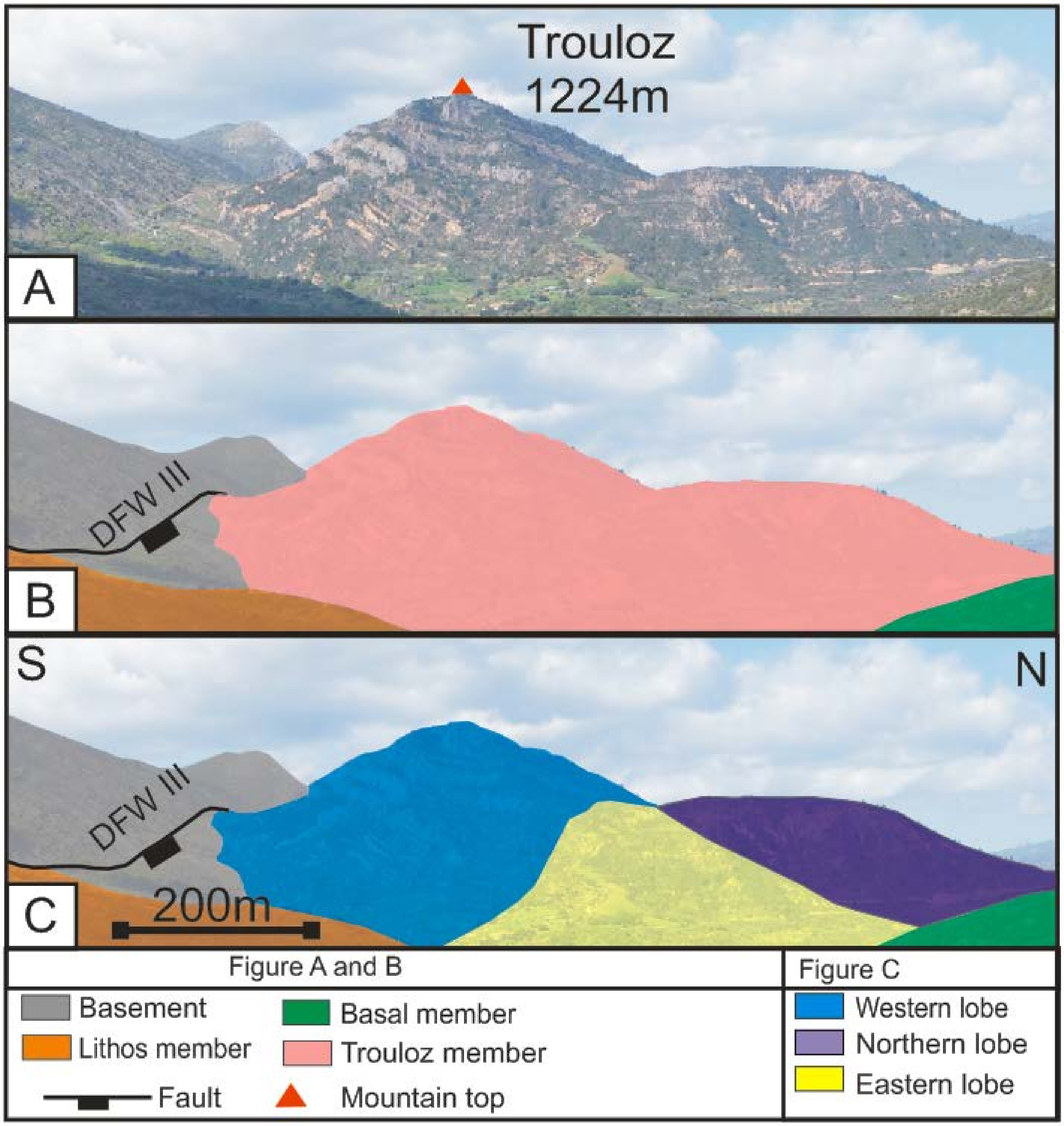


Figure 59: Display the different lobes of the Trolouz member. Abbreviations : DFW3, Doumena Fault West III.

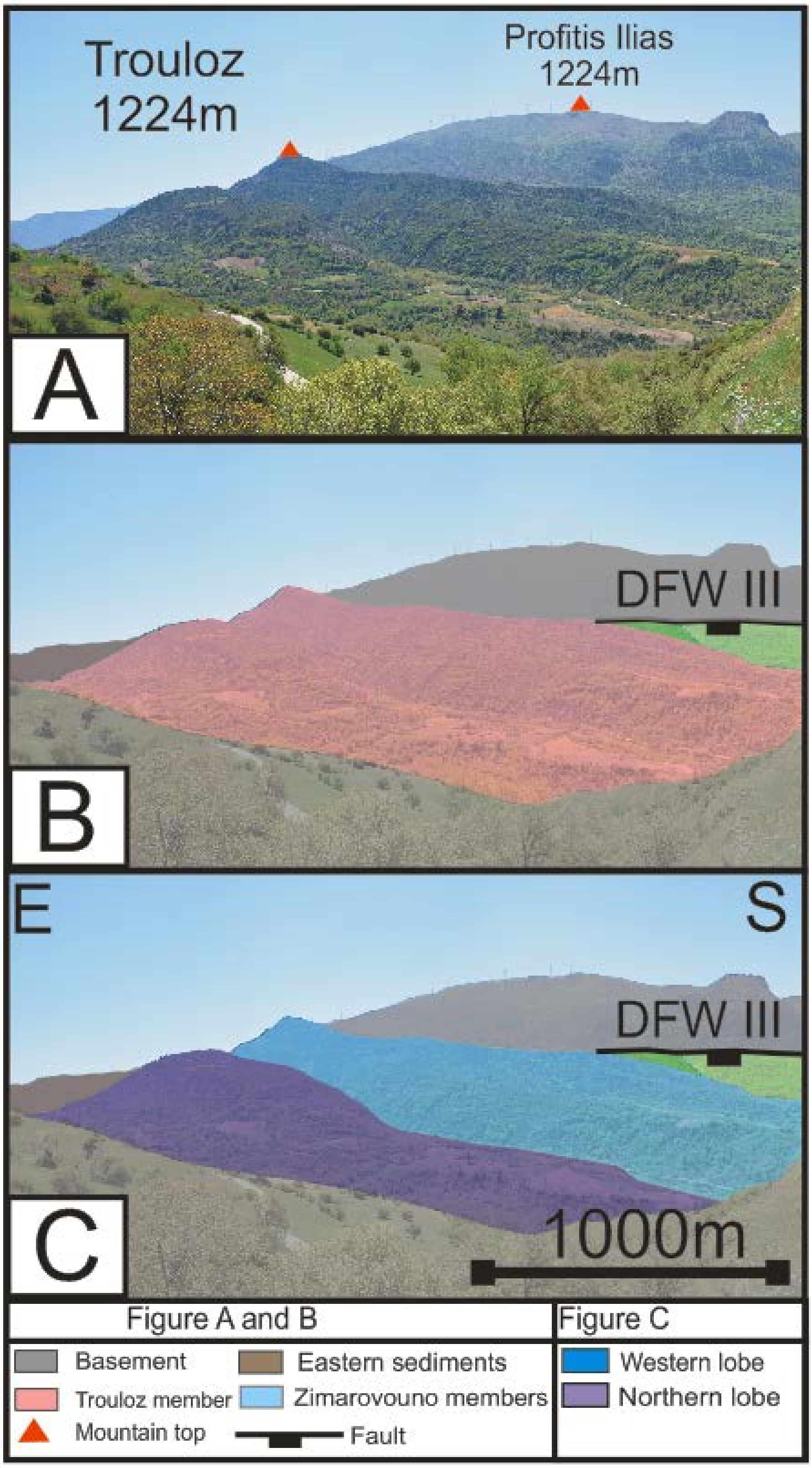


Figure 60: Display the different lobes of the Trouloz Member. Abbreviations : DFW3, Doumena

5.6.3 Texture and geometry

The three lobes of the Trouloz

5.6.3.1Texture and geometry – Western lobe

The western lobe consist of thick and continuous sediments that belong to the coarse conglomerates. The coarse conglomerates onlap and cover the marl in the western lobe. The marl is rarely exposed on the southern side of the western lobe, but it can be seen in the westernmost part of the lobe.

The Doumena Fault marks the southern extent of the Western lobe, and one can determine the contact between the sediments and the fault. The sediments in the western lobe thin toward the NW, and the lithology which is most exposed in the western lobe is the coarse alluvial conglomerate that are described in the sub section 6.6.2.2 There is an overall fining change from the presumed apex towards the west in clast size. The change is gradual towards the centre, and one can observe that there is an increase in sand content. The base of the layers are often sharp and erosive and one can observe a general fining upward sequence in the section. Bed boundaries are often sharp erosive, especially the base of coarser conglomeratic beds.

Bedding and bedding surfaces are more distinguished in the distal parts of the lobe to the west, while the conglomerates in the east appear more chaotic and massive. Bed thickness varies from several meters to several centimetres. In addition, the general grain size decrease from east towards west is most likely represented by the loss of depositional energy and distance from the source point. At the toe of the western lobe one can view that a recent mass flow have deposited on the outer boundary of the lobe. These deposits have a fan like shape that are narrow at the top and wider at the base (Figure 60).

5.6.3.2 Texture and geometry - Northern lobe

The northern lobe is located directly north of the Western lobe, and it is limited by the immediate hanging wall of the Doumena Fault and the Dhigela member towards the West. The northern lobe consist of marl in addition to some clast supported conglomerates. The fine nature of the marl has led to very vegetated outcrops. The thickness of the beds decrease from packages of several meters (Figure 56 and Figure 57) to centimetre thin layers of marl most toward the northwest and west, where the height above the topography tapers out. This is a trend that is observed only within the northern lobe, but it is suggested here to be a trend within the marl hidden by poor outcrop exposure.

The marl generally seem uniform in both appearance and texture, with pronounced bedding that can only be viewed most proximal. Bedding and bedding contact are well exposed when one view the northern lobe from east towards west at the southern most point across a perennial river. The beds that are exposed here are dipping towards the northwest -west with approximately the same dip as the coarse alluvial conglomerate. Further north in the Northern lobe one can observe that the dip of the unit change towards the fault with dips up to 10 *, and that the structure make up a syncline.

5.6.3.3 Texture and geometry – Eastern lobe

The eastern lobe is located directly east of the western and northern lobe. The topographic expression of this area has the appearance of collapse structure, and it is dipping approximately 15 degrees northeast way from the Doumena Fault West III. The bedding of the conglomerate is characterised by thin conglomeratic deposits most likely derived from the coarse alluvial conglomerate. The conglomerate is clast supported to the south, before it rapidly become more matrix supported to the north.

Bedding and bedding contacts are well defined to the south and poorly defined to the northeast. The thickness of single beds to the south have thicknesses up to 50 cm, but they thin rapidly toward the northeast. The conglomerate is poorly sorted, and the thicknesses of the clasts range from 2 to 15 cm.

5.6.4 Summary

The Trouloz member is made up of two different lithologies that can be roughly divided into the lower and upper section that is represented by the marl and the coarse conglomerates, respectively.

Each section will get a short interpretation below.

The lower section:

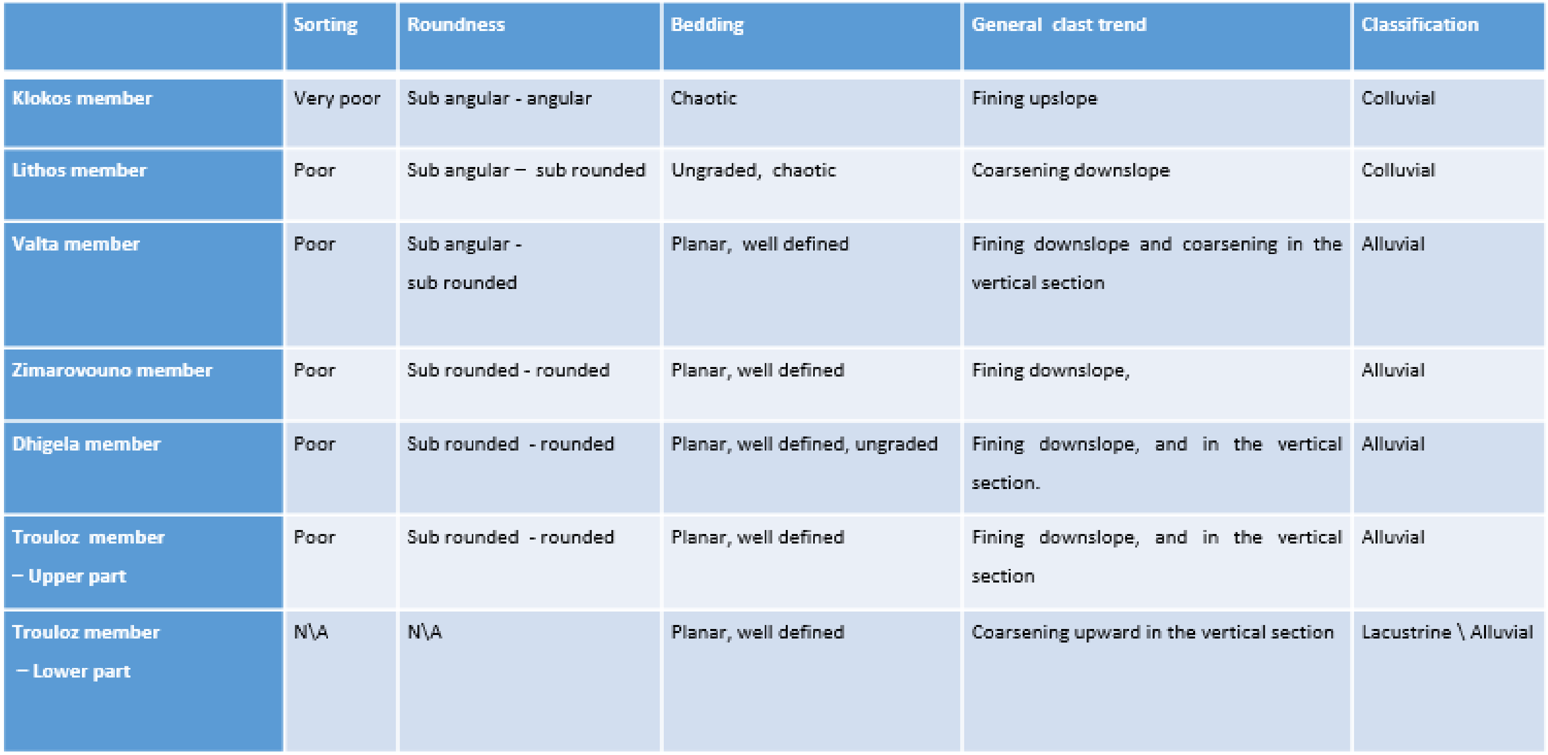
The marl is covers the Basal member and it is situated in the northern and western lobe. And it is highly possible that the marl was deposited as one large lobe that was later overlain conglomerates in what has been defined as the western lobe. The fine nature of the marl is anomalous in the Doumena Fault Block, and it could possibly represent deposition into a lacustrine environment. The marl is folded and it is overlying the Basal member. This mean that it is the second oldest unit in the Doumena Fault Block. The dip angle of the Marl is approximately 15 * to the northwest.

The upper section:

Is comprised of the coarse conglomerates that can only be found in the western and northern lobe. The conglomerates are clast supported and the coarse conglomerate fine toward the northwest. The roundness of the conglomeratic clasts, and the ungraded nature of the beds, in addition to that the conglomerates fine toward the north westwest and the large clasts that can be observed in addition to the rough fining sequence of the deposits suggest that the conglomerate was alluvial with significant fluvial support.

5.7 Summary of Chapter 5

Table 3: Summary of the key characteristics presented for the colluvial and alluvial units.



	Sorting	Roundness	Bedding	General clast trend	Classification
Klokos member	Very poor	Sub angular - angular	Chaotic	Fining upslope	Colluvial
Lithos member	Poor	Sub angular – sub rounded	Ungraded, chaotic	Coarsening downslope	Colluvial
Valta member	Poor	Sub angular - sub rounded	Planar, well defined	Fining downslope and coarsening in the vertical section	Alluvial
Zimarovouno member	Poor	Sub rounded - rounded	Planar, well defined	Fining downslope,	Alluvial
Dhigela member	Poor	Sub rounded - rounded	Planar, well defined, ungraded	Fining downslope, and in the vertical section.	Alluvial
Trouloz member – Upper part	Poor	Sub rounded - rounded	Planar, well defined	Fining downslope, and in the vertical section	Alluvial
Trouloz member – Lower part	N\A	N\A	Planar, well defined	Coarsening upward in the vertical section	Lacustrine \ Alluvial

Chapter 6: Structural observations

The Doumena Fault Block is the main study area of this thesis, therefore the Kerpini and Mamoussia – Pirgaki Faults have not been thoroughly investigated. Faults generally appear as subtle features in the Doumena Fault Block, and only a few intra-block faults have been identified and investigated. One of these intra-block faults (Fault A) was previously identified by Dahman (2015), and this fault was further investigated in detail. Faults have been identified based on basement outcrops, lithologic contacts and the angular relationship between sediments. A south dipping fault that was previously interpreted by Ford et al. (2013), was not identified in this study as there were no evidence to support it. The Doumena Fault marks the southern boundary of the fault block, and the Mamoussia – Pirgaki Fault marks the Northern boundary. North – South striking transfer faults have previously been interpreted to be located through Roghi Village in in the Kerpini Fault Block, in addition to the Vouraikos and Kerinitis Valley (Dahman, 2015; Hadland, 2016). These faults have been extended further north, and the presence of these transfer faults will be further discussed in the following chapter.

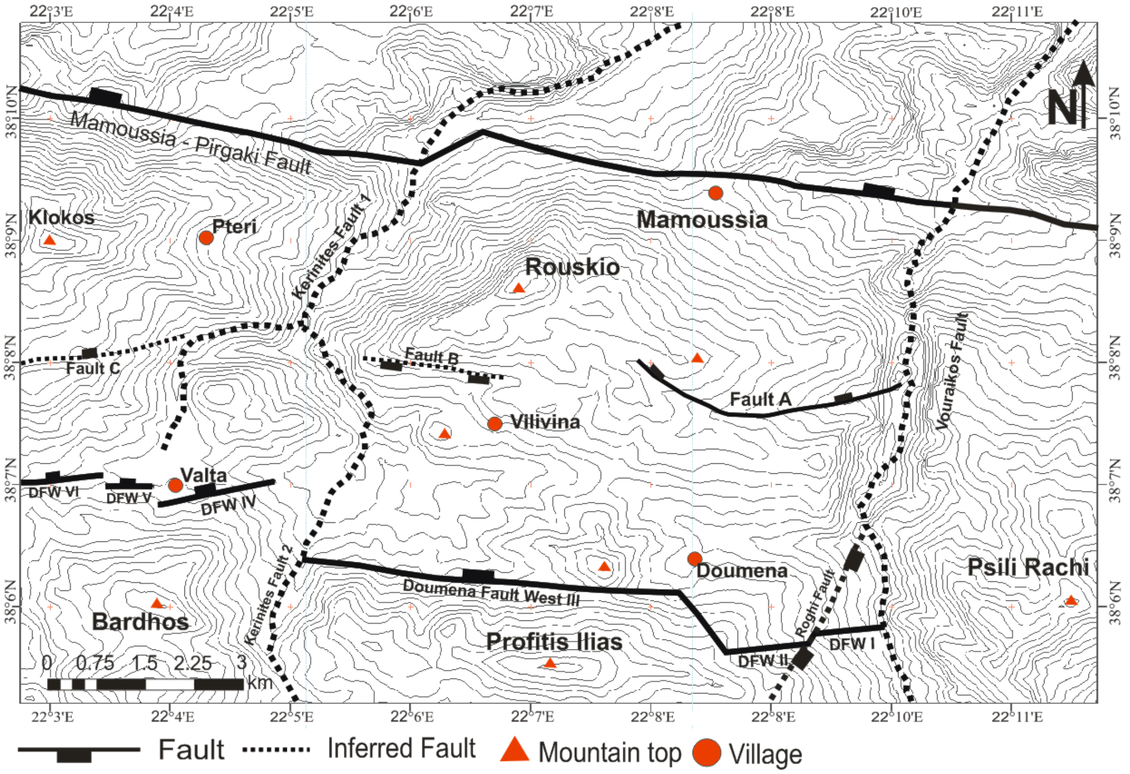


Figure 61: Structural map of the Doumena Fault Block. There are two fault families with main strike directions east – west and north – south. All the faults have been given a specific name, and each of the faults are described in the following chapter. Abbreviations: DFW = Doumena Fault West7.1 Doumena Fault West.

Table 4: Summary of the different faults located within the Doumena Fault Block. The data shown in the table are based on field observations, cross sections and previous work.

Fault	Location	Type	Strike	Dip angle	Dip Direction	Max Displacement	First observation	Footwall Unit	Hanging wall Unit
Doumena Fault East	East of Vouraikos Valley, south of Mega Spileon Monastery	Normal Fault	N103°E	40-50°	North	800m	Rohais, 2007	Basement	Unknown
Doumena Fault West I	Easternmost part of Doumena Fault Block, north of Roghi Mountain.	Normal Fault	N92°E	43-52°	North	Unknown	Veiteberg, 2017	Basement	Lithos member
Doumena Fault West II	West of Roghi Mountain until to Doumena Village	Normal Fault	N101°E	43-52°	North	1110m	Ford, 2013	Basement	Lithos member
Doumena Fault West III	From Doumena Village to Platinotissa Village	Normal Fault	N105°E	43-52°	North	1170 - 1520m	Ford, 2013	Basement	Trouloz, Zimarovouno and Dhigela members
Doumena Fault West IV	From Kerinitis river to Valta Village	Normal Fault	N74°E	43-52°	North	880m	Ford, 2013	Basement and Valta member	Basal member
Doumena Fault West V	From Valta village and 500m to the west	Normal Fault	N88°E	43-52°	North	410m	Ford, 2013	Basement	Basal member
Doumena Fault West VI	Westernmost part of the Doumena Fault Block, south of Klokos Mountain.	Normal Fault	N93°E	43-52°	North	420m	Ford, 2013	Basement	Basal member
Fault A	Easternmost part of the Doumena Fault Block	Normal Fault	N110°E	55°	North	300 – 400m	Syahrul, 2014	Basement	Basement
Fault B	North of Vilivina Village	Normal Fault	N110°E	60°	North	35 - 45m	Veiteberg, 2017	Lithos member	Basement
Fault C	South of the peak of Mount Klokos	Normal Fault	N75°E	60°	North	300m	Veiteberg, 2017	Basement	Basement
Roghi Fault	Through the Lithos member in the Doumena Fault Block	Transfer Fault	N35°E	Close to vertical	North - South	Unknown	Syahrul, 2014	Transfer Fault	Transfer Fault
Vouraikos Valley Fault	Eastern extent of the Doumena Fault Block	Transfer Fault	North - South	Close to vertical	North - South	Unknown	Dahman, 2015	Transfer Fault	Transfer Fault
Kerinitis Valley Fault	In the middle of the Doumena Fault Block	Transfer Fault	North - South	Close to vertical	North - South	Unknown	Hadland, 2016	Transfer Fault	Transfer Fault

6.1 Doumena Fault

The Doumena Fault can be separated into the Western Doumena Fault and Eastern Doumena Fault. They have been interpreted to be separated by a ~1000m right step in the Vouraikos Valley. The eastern Doumena Fault is outside the scope of this thesis project, but the sediments in the Eastern Doumena Fault Block (referred to as Eastern sediments in this thesis) have been given a general description in subsection (subsection 4.2.6).

The Doumena Fault can be subdivided into six distinct segments, segment I, II, III, IV, V and VI. The six segments have different strike: Segment I strikes N92°E, segment II strikes N101°E, segment III strikes N105°E, segment IV strikes N074°E, segment V strikes N088°E and segment VI strikes N093°E. The distinct steps that differentiate the segments of the fault generally relocate displacement by right stepping, and some of the steps described below coincide with inferred south north striking faults, while one of the steps is suggested to be controlled by a relay ramp. There are a total of 5 steps, where of four steps appear to be related to transfer faults.

1. The first step between segment I and II coincide with the south - north striking Roghi Fault, and it is suggested to control the step between segment I and II in the Doumena Fault. The Roghi fault have previously been suggested to control a step in the Kerpini Fault, and it is here inferred that it also control a step in the Doumena Fault. This step represent the only left step in the Doumena Fault Block.
2. Sediments from the Lithos member cover the second step between segment II and III, but based on the nature of the sediments in the Lithos member it has been interpreted that the connection between the second and third segment is controlled by a relay ramp.
3. The third step between segment III and IV coincide with another large inferred south – north transfer fault in the Kerinites Valley. This is marked by a large right step of 700 m that is suggested to be controlled by the Kerinitis Fault 1. Otherwise, the fault would truncate against the opposite valley side in the Kerinitis valley with large displacement, or lose over 1500m of displacement over a short distance.
4. Segment IV and V is possibly controlled by the Kerinitis Fault II, since the step coincide with the trend of the Kerinitis Fault II. However, a large difference in displacement was not noted between these segments.

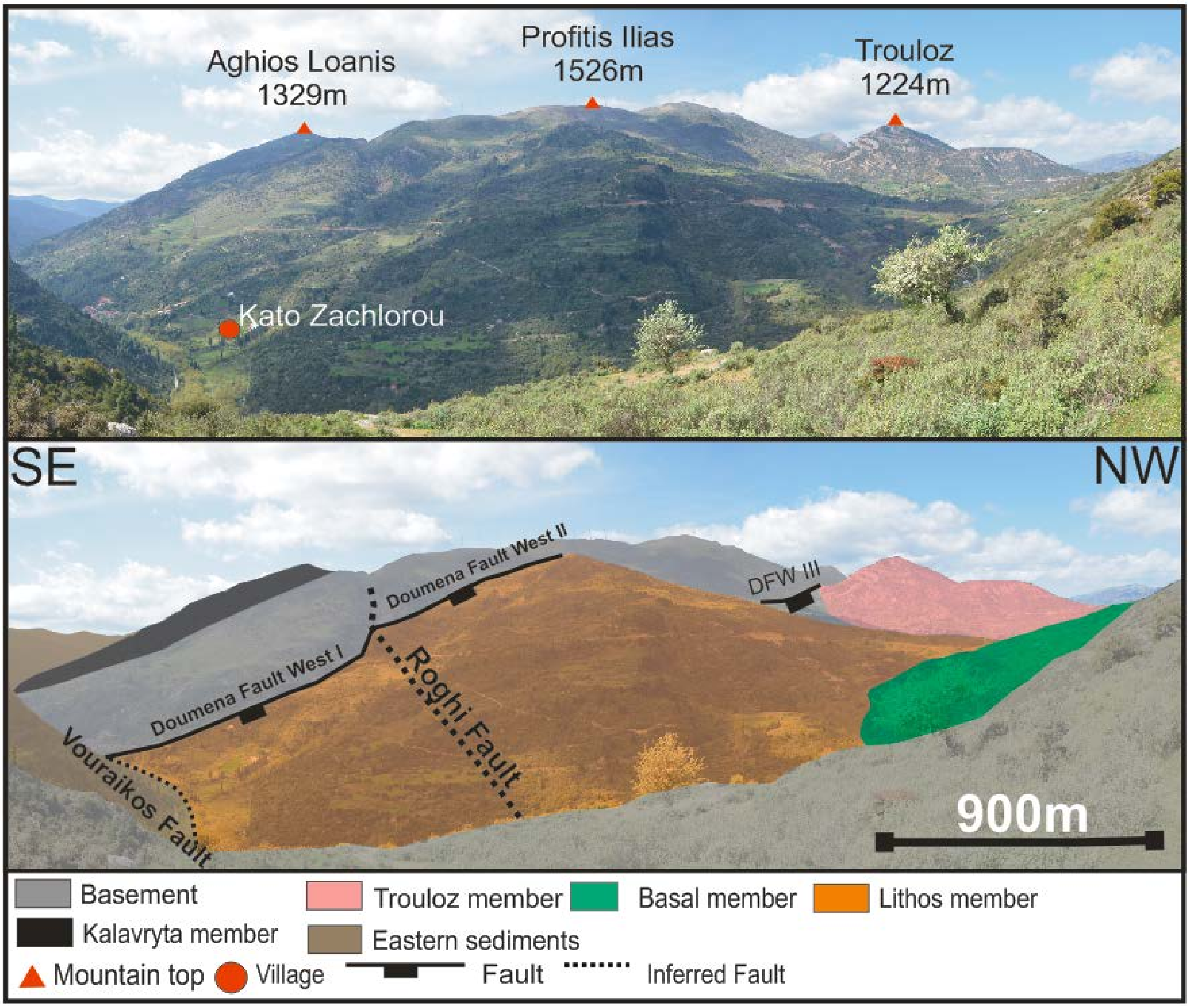


Figure 62: Overview of segment I, II and III of the Doumena Fault. Photo is looking southwest. The Rohgi Fault is assumed to go through a huge gorge in the immideate footwall of the Doumena Fault.

6.1.1 Doumena Fault - Segment I

Segment I (Figure 62) is the easternmost segment of the Doumena Fault, and the length of the segment is approximately 950m. The eastern end is marked with a significant left step, where the Eastern Kerpini fault is located 750m to the north along the Vouraikos Valley, while the western end of the segment is marked by the Roghi Fault that have made the fault step 100m south.

The Lithos member is located in the hanging wall of segment I, while basement is located in the immediate footwall. Based on displacement measurements, the displacement of the Doumena Fault have not been estimated to since the immediate hanging wall to the Doumena Fault cannot not be found approximately perpendicular to the strike of the fault. Another issue is that the uncertain effect of the Roghi Fault on the displacement of the Doumena Fault I. However, it is assumed that the basement is downthrown by the Roghi fault by more than 100m, since the Kerpini Faults displacement increase by 400m. This imply that the displacement have increased with almost 100m from segment II to segment I due to the Roghi Fault,(against the regional trend) that intersect both the Kerpini and Doumena Fault Blocks. This fit well previous work by Hadland (2016) that noted a large increase in displacement of the Kerpini Fault, that could be due to the Roghi Fault. A significant change in displacement along the segment is not observed, thus the displacement is high at the eastern end of segment I where the fault step south in the Vouraikos Valley.

6.1.2 Doumena Fault - Segment II

Segment II is approximately 1500m long, and it stretches between segment I and III. Sediments of the Lithos member are located in the hanging wall of segment II, while the immediate footwall is composed of basement. This segment is connected to segment III through a relay ramp, and the displacement of this segment have been measured to 1110m. A cross section of the segment display that the displacement of the Doumena Fault (segment II) increase westwards and eastwards from segment II.

6.1.3 Doumena Fault - Segment III

Segment III is the main segment of the three Doumena Fault segments located between the rivers of Kerinites and Vouraikos. The segment stretches 4.5 km in length westwards from segment II to the Kerinites Valley where the fault steps 850 m to the right (north). The Trouloz member is located in the hanging wall of the eastern part of segment III, while the Zimarovouno Group and the Dhigela member is located in the western part of segment III's hanging wall. Local rockfall and avalanche deposits from the immediate footwall can found at both the eastern and western end of the segment, and these are suggested to displace sediments from either the Trouloz or Lithos member. The immediate footwall of segment III contain only basement, and based on the cross sections one can observe that the displacement profile increase with several hundred meters from 1170m to the east to 1520 m in the west. No significant negative change in displacement have been recorded close to the Kerinites Valley, thus the displacement is large when the fault intersect with the Kerinites Valley and have to step north.

The fault plane is exposed at several locations in the Doumena Fault Block and the outcrop 300m east of the Trouloz member represent one of the best exposed fault planes in the Northern Peloponnese. It is an outcrop that laterally extensive covering an area of approximately 150 x 150m. N-S lineation on the exposed fault plane indicate that there has not been any oblique movement. Dip angle and dip directions measured on exposed fault planes range from 43 – 52° three different localities, along this segment. The fault plane is undulating in dip section and wavy along strike. This made it difficult to do find a dip measurement that account for the whole segment. Therefore, a dip angle of 45 ° was used when estimating the displacement in the cross sections.

6.1.4 Doumena Fault - Segment IV

Segment IV is the first segment on the Western side of the Kerinites Valley in the Doumena Fault Block. The segment stretches approximately 1.6 km and the displacement on the western side of the Kerinitis Valley is much lower than the displacement estimated in segment III. Based on a cross sections it was estimated that the displacement of the Doumena Fault (segment IV) was measured to 880m. The hanging wall of the segment is made up of the Basal member, while the immediate footwall is composed of basement and the Valta member. The fault step 300m to the right (north) at the westernmost end of the segment, where it is overlain by the Valta member.

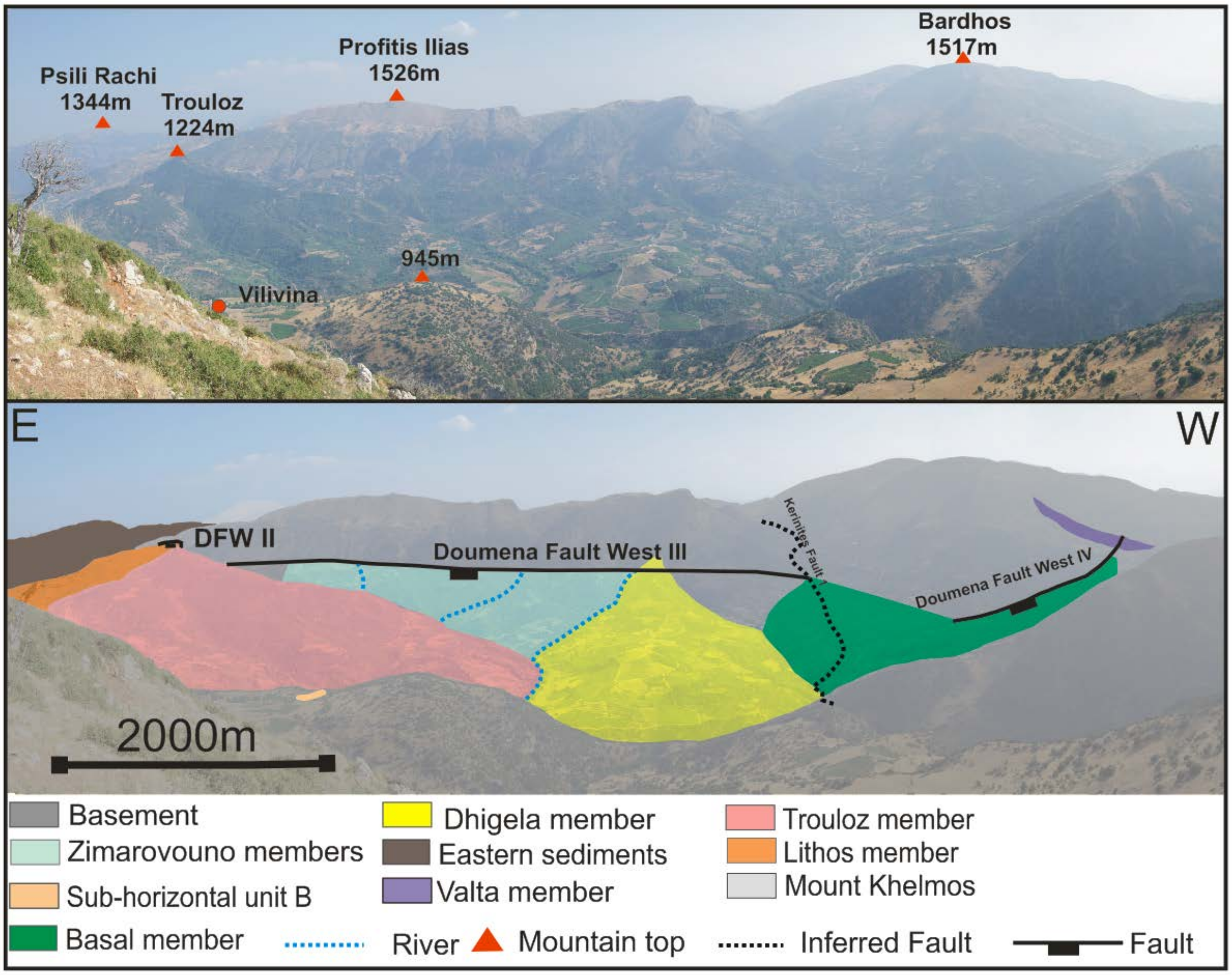


Figure 63: Overview of the Doumena Fault displaying segment II,III and IV. Photo is looking south. The footwall of the Doumena Fault is mostly composed of basement, with very little sediments above the fault. Abbreviations: DFW = Doumena Fault West.

6.1.5 Doumena Fault – Segment V

Segment V is the central segment on the western side of the Kerinites Valley, located between Doumena Fault segment IV and VI. The segment stretch approximately 400m in length westward from segment IV, and the Basal member can be located in the hanging wall. The immediate footwall is made out of basement, and a few shales that are situated on top of basement at close to the westernmost end of segment V. Based on cross section the displacement of the fault have been estimated to 410m.

6.1.6 Doumena Fault - Segment VI

Segment VI is the westernmost and last segment of the Doumena Fault within the current study area. The segment stretch 650 m before it terminate in the Kerinitis valley. The Basal is located in the hanging wall of the fault (segment VI) and the immediate footwall is composed of basement. The displacement of the Doumena Fault VI have been estimated to 420m

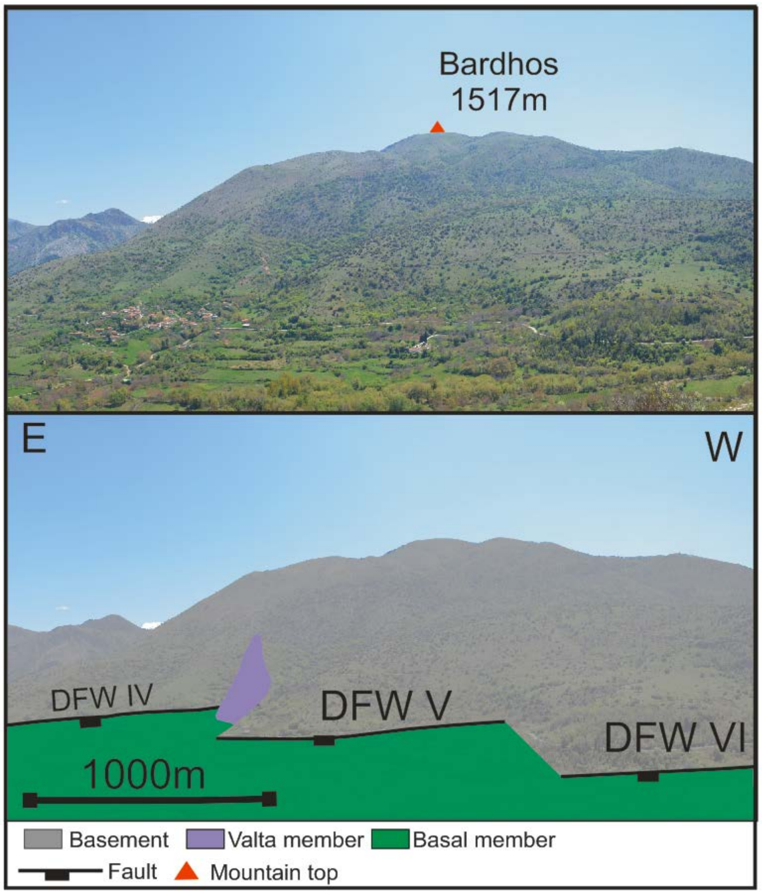


Figure 64: Display the fourth, fifth and sixth step of the Doumena Fault. Abbreviation: DFW = Doumena Fault West.

6.2 Minor faults

7.2 Fault A

Fault A is located on the Easternmost flank of the Doumena Fault Block, separating two different blocks of basement. A part of the fault plane can be viewed from east towards west across the Vouraikos valley, and the fault has been measured to have a mean strike of N110°W and a dip angle of 55°.

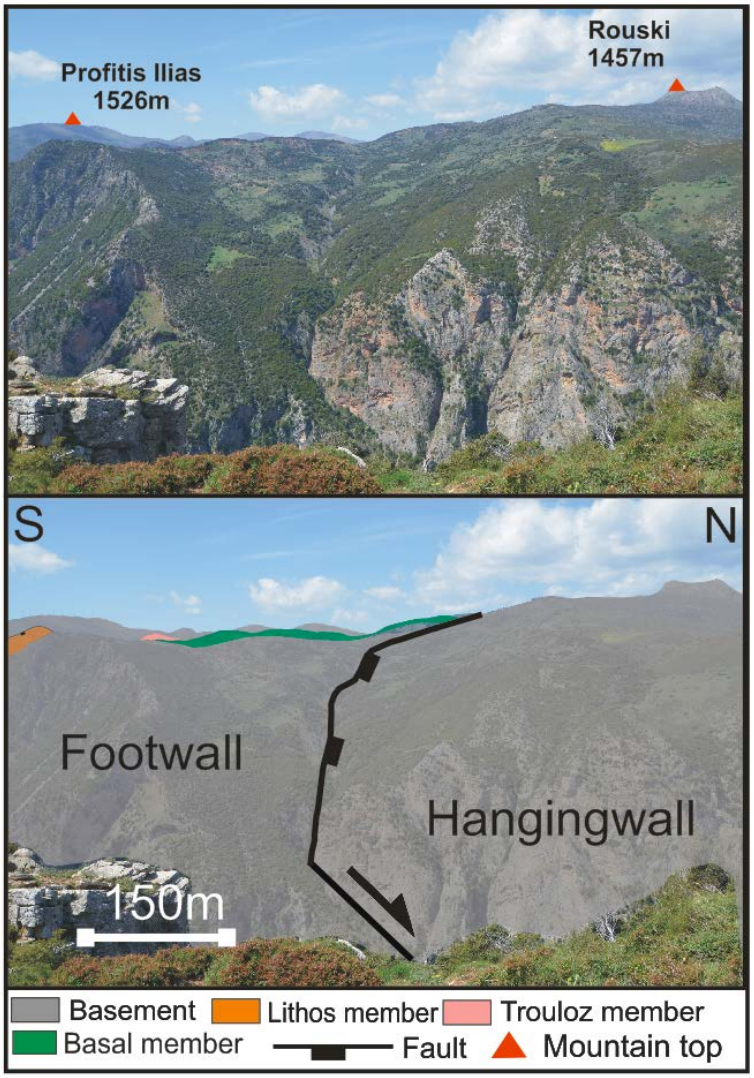


Figure 65: Photo of Fault A looking west. The displacement of the fault is largest at the eastern end of the fault, and the displacement stops abruptly in the Vouraikos Valley. Scale is relevant to centre of image.

The fault is dipping north- northeast, and it is approximately 3.5km long. Figure 65 show an interpreted picture and a clean uninterpreted picture of Fault A. The fault has been interpreted to be an internal basement fault. Most of the basement seen in the footwall of the fault is covered by vegetation, but basement is clearly exposed at several locations in the both the hanging wall and footwall of the fault. The displacement of the fault gradually increase from west towards east, and the maximum displacement has been estimated to 400 m before the fault abruptly end in the Vouraikos Valley. At this point the fault still has displacement that leads to the speculation of a possible transfer fault in the Vouraikos valley. A displacement pattern observed for this fault is not reasonable with high displacement on the western side of the Vouraikos Valley, and no displacement on the eastern side of the Vouraikos Valley. A transfer fault would in this case accommodate the displacement and transfer it elsewhere. Transfer faults and their presence in the study area will be further discussed in subsection 6.3.

6.2.3 Fault B

Fault B is located immediately north of Sub-horizontal unit A, northwest of Vilivina Village. The Fault plane is not exposed and the strike of this fault has been measured to be N110°E. A fault has been inferred to explain the dip relationship between the subhorizontal unit A and the Basal member in the immediate hanging wall of the Doumena Fault. Sub-horizontal unit A have a dip angle of 10° and a dip direction to 220°. This is anomalous compared to the other conglomeratic deposits in the immediate hanging wall of the Doumena Fault that have a dip angle of 25° and a dip direction of ~200°.

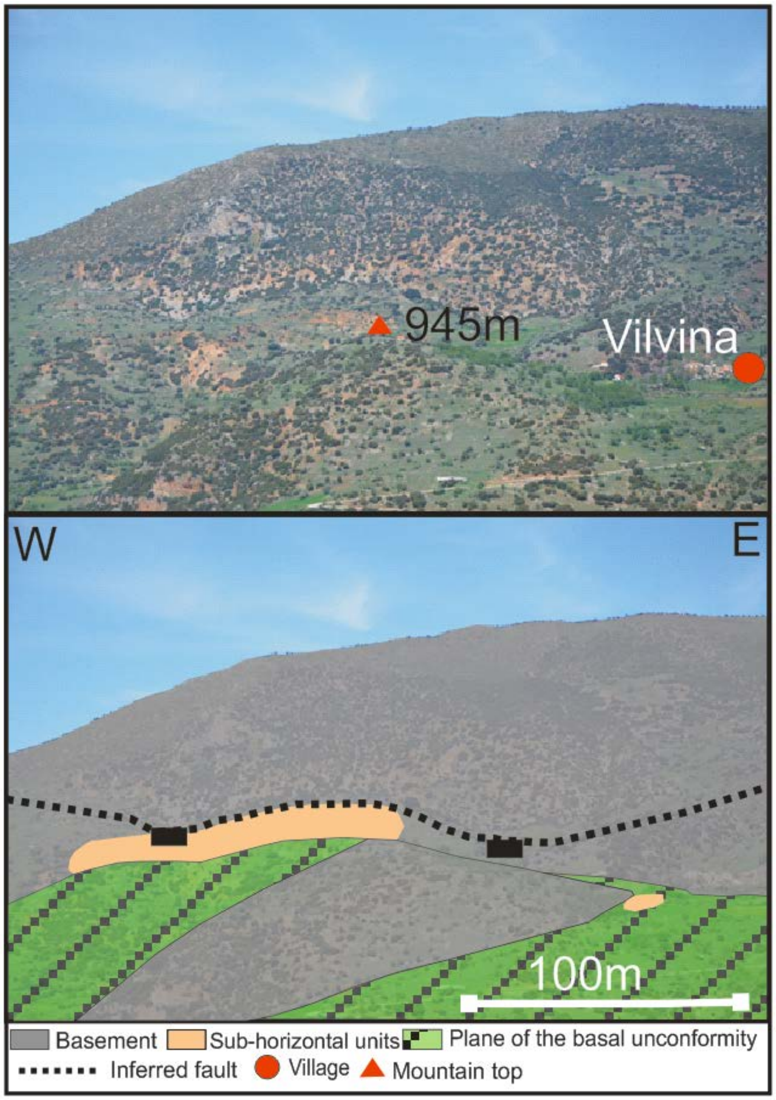


Figure 66: This photo is taken from the top of the Trouloz member looking north. The south dipping sub horizontal conglomerate is located in the hanging wall of the fault, and the plane of the basal unconformity can be viewed stretching across the mapfrom east to west. Scale is relevant for the large sub-horizontal unit (Sub- horizontal unit A).

Sub-horizontal unit A and B are marked in Figure 66, in the hanging wall of the fault. The length of the fault is approximately 1.2 km, and the dip of the fault could not be measured since the fault plane is not exposed. However, the dip of the fault is suggested to be to the south. Displacement is difficult to estimate since the sub-horizontal unit is poorly exposed close to the inferred fault due to farming. Farmlands also made it difficult to trace the unconformity contact of the sub-horizontal unit, and the complete extent of the unit is therefore uncertain. This fault has been inferred because the basement make up a planar feature north of Sub-horizontal unit A that could explain the dip relationship between Sub-horizontal unit A and the Basal member in the hanging wall of the Doumena Fault. The difference in dip angle between the units, imply that the conglomerate beds have been rotated up to 15 °. But

Based on the geometry of the planar basement scarp, a dip of approximately 60-70° can be estimated. by using the trigonometric relationship of the fault, and the "known" rotation. it is possible to postulate that the displacement of the fault is approximately 40m.

6.2.4 Fault C

Fault C is located approximately 2km south of the peak of Mount Klokos, and ~ 800m south west of the village of Ag. Panteleimon. The fault plane is not exposed, thus the dip angle of the fault is unknown. Most of the basement at this location is covered in vegetation, but basement is clearly exposed at several locations in both the hanging wall and footwall. The strike of the fault have been measured to N75°E and the fault has been inferred to explain the large topographic feature that can be viewed in the southern part of the Klokos Mountains.

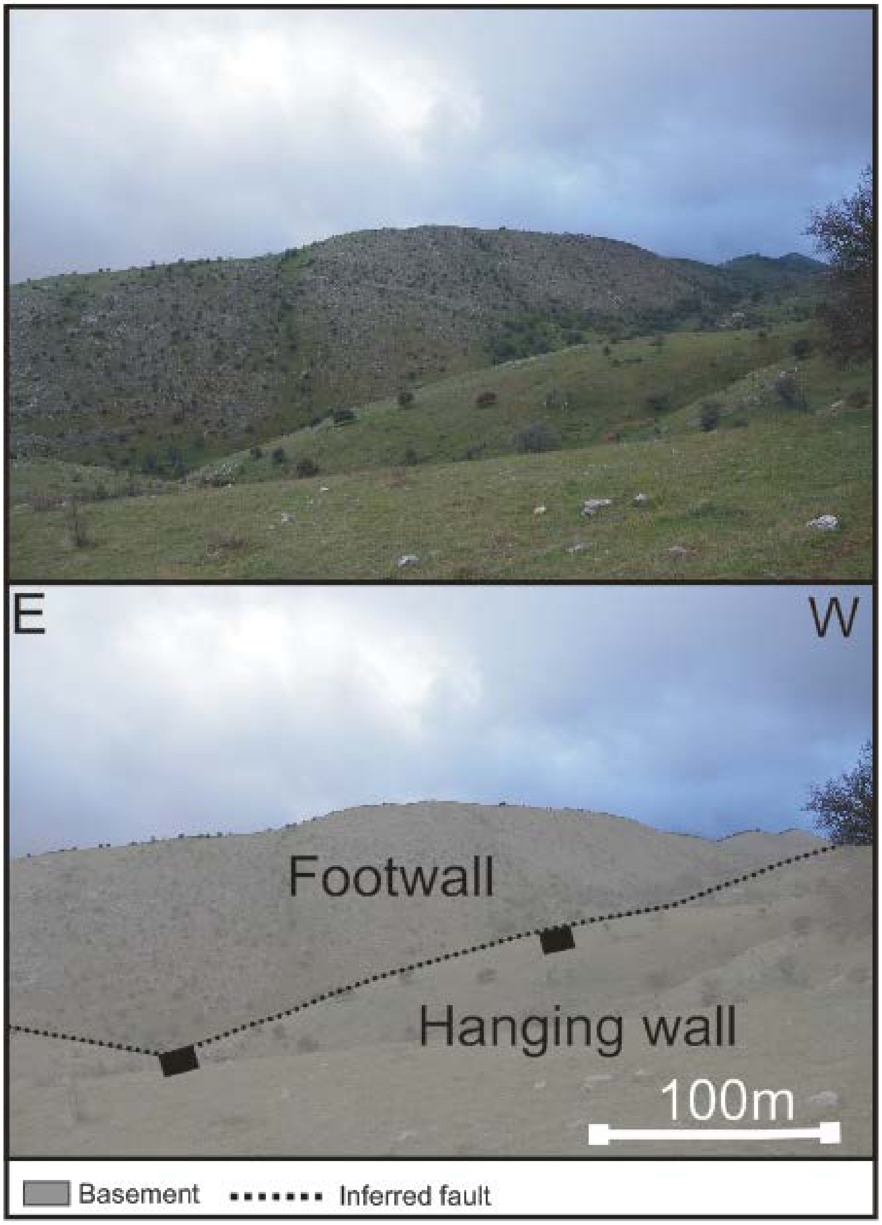


Figure 67: Photo of Fault D looking south. The footwall of this fault make up a large topographic feature that can be viewed from large distances. Scale is relevant to the eastern part of the footwall.

Figure 67 display an interpreted and an uninterpreted picture of Fault D. It is an internal basement fault and the length of the fault is approximately 4.5 km. The fault has been inferred due to the large topographic feature in the southern part of the Klokos Mountains, that display a linear and planar surface that is inclined to northwest. There is a river running along the strike of the fault that terminate in the Seliounas valley. Displacement is gradually increasing to the west, with a maximum displacement of 300m, before the fault abruptly end in the Seliounas Valley. At this point the fault has a large displacement, and it is another indication of that the river valleys might represent transfer faults that have transferred the displacement elsewhere. Transfer faults and their presence in the study area will be further discussed in subsection 7.3

6.3 Transfer Faults

Two north-south orientated river valleys, Vouraikos and Kerinites, go through the Doumena Fault Block. These river valleys are laterally continuous throughout the northern Peloponnese toward the Corinth Gulf, and many major faults in the Corinth rift system either terminate against or step in these river valleys. In the greater Kalavryta – Diakofto area one can observe that the Doumena and the Kerpini, and Mamoussia Pirgaki faults cross these river valleys.

In the case of the Doumena Fault, it is stepping southwards to the east, and northwards to the west across these river valleys. This is the opposite of the Kerpini Fault (Hadland, 2016) that steps to the north across both the river valleys, while the larger Mamoussia – Pirgaki Fault step south (east to west) only across the Kerinites river. It can thus be argued that the river valleys represent south-north orientated transfer faults that segment the rift system.

6.3.1 Vouraikos Fault

By projection the main bounding faults in the across major river valleys, it is clear that the Doumena and Kerpini Faults cannot traced across the Vouraikos Valley. This is most clear for the Kerpini Fault where one can observe that the lithology changes from conglomerate (west side of valley) to basement (east side of valley). This means that the fault is most likely stepping, which in the case for the Kerpini fault is northwards (Hadland, 2016). The same argument regarding changing lithology is difficult to apply for a step across the Vouraikos Valley for the Doumena Fault, since both basement and sediments are exposed there. However, additional evidence supporting the step for the Doumena Fault is that the thickness, texture and type of facies on the eastern side of the Vouraikos Valley is vastly different to the western side. On the western side of the Vouraikos Valley, the Doumena Fault Block appear as a starved half graben in comparison to the large amount of sediments that are exposed on the eastern side of the Vouraikos Valley. This difference might, be at least partly explained by a transfer fault since one can observe that the height of the unconformity at each side of the valley is at different elevations. The unconformity sits in the base of the valley on the western side, while on the eastern side, the unconformity sits in the middle of the slope about 120m higher. The Mamoussia – Pirgaki Fault goes continuously across the Vouraikos valley.

Indications of a transfer fault in the Vouraikos Valley are as followed:

- It is not possible to project the faults directly across the Vouraikos Valley
- The facies and texture of the sediments across the valley are different
- The height in unconformity elevation is different (more than 500m across the valley)
- The displacement across the valley have changed drastically.

The fault plane of the inferred Vouraikos Fault is not exposed, but the dip is assumed to be close to vertical.

6.3.2 Kerinites Fault I

By projection the Doumena Fault IVacross the smaller Kerinites river to the Doumena Fault V in the field, it is obvious thatthe Doumena Fault did not propagate directly across the smaller Kerinitis Fault I. This can be observed from the change in lithology from east (conglomerate) to west (basement) across the. This means that the Doumena Fault have to step northwards across the smaller Kerinites river possibly through a transfer fault. There is an abrupt decrease in displacement of more than 400m across the river valley for the Kerinites Fault I. This can be seen from the difference in displacement between cross section B and C.

A similar pattern was also recorded in the Kerpini Fault Block were the Kerinites River experienced an abrupt loss of 300m in displacement (Hadland, 2016).

Indications of a transfer fault in the smaller Kerinitis river are as followed:

- The height in unconformity elevation is different
- The displacement change abruptly across the Kerinites river.

The fault plane of the inferred Kerinites Fault I is not exposed, but the dip angle is assumed to be close to vertical.

6.3.2 Kerinites Fault II

By projection the Doumena Fault III across the large Kerinites river in the field to the Doumena Fault IV, it is obvious that the Doumena Fault did not propagate directly across the larger Kerinitis river. This can be observed from the change in lithology from east (conglomerate) to west (basement) across the Kerinites River. This means that the Doumena Fault have to step northwards across the Kerinites river possibly through a transfer fault. Another evidence supporting a transfer fault in the Kerinites river is that the dip angle of the unconformity increase from 28° to 30°, while there is an abrupt decrease in displacement of more than several hundred metres across the river valley for both the Kerinites Fault I and II. This can be seen from the difference in displacement between cross section B and D, and the cross section H in Figure 76.

A similar pattern have been observed in the Kerpini Fault Block, where the displacement of the Kerpini Fault get an abrupt ending across the Kerinites river against Skepasto Mountain (Hadland, 2016). The Mamoussia – Pirgaki Fault do not propagate directly across the Kerinites River. This can be observed from the change in lithology from basement (east) to conglomerate (west). This means that the fault has to step south across the Kerinites river (from east to west).

Indications of a transfer fault in the Kerinitis River Valley are as followed:

- It is not possible to project the faults directly across the Kerinites river.
- The height in unconformity elevation is different
- The displacement change abruptly across the Kerinites river.

The fault plane of the inferred Kerinites Fault II is not exposed, but the dip angle is assumed to be close to vertical.

6.3.3 Roghi fault

The Roghi Fault has previously been interpreted and investigated by Syahrul (2014) and Sigmundstad (2016) in the Kerpini Fault Block. However, the fault was previously limited to the Kerpini Fault block while in this thesis the fault have been extended into the Doumena Fault Block through a large gorge in the footwall of the Doumena Fault (Figure 62). It has a strike N35°E, and a total length of 8 km across the Doumena and Kerpini Fault Blocks.

By projecting the Doumena Fault across the Roghi Fault it is evident that the Doumena Fault do not cross over directly, but step north along the Roghi fault. This can be observed based on the lithology change from conglomerate (west) to basement (east) toward Vouraikos Valley, and that the Doumena Fault have to step approximately 200m north (from segment II to segment I of the Doumena Fault).

Indications of a transfer fault in the Roghi Mountain are as followed:

- It is not possible to trace the Doumena Fault directly across the fault.
- The height of the unconformity is at a lower elevation on the eastern side of the fault.
- The displacement of the Doumena Fault was decreasing toward the fault, but it increase across the fault

The fault plane of the inferred Roghi Fault is not exposed, but the dip angle is assumed to be close to vertical.

6.4 Cross sections

This subchapter will include 8 different cross sections, where seven are in the north - south direction and one in the east - west direction. When making the cross section, the following assumptions were made:

- That the paleo slope on the hanging wall and the footwall have a planar surface.
- That the dip angle and dip direction of the units where the unconformity is not visible have the same general trend as adjacent outcrops of the unconformity.
- That faults and contacts are not perpendicular to the cross sections, and that the dip angle in the cross section does not represent the true dip angle and dip direction.
- That transfer faults accommodate displacement and transfer it along strike.

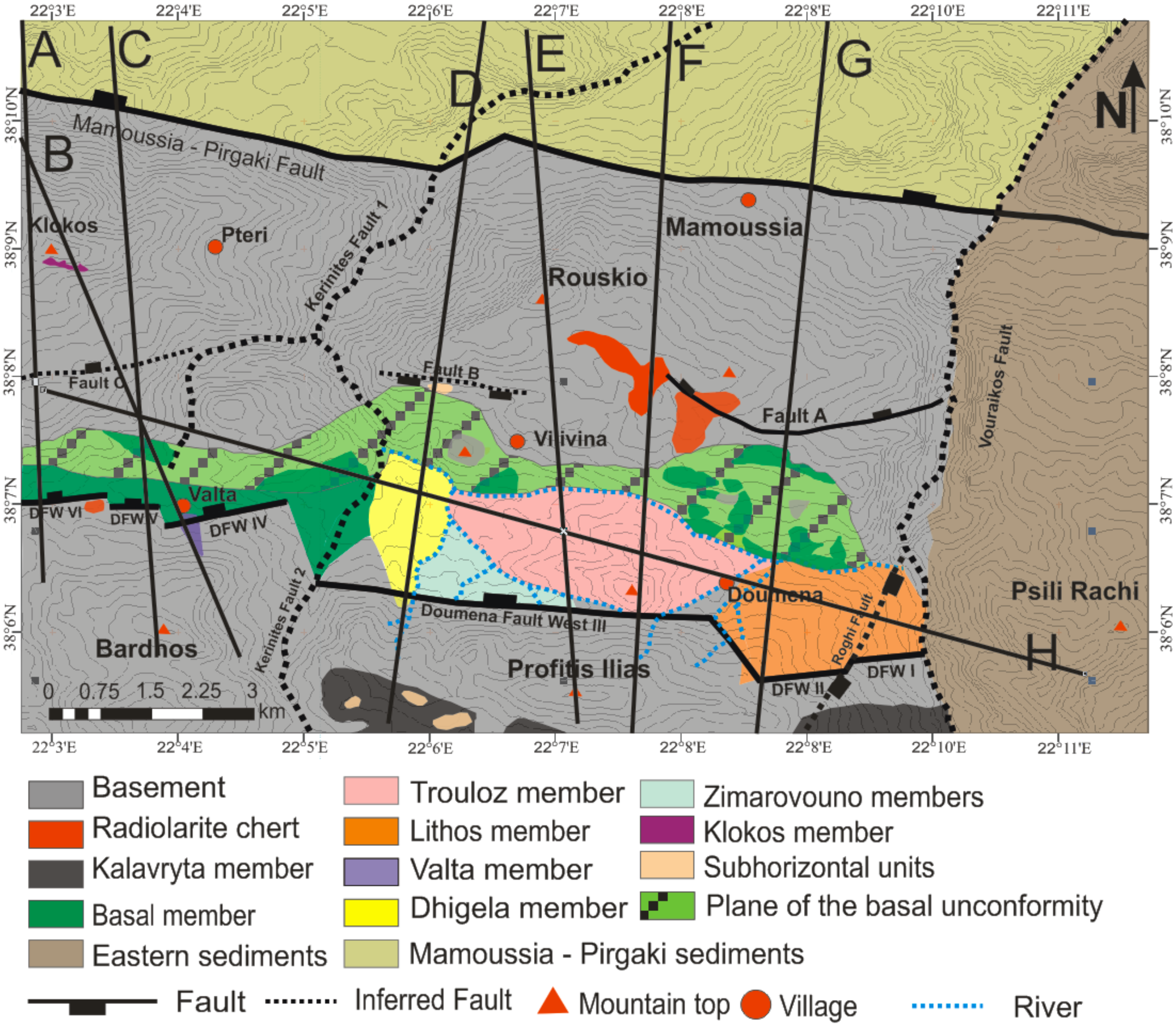


Figure 68: Map showing the locations of the crossections. Crossection A is oriented toward NW – SW, while B until F are oriented north to south and crosssection g and H are east – west oriented.

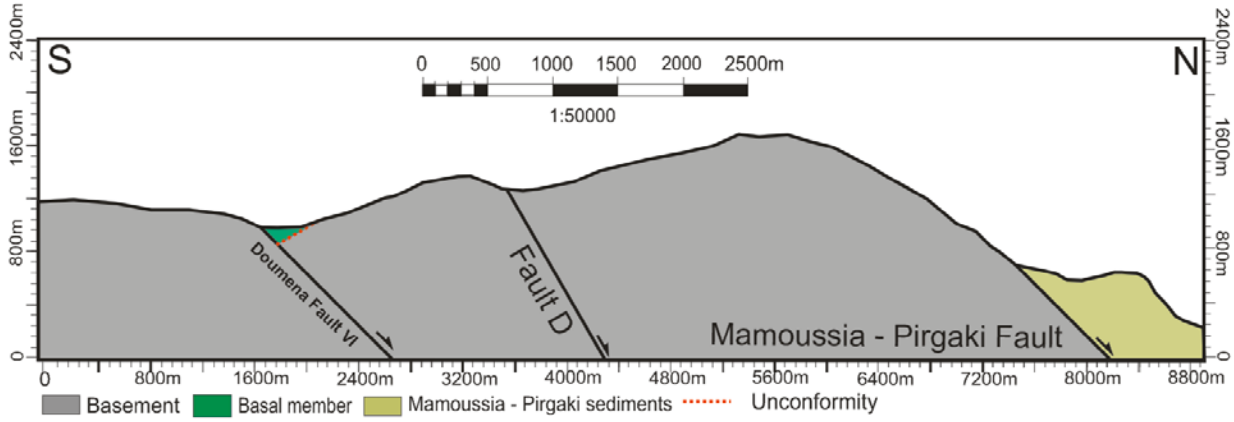


Figure 69: Crossection A, the westernmost cross section. This section display the displacement of the Doumena Fault VI. This segment has the least displacement of the six segments, and at this location the Doumena Fault VI has has a displacement of 420m.

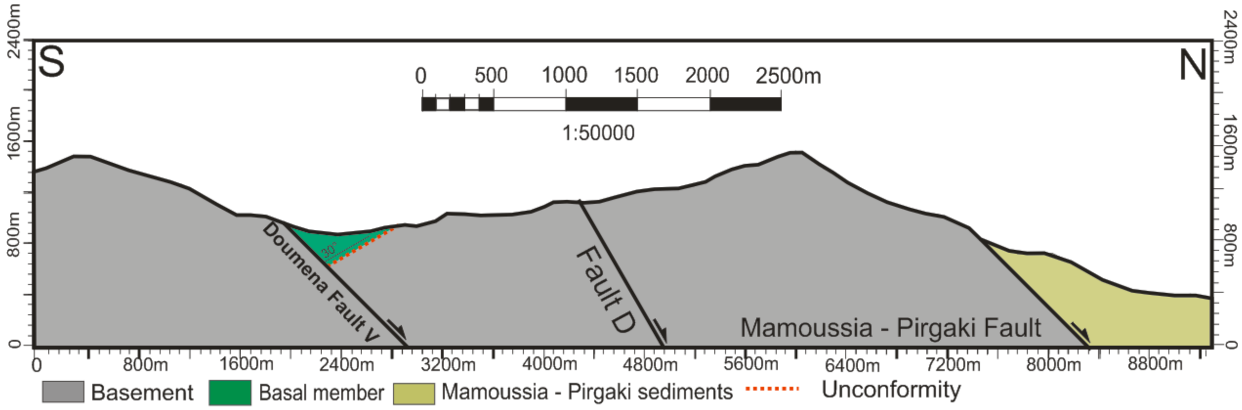


Figure 70: Crossection C. This section display the displacement of the Doumena Fault V- this segment has a displacement of 410. The displacement of Fault D is unkown, but it is suggested to be a maximum of 300m at the western end.

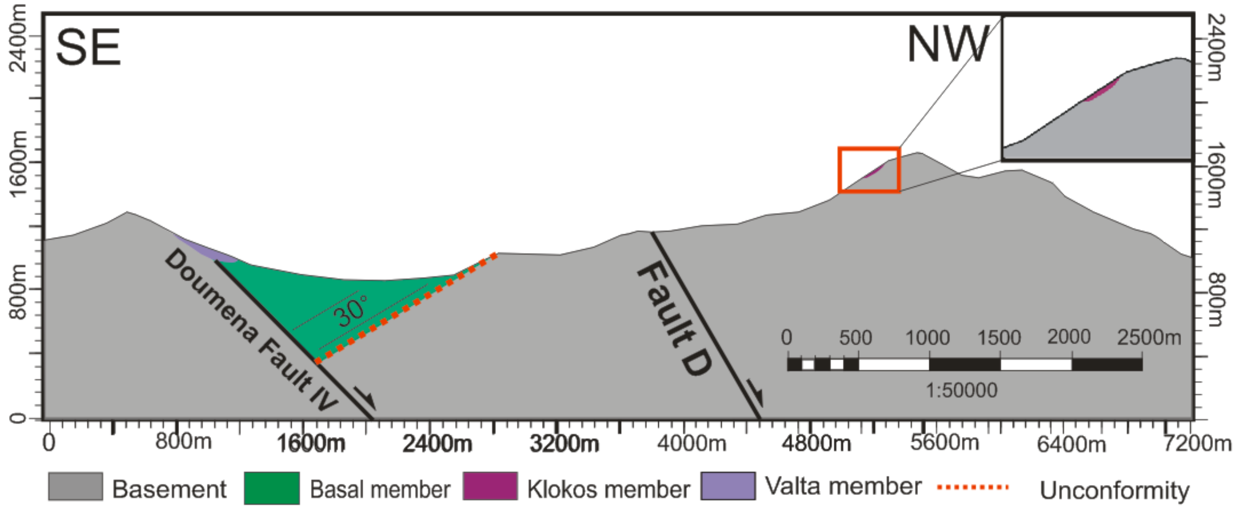


Figure 71: Cross section B. This section show the displacement of Doumena Fault IV, this segment has a displacement of 880m. Note that this section is not paralell to the immideate uplifted hangingwall, and therefore show a larger displacement.

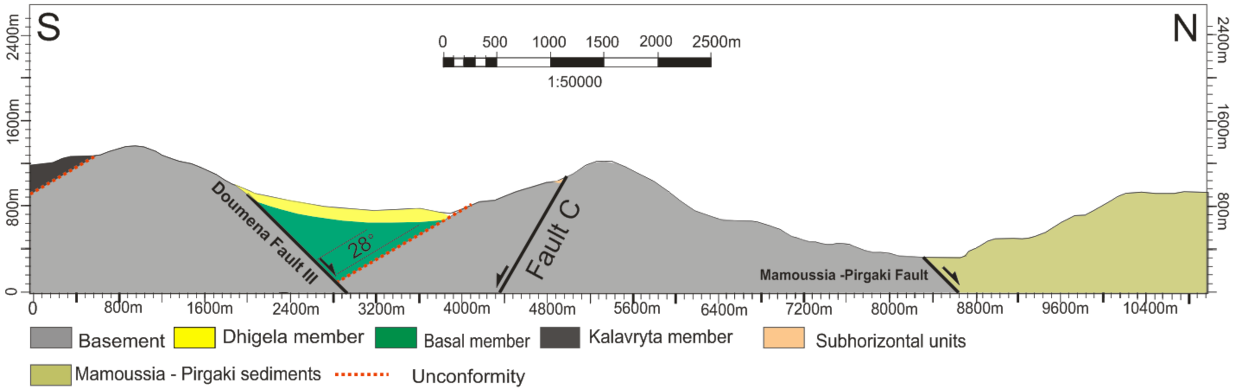


Figure 72: Cross section D. This section show the displacement of the western part of Doumena Fault III. The segment has a displacement of 1520m.

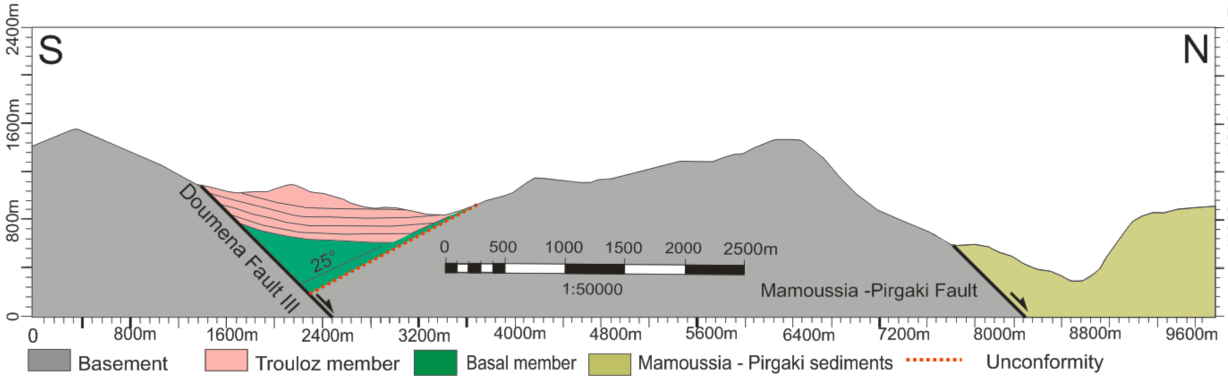


Figure 73: Cross section E. This section show the displacement of the central part of Doumena Fault III. The western part of the segment has a displacement of 1420m.

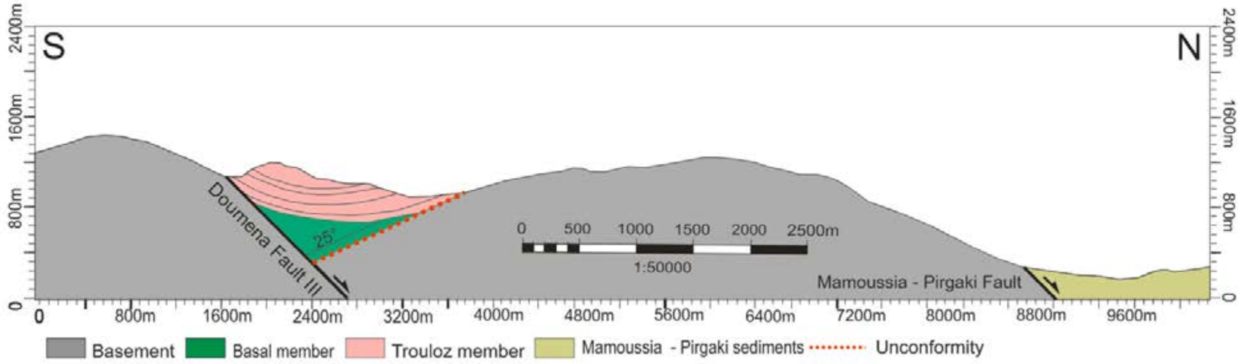


Figure 74: Cross section F. This section show the displacement of the eastern part of Doumena Fault III. The eastern part of the segment has a displacement of 1170m.

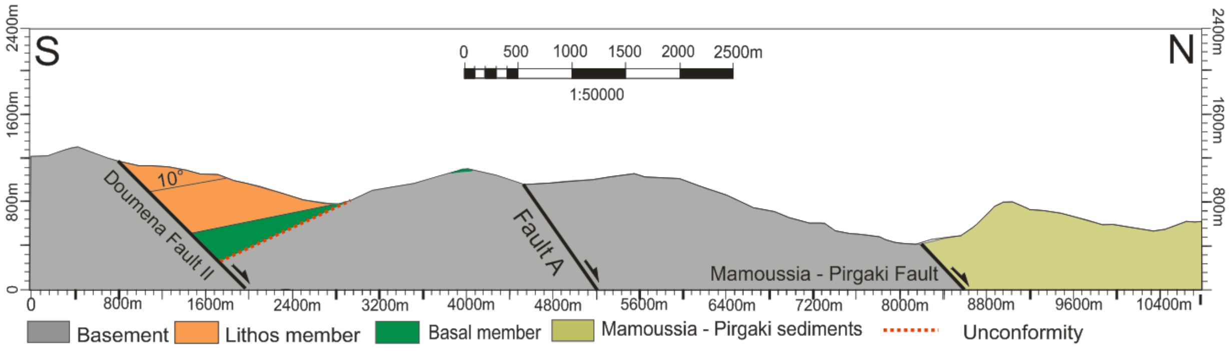


Figure 75: Cross section G. This section show the displacement of Doumena Fault II. The segment has a displacement of 1110m.

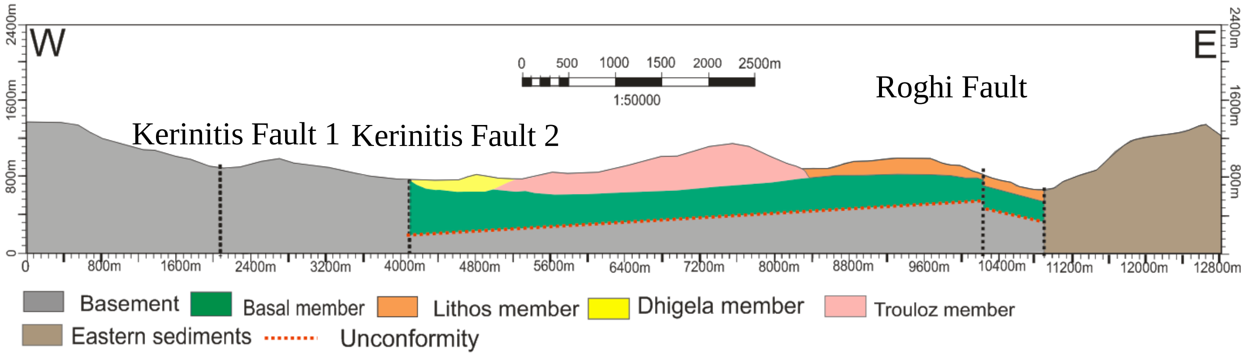


Figure 76: Cross section H. This is the east – west crosssection. Four possible transfer fault have been marked by dashed black lines. The uconformity within segment III drop in hegiht toward the west, because the Doumena Fault is stepping to the north. The eastern part of the segment has a displacement of 1040m, that increase due to the Roghi Fault.

6.5 Relative age

6.5.1 Relative age

The Doumena Fault Block can be defined as a single tectonostratigraphic unit where stratigraphic units are divided by several stratal surfaces. The displacement of the Doumena Fault has largely influenced the geometry of the stratal surfaces, and the characteristics of the facies that have been deposited in the Doumena Fault Block. In this section, (i) the angular relationship between the key stratigraphic units and the immediate hanging wall of the Doumena Fault, (ii) facies characteristics and (iii) abrupt changes in facies was applied to separate old and young units of strata, since the factors have a chronostratigraphic significance. Limited outcrop availability and exposure due to heavy vegetation, farmlands or interfingering of stratigraphic units made it difficult to interpret at some locations. However, by tying together outcrop descriptions one was able to get a general understanding of each of the stratigraphic units.

Five different phases of deposition were established for the Doumena fault Block. The first phase was the deposition of the basement, before there were 4 four different phases of syn rift deposition.

1. Deposition of the basement that is made up of limestone and radiolarite chert.
2. The Basal member lie parallel to the immediate hanging wall of the Doumena Fault, and it makes up the Pre – Doumena Fault unit in the Doumena Fault Block.
3. The lower part of the Trouloz member that is comprised of marl.
4. The upper part of the Trouloz and Dhigela members that contain rounded clasts, and possibly the Lithos Member.
5. The deposition of the very recent Lithos and Klokos members.

Observations along the stratal surfaces in the stratigraphic units generally include shifts in the angular relationship, erosion or basinward shift in facies. Nonetheless, there are also sharp lithological boundaries, as between the radiolarite chert and the basement that does not show basinward nor landward shift in facies. The surfaces show a wide variety of characteristics with unconformities, marker beds, planar and non-planar surfaces in combination with erosive surfaces and lithological boundaries.

6.5.2 Types of surfaces

The stratal surfaces in the key stratigraphic units feature mainly two different types of unconformities that include either basinward shifts in facies, clear truncation or angular unconformity between the deposits, indicating a time of non-deposition. The two main types of unconformities that have been recognized when establishing relative age are the angular and basal unconformity. A short description for each of the unconformities are stated below.

6.5.3 Angular unconformity

Several of the stratigraphic units un the Doumena Fault Block show angular differences between strata, with truncation of the underlying inedclined beds, indicating several angular unconformities. The surfaces in the Doumena Fault Block are both horizontal and inclined relative to the immediate uplifted hanging wall. They have different characteristics featuring fluvial and alluvial fan sediments interfingering above and below the unconformity, where one can observe clear erosion of the underlying stratal packages.

The angular unconformities seen in the Doumena Fault Block are have been interpreted to be due to rotation of the immediate footwall and hanging wall of the Doumena and Kerpini Fault. The rotation of the fault blocks shifted the depositional center toward the footwall of the Doumena Fault, were strata that was inclined at a low angle or parallel to the immediate hanging wall of the Doumena Fault was was truncated by an overlying depositing unit in the form of alluvial, colluvial or fluvial sediments. In addition, erosive surfaces due to migrating alluvial or fluvial systems might have created angular differences internally in the fluvial or alluvial unit, by toe cutting or incision.

The angular unconformities could also be a result from asymmetric subsidence related to basin formation, tectonism, regional response to flexural loading, extreme weather event or seasonal autogenic to long term geomorphic processes. However, this is not discussed in this thesis.

6.5.4 Disconformity

The Doumena Fault Block have a very well exposed basal unconformity. The basal unconformity can be classified as a disconformity that divide the parallel to sub parallel bedded strata with the basement with no clear sign of an unconformity. However, when traced up along the hanging wall, toward the basin flanks the surface often changes and truncate due to the sub angular relationship. This is quite evident in the Doumena Fault Block were the parallel to sub parallel layers indicate an unconformity along the entire surface.

The surfaces are interpreted as disconformities, or paraconformities, within parallel-bedded strata where there are no clear signs of an unconformity, paraconformities can generally be recognised within alluvial fan units in both the Doumena and Kerpini Fault Blocks, while the basal unconformity is viewable as a laterally extensive plane in the Doumena Fault Block.

Chapter 7: Discussion

7.1 Introduction

This chapter will summarize and discuss the most important observations described in the previous chapters. Chapter 4, 5 and 6 have described the different stratigraphic units, facies and faults in the study area. The chapter will attempt to link the different observation together in order to answer the problems addressed in this thesis.

1. Identify and distinguish the different sedimentary units in the Doumena Fault Block.
2. Determine the relative age of the different units in the Doumena Fault Block.
3. Determine how the Doumena Fault has influenced sedimentation.
4. Confirm the presence of the fans identified by Ford et al. (2013) and Kolbeinsen (2013).
5. Compare structural and stratigraphic features between the adjacent fault blocks.
6. Develop a tectono- sedimentary evolutionary model for the Doumena Fault Block.
7. Determine if the cross faults seen in the Kerpini Fault Block continue into the Doumena Fault Block.

This study is the first detailed study in the Doumena Fault Block, and the work done in this Fault Block does therefore represent frontier work. This section will try to summarize and solve the main objectives for this thesis and present a tectono - stratigraphic model for the Doumena Fault Block.

7.2 Facies Distribution – Doumena Fault Block

The main aim of this study was to identify and distinguish the different sedimentary units of the Doumena Fault Block. Moreover, determine the relative age of the different units in the Doumena Fault Block. Poor outcrop exposure, heavy vegetation and the extent of the area is 65 km^2, meant that it would be a difficult task and a lot to cover.

Six stratigraphic units, six different lithologies (shale, breccia, limestone, radiolarite chert, conglomerate and marl) and four different facies associations of conglomerate have been identified in the Doumena Fault Block. The stratigraphic units of the Doumena Fault Block have been given a general description in this thesis in addition to the fans that was proposed by Ford et al. (2013) and Kolbeinsen (2013). Following the nomenclature in the area, each of the stratigraphic units in this thesis has been named after the nearest mountain, river or village.

7.2.1 Clast composition

Clast composition of the conglomerate in the Doumena Fault change based on the stratigraphic unit. But, generally the conglomerate in the west contain less sandstones than the conglomerate in the east close to the Lithos member where they are more abundant. This might correspond to significant channels in the Kalavryta fan that later have been eroded or redeposited. The conglomerate is generally dominated by sub angular to angular limestone, however some of the more recent deposits show more rounded and well sorted characteristics. Chert usually display as sub angular, and this is mostly attributed to the hardness of the radiolarite chert (7). Clasts generally fine towards the north and west, and this can be seen from the paleo currents, throw profile and the river system.

7.2.2 Sediment provenance

The Vouraikos and Kerinites river have been interpreted to be the main sediment source in the greater Kalavryta – Diakofto area. The Doumena Fault has a distinct maximum displacement at the toward the Kerinites river in the central part of the Doumena Fault Block. Up dip in the Kerinites river this is the equivalent to the western part of the Kerpini Fault block. The Vouraikos and Kerinites river has been interpreted as an antecedent river that were the main sediment source in the Kerpini and Doumena Fault Block. Initially it is suggested that the rivers might have run straight south – north orthogonal to the Kerpini and Doumena Faults early in the evolution of the faults onshore. And as the faults propagated, the uplifted immediate footwall would act as a barrier for the river, forcing it to step and possibly reverse it course for some period of time with increasing displacement in the Kerpini Fault Block. Depending on the strength of the river, this would then lead to incision and deposition in the Doumena Fault Block of coarse grained facies. Footwall uplift have played an important role in sedimentation early syn rift and it could at least partly control the direction of paleo drainage.

7.3 Structural development

7.3.1 Introduction

Several faults have been described in the structural observation chapter. Some of these fault was identified in previous projects while others were first introduced in this project. The Doumena Fault and the interaction between transfer faults (Vouraikos, Kerinites I and I, Roghi Fault) will be considered in this subsection.

From the throws calculated from the cross section is evident that the Doumena Fault truncate against the Vouraikos Valley with significant displacement, and that the displacement across the Kerinites Fault II and I coincide with a step in the Doumena Fault. Additional evidence of the Vouraikos Fault have been interpreted as a transfer fault because Fault A has an approximate displacement of 300m west of the fault, while to the east of the fault it is absent. This imply that Fault A terminate against the Vouraikos Fault with a significant displacement of 300m or more. The Vouraikos Fault also coincide with the area where the Doumena Fault have been interpreted to step at least 600m to the right (south), and the Kerinites Fault step 750m left (north) from west to east.

An observation supporting this is that both the displacement and width of the Doumena Fault Block increase from the Vouraikos Valley (east) toward Kerinites River (west). Even though the Corinth Rift is less extended and less mature in the western part of the rift compared to the eastern part of the Corinth Rift (Sachpazi et al., 2007).

The development of the syn rift units situated in the Doumena Fault Block is believed to have initiated in Pleistocene, and this thesis will argue that it was controlled by the Doumena Fault combined with relay ramps and transfer faults that cut through several different half grabens (subchapter 6.3). In this study several observations supporting the presence of transfer faults have been presented, and the transfer faults that crosscut the Doumena, Kerpini and Mamoussia - Pirgaki Fault Blocks are believed to have acted as pathways for sediment distribution, in addition to controlling basin configurations affecting the bathymetry and width.

The current tectono-stratigraphic model by Ford et al. (2013) does not take into account the existence of transfer faults. Even though the elevation of the unconformity change up to 500m at several localities across the N-S trending rivers (Vouraikos, Kerinites). They explained the asymmetric evolution of the basins in the Northern Peloponnese to be due to significant paleo topography inherited from the Alpine orogeny. However, their assumption that the bedrock have experienced extreme differential erosion at only some locations seem highly doubtful, and should be questioned since these changes appear across linear to curvilinear features (south - north rivers), that they occasionally recognize as cross faults.

Ford et al. (2013) calculated the maximum displacement of the Doumena fault Block to 800m by using the basal unconformity, and truncate it against the fault at depth. The same procedure was followed in this thesis and the maximum displacement was measured to 1520m. The large difference in displacement ~720m by enabling the same method should not be possible. According to Ford et al. (2013), she stopped her projections at ~1km on the basis that the basement offshore have a curved to biplanar geometry at depth (50° → 30°). This method of determining displacement seem structurally inconsistent and at best highly speculative, since there are no data to constrain fault geometry onshore. In addition, the pronounced north west - westwards deposition of the Trouloz member toward the Kerinites River observed in this thesis, have previously been explained to be a anomalous by Ford et al. (2013) since it does not fit her structural interpretation. However, with the transfer fault and the current displacement measurements it is structurally consistent (Cross section H).

7.4 Pre - Doumena Fault Strata

7.4.1 Kalavryta and Basal members

The Kalavryta member are considered the oldest sedimentary deposits in the Kalavryta and Kerpini Fault Blocks. It is part of a larger alluvial fan system that is suggested to be sourced from the Kalavryta Fault (Hadland, 2016; Wood, 2013). The unit sits unconformable on top of the basement in both of the respective fault blocks and it is presently been defined to be of pre - Kerpini Fault origin due to the lack of growth strata and paleo flow currents (Hadland, 2016; Stuvland, 2015). However, it has also been postulated that the lack of growth strata could be due to periodic movement of the Kerpini Fault (Syahrul, 2014). Therefore, assuming this alluvial fan is pre-Kerpini Fault, it is thus also pre-Doumena Fault based on the assumption that the faults to the north are younger.

Observations made during this thesis suggest that the Doumena Fault Block is also comprised of both pre and syn Doumena Fault strata. The Basal member have previously been interpreted as the fluvial sandstone and conglomerate by (Ford et al., 2013). However, based on observations in this study it would be more accurate to define these south dipping conglomerates as alluvial, origination from south with a flow direction toward northeast. The Basal member sit on top of the basement in the Doumena Fault Block, and represent the oldest deposit in the Doumena Fault Block. It is here suggested that it is the northern extension of the Kalavryta member. This imply that a large alluvial fan most likely sourced the Kalavryta fault were present before the Kerpini and Doumena Fault were active. Conglomerate clasts are larger for the Kalavryta member than the Basal member, and both contain thin sandstone lenses. Better sorting in the Basal member might be attributed to more streamflows have created moderately to well sorted conglomerates. Within some aspects, their sedimentary structure is similar, only that the clasts in the Kerpini and Kalavryta Fault Block are much coarser (cobble to boulder), chaotic and that the beds are worse defined. The theory of a large alluvial fan sourced from the south is supported by Ford et al. (2013) and (Wood, 2013). Their work is rather simplistic and the larger Kalavryta Fan is put as a single package across the Kalavryta, Kerpini and Doumena Fault Blocks. Both authors believe the large alluvial fan expanded to the Doumena Fault Block.

7.4.2 Syn – Doumena Fault Strata

7.4.2.1 Trouloz member

The Trouloz member is the main target of this thesis. One of the objectives in this thesis was to confirm the presence of an alluvial fan that was previously proposed by Ford et al. (2013).

The Trouloz member can generally be divided into two sections; the upper and lower section that represent two distinct facies separated by an unconformable surface. The upper part of the Trouloz member is made up of conglomerates, whereas marls dominate the lower part. The origin of the marl will be discussed in detail below as it could represent different depositional environments.

Upper part

The upper part of the Trouloz member consist of coarse conglomerates that become more mature toward the northwest, away from the Doumena Fault. This is evident from the decrease in conglomerate clast size, transitional morphology of the bedding and thinning of the beds towards the west. In addition to the lateral facies changes, vertical changes can also be observed, where ungraded and chaotic conglomerate show at least three phases of rough normal grading throughout the vertical section. The facies become most immature at the Trouloz peak in the middle of Doumena Fault III. This suggest that the apex of the fan is located at the top of the Trouloz member (1224m) and that the upper part of the fan is sourced orthogonal to the Doumena Fault. The decreasing bed thickness and clast size away from the apex could be due to loss in the depositional energy and flow capacity.

Lower part

The lower part of the Trouloz member is the largest part of the alluvial fan. It is composed of fine-grained marl that have been unconformably on lapped by coarse conglomerates. The fine-grained marl represent an anomaly in the Doumena Fault Block, since other sedimentary deposits in the Kalavryta and Kerpini Fault Block (up dip relative to the Doumena Fault Block) have much coarser clasts\ grains. According to Blair (1987) this can represent a sudden transition to a lacustrine environment, and it could also explain the anomalous deposition of fine-grained material early syn rift.

Structural geometry

The geometry of the bedding in the Trouloz member make up a gently folded syncline or bent soft deformation structure. This is based on the interpreted geometry of the bedding in Figure XX. The longitudinal fold of this unit suggest that it must have been in place early in the development of the Doumena Fault, otherwise the geometry of the beds should be different.

Gently folded monoclinal structures in extensional settings is generally a product of either extensional tectonics (folding) or soft deformation (sedimentary). This yield four possible solutions that can explain the geometry of the Trouloz member: Fault propagation fold, fault bend fold, differential compaction and deposition into a lacustrine environment. Drag folds will not be discussed as an alternative her, since it can be formed from fault propagation folding, differential compaction and fault bend folding.

Based on the previous work on the Doumena Fault plane by Bastesen et al. (2009), it was concluded that the Doumena Fault have a weak a ramp-flat-ramp geometry were the length of the flat is no more than 5 – 10 m long at the most. Therefore, one can disregard that the sediments have been folded due to a fault bend fold. It would not be sufficient to create a fold with a half wavelength of 600m.

Differential compaction does not seem as a suitable alternative either since the thickness of the marl seem reasonably uniform throughout the section (south – north), and have not been compacted much more at the location where the coarse conglomerates are overlying the unit.

The evidence for either a lacustrine environment or fault propagation fold is ambiguous, and neither of the options can be disregarded. Nonetheless, due to the anomalous fine nature of the sediments, the rapid transition from large cobble to boulders clasts in the Kerpini Fault Block, to finely layered grains in the Doumena Fault Block, it is suggested here that it might represent a sudden transition into a lacustrine environment.

7.4.2.3 Dhigela member

Based on the roundness, the moderately well sorted clasts, the location of the fan at the base of the mountain, the general fining upward sequence of the beds at the toe, and the continuous parallel bedding this fan can be interpreted to be of alluvial origin, with substantial fluvial input with stable sediment supply for a significant period of time. The Dhigela member have a very elongate fan (Figure 16) shape perpendicular to the Doumena Fault. The shape of the fan indicate that there was substantial accommodation place at the time of deposition that the sediments utilized. It is here suggested that the accommodation space could be a result of recent extension, reactivation of pre-existing structures (transfer faults) and or previous lack of sediments.

7.4.2.4 Lithos member

The Lithos member is today an active colluvial fan that deposits debris flows due to heavy rain or melting snow. This is based on the position of the apex high up on the mountain slope and the large immature clasts that can be observed near the toe at the fan. There are several indications for that the Lithos member was a previously an alluvial fan. This is supported by the coarse grained, sub angular to sub rounded massive conglomerate with thick normal graded sandstone beds that are located close to the apex of the Lithos member. It is dipping toward the fault, and it indicate that it was deposited possibly prior to rotation. For the evolutionary model the Lithos member have been assumed to be either late or post Doumena Fault.

7.4.2.5 Eastern sediments

The thickness of the eastern sediments are much greater than similar deposits in the Doumena Fault Block. And this thesis will argue that the main reasons for the difference in thickness, is that the Vouraikos River (Demoulin et al., 2015) that represent a large antecedent drainage network, have transported and deposited the sediments toward northeast, east of the Doumena Fault Block into large accommodation zones created by the Vouraikos Transfer Fault. Different segments in an extensional rift setting develop independently from each other due to the transfer fault, and the larger Vouraikos River is much more likely to have deposited larger quantities of sediments during early syn rift than the smaller Kerinites River.

Additionally, the mean northeast direction of the sediments in the larger Kalavryta – Diakofto area coupled with the Klokos and Skepasto Mountains that act as a sediment barrier into the Doumena Fault Block from the Seliounas river is likely to have prevented sediments from reaching the Doumena Fault Block. The current models on sedimentation in rift systems does not take into account the presence of an pre-existing antecedent drainage system (Figure XX), and the effect of it during early syn rift. Below is an updated figure for sediment yield in an area which are supported by an antecedent drainage system.

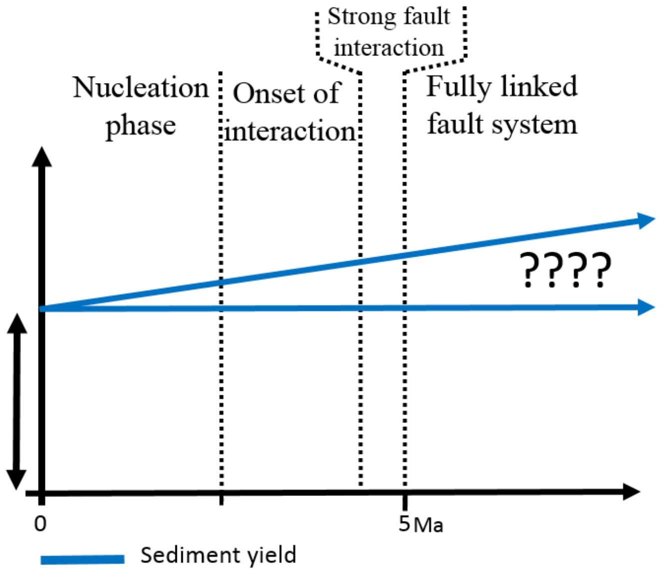


Figure 77: Showing an updated model for sediment yield for an area that is supported by an anteceden drainage systm. Modified from (Cowie et al., 2006)

7.4.2.6 Relative age

The relative age for the different stratigraphic units in the Doumena Fault Block can be fitted within Lower Group of the tectonostratigraphic model by the Ford et al. (2013). The Lower Group is subdivided in the Lower, Middle and Upper sections. It would yield the following result.

Table 5: Table of the main stratigraphic units divided into the lower, middle and upper section of the Lower Group.

Doumena Fault Block	Upper	Lithos and Klokos members
	Middle	Upper Trouloz and Dhigela members Lower Trouloz (Marl) member
	Lower	Basal member

7.5 Evolutionary model for the Doumena Fault Block

The evolutionary model of the Doumena Fault Block has been generated based on the field data and the current understanding of the Doumena Fault Block.

Stage 1: Alluvial fan.

The first stage of the evolutionary model assume that the Kalavryta Fault is active, and that the deposition of the Kalavryta member stretch into the Kalavryta, Kerpini and Doumena Fault Blocks. It is uncertain wether the deposits originate from the vicinity of the Kalavryta Fault from a single point source or several different sources. Large significant channels within the alluvial fan stretch from the Kalavryta Fault Block in the South toward the Doumena Fault in the North At this stage the Kerpini and the Doumena Faults are inactive, and the Doumena Fault Block is assumed to represent a slightly tilted planar surface..

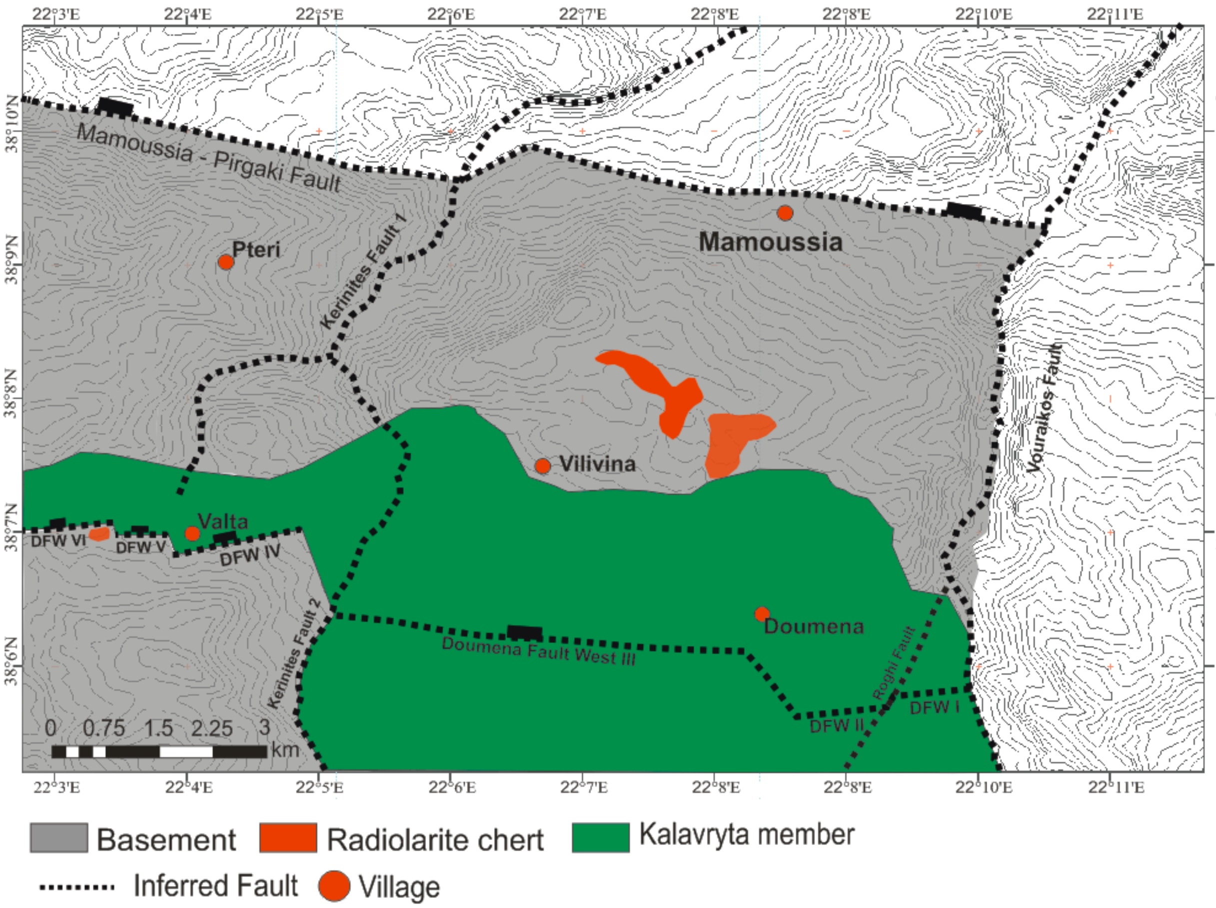


Figure 78: Stage 1 of the evolutionary model when the thick basal Kalavryta member was deposited.

Stage 2: Lacustrine environment

During the second stage of the evolutionary model the Doumena Fault displaces the Kalavryta member together with at least one transfer fault. The second stage requires the Doumena Fault and the Kerinitis Fault II (Transfer Fault) to be active in order to have a significant barrier that can form the lacustrine environment and get the deposition of the marl, that trend toward the Kerinitis river. It is here assumed that the fault blocks have not been incised.

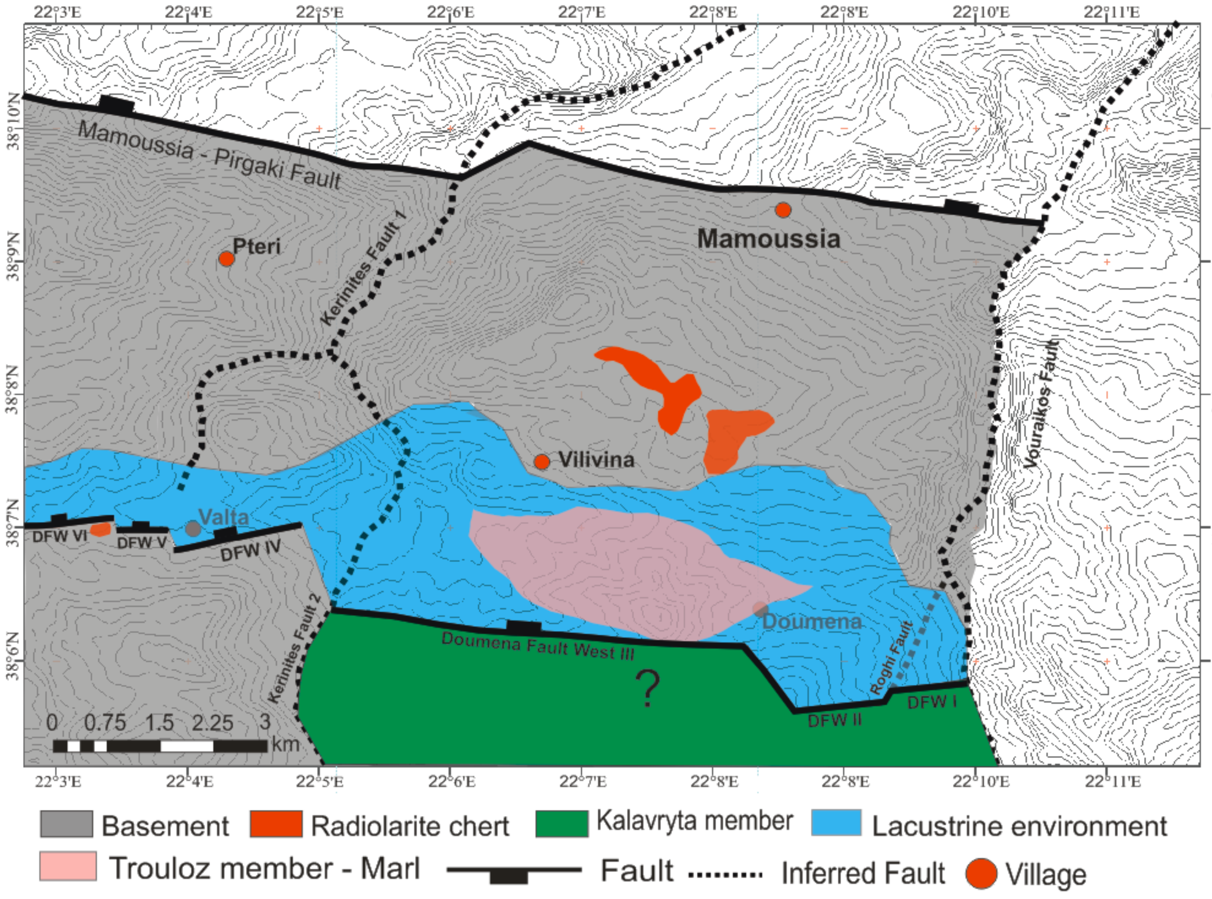


Figure 79: Stage 2 of the evolutionary model. Deposition of the lower section of the Trouloz member in an lacustrine environment.

Stage 3: Fluvial incision

During the third stage fluvial incision cut through the Kerpini Fault Block and it lead to the deposition of the Dhigela, Zimarovouno and Trouloz members (coarse conglomerates). Remnants after this event can still be seen in the form of sub- horizontal sediments located high up on the flank of the Kerpini Fault Block. The common denominator for the units is that they have rounded and relatively coarse grained deposits. The Zimarovouno members are here assumed to be a result of a migrating river due to increased displacement on the Kerpini Fault (The displacement is highest toward the east in the Kerpini Fault Block). Valta member have been interpreted to have been deposited later in the transition to the upper section.

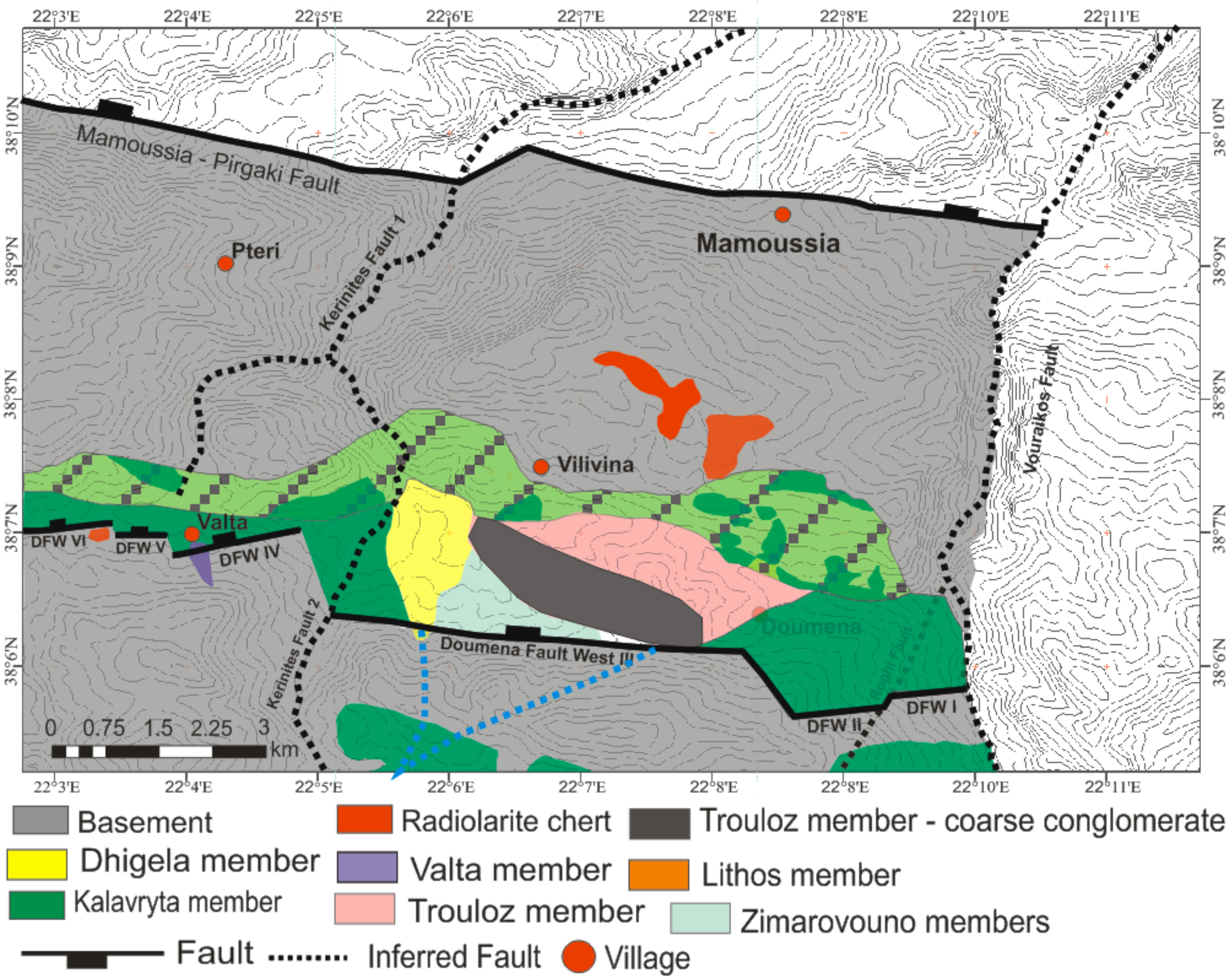
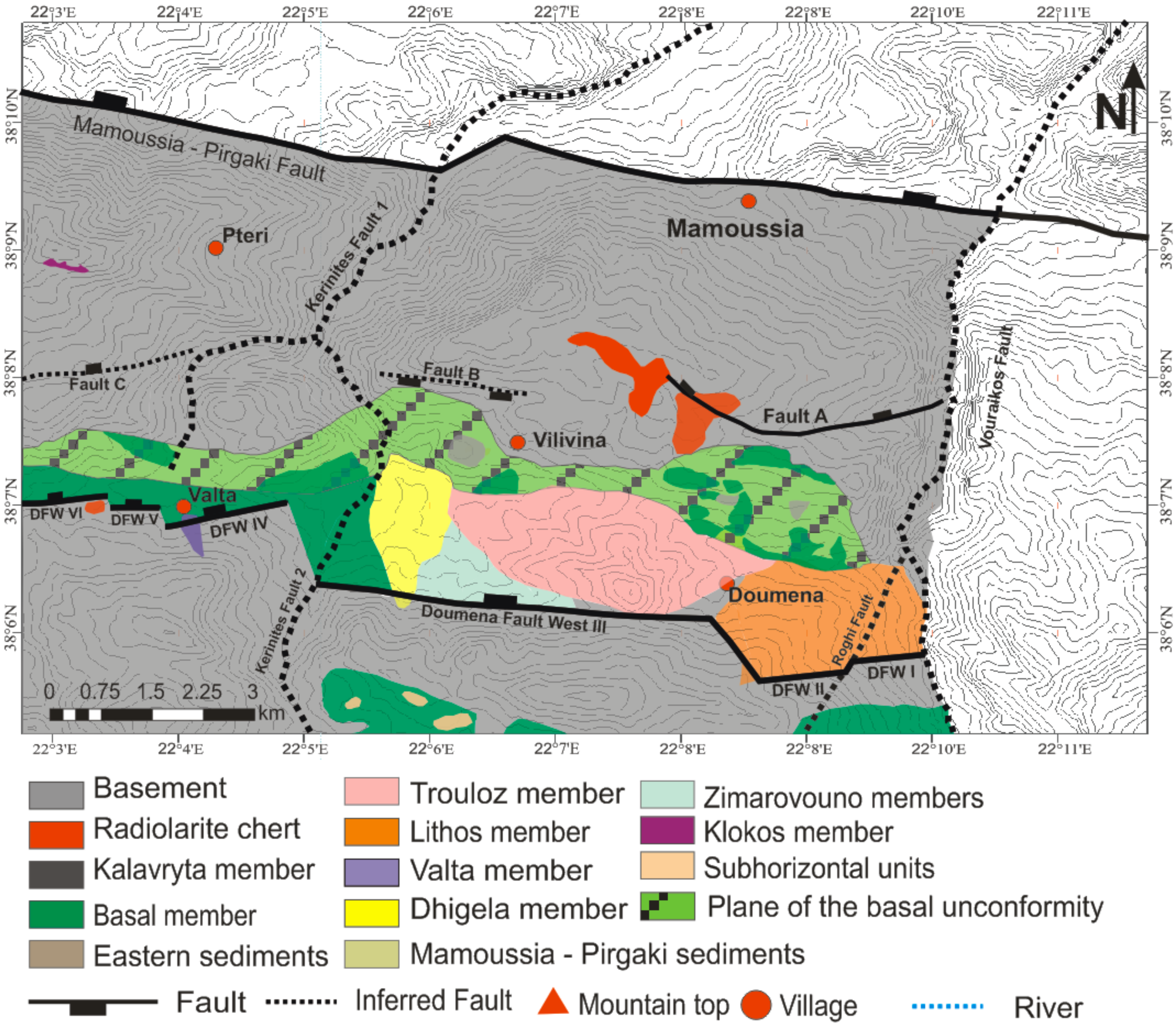


Figure 80: Stage 3 of the evolutionary model.

Stage 4: Late to post Doumena Fault colluvial deposition.

During the late syn or post Doumena Fault the Klokos and Lithos members were deposited. These represent unlithified and poorly consolidated sediments. They are gravity driven and they have been interpreted to be a direct result of rotation and uplift of the different fault blocks. The age of the basement faults are here inferred to be late syn or post Doumena Fault.



‘Chapter 10: Conclusion

The Doumena Fault Block had not been studied in great detail before this thesis project, and only a few detailed local studies had been undergone in the area (Bastesen et al., 2009; Kolbeinsen, 2013). This thesis project has contributed further to increase the knowledge and understanding of the Doumena Fault Block.

The Doumena Fault Block consists of several stratigraphic units that contradicts some of the previous work that have been done by Ford et al. (2013) were a general and simplified stratigraphic framework was applied. The presence of these smaller intrabasinal members imply that a general stratigraphic framework for the Gulf of Corinth Rift system cannot be applied to fit within individual fault blocks.

The most important conclusion that can be drawn from this thesis is that:

- The Doumena Fault Block consist of six different lithologies (Limestone, Radiolarite Chert, Shale, Breccia, Conglomerate, Marl) that represent at least three different depositional environments and at least three different phases of deposition.
- Six different colluvial and alluvial fans have been identified, whereof two different modes of colluvial deposition with debris flow and rock fall have been observed.
- Fault movement has had a big impact on the sedimentation of the internal sedimentary units in the Doumena Fault Block. This can be observed from the angular relationship that the sediments have with the immediate hanging wall of the Doumena Fault. Fault movement can cut and later Fault movement have had a large impact on the sedimentation of the deposits related The most important conclusion to be drawn is that 6 different colluvial and alluvial fans have been identified that represent at least three different fan formation processes.
- The two fans previously studied by the Kolbeinsen (2013) and Ford et al. (2013) have been investigated and it have been concluded that they are internal fans of the Doumena Fault Block.

- Doumena Fault Block consist of both pre and syn-fault strata that were deposited during the Corinth Rift. The pre – fault strata consist of the Basal member that can be correlated with the Kalavryta member in the Kalavryta and Kerpini Fault Block. The syn- fault strata consist of the Dhigela, Trouloz, Zimarovouno and Lithos members and possibly the Klokos member.
- The Doumena Fault can be subdivided into six different segments, with a right step from east to west separating the different segments. Transfer faults are continuous throughout several fault blocks and the transfer faults have been extended into the Doumena Fault Block. The Transfer faults the segment the displacement of the Kerpini and Doumena Fault at three locations, which is evident by the elevation difference of the unconformity and lithology change across these north-south trending transfer faults.

There are still unanswered questions and features that need further investigation. This thesis project has reached some conclusions that has contributed further to the understanding of the Doumena Fault Block, but the following subjects need further explanation to get an even better understanding of the Kalavryta depositional system.

- Detailed structural/sedimentological analysis of the Lithos member. This project would emphasize on establishing the relative timing and development of the Lithos member and the other stratigraphic units of the Doumena fault Block. This study could also potentially contribute to a better understanding of the relative timing between the Kerpini and Doumena Faults.
- Detailed investigation of the presence and contribution of the transfer faults within the Doumena Fault Block.
- Detailed sedimentological analysis and provenance study of the Marl in the Trouloz member in order to confirm the depositional environment.

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