University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Petroleum Geosciences Engineering	Spring, 2013 Open
Writer: Anita Kolbeinsen	 (Writer's signature)
Faculty supervisor: Alejandro Escalona	
Title of thesis: Analysis of Structural Controls in Alluvial Fan Deposition During Late Syn-rotational Faulting Phase in a Half-graben Rift System. The Gulf of Corinth, Greece.	
Credits (ECTS): 30	
Keywords: Colluvial fans Gulf of Corinth Snorre field Outcrop analogues Late syn-rotational phase	Pages: 84 + enclosure: 84 Stavanger, June 24th, 2013

Analysis of Structural Controls in Alluvial Fan Deposition During Late Syn-rotational Faulting Phase in a Half-graben Rift System. The Gulf of Corinth, Greece.

by

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Master thesis

Presented to the Faculty of Science and Technology

The University of Stavanger

The University of Stavanger

June, 2013

Acknowledgements

The following are acknowledged for their help and support during the research and writing of this thesis:

My supervisor, Alejandro Escalona, for his support, advice and comments throughout the field work and the writing process.

Chris Townsend, for introducing the field area and for guidance and discussions during the field work.

My field assistant and friend, Stine Finnesand, for her assistance, encouragement and moral support.

Lisa Bingham, for GIS support and help with the field equipment.

Andreas Habel, for computer support and help with the field equipment.

Students and other attendees on the field campaigns that have visited the Corinth rift with me, are thanked for their assistance and fruitful discussions.

Total E&P Norge and BP Norge AS are acknowledge for funding the field work.

Abstract

Analysis of Structural Controls in Alluvial Fan Deposition During Late Syn-rotational Faulting Phase in a Half-graben Rift System. The Gulf of Corinth, Greece.

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The University of Stavanger, 2013

Supervisor: Alejandro Escalona

The Kalavrita region is located at the southern margin of the Gulf of Corinth, Greece, and is considered a perfect academic and research laboratory to study the evolution of rift systems and the interaction between tectonics and sedimentation. Furthermore, individual faulted blocks, represent up to scale analogues to many rifted blocks and hydrocarbon fields at the Norwegian Continental Shelf. The wedge shaped structure situated in the hanging wall of the Dhoumena east fault was mapped in order to understand its geometry, provenance and relation to the fault and neighboring faulted blocks, e.g. the Kerpini fault. Field observations suggest that studied wedge shape is a debrisflow colluvial fan, fed from the Dhoumena footwall or Kerpini fault block and down the relay-ramp. To implement the lessons learned in the field to subsurface data, the clastic wedge shaped syn-rift structure situated in the hanging wall of Inner Snorre fault, close to the Snorre field in the North Sea, was mapped. In the Norwegian sector, these Jurassic to

Lower Cretaceous wedge shaped hydrocarbon reservoirs represents underexplored hydrocarbon plays. In contrast, across the border in the UK sector, they are producing from comparable wedge shaped strata. To explore if these syn-rift exploration plays could be profitable in the Norwegian sector, volume calculations and a study of reservoir properties were conducted. Observations of sandyfacies and calculated volumes of 11 – 12 mmboe, suggest that for a smaller oil company, the studied clastic wedge represents an attractive play, given the existing infrastructure in the region.

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1. INTRODUCTION

The North Sea region is one of the most proliferous hydrocarbon provinces in the world. Since its initiation, in 1964, the exploration targets in the region have evolved as new hydrocarbon plays emerged. The main present-day play concepts in the Norwegian sector of the northern North Sea focus mostly on uplifted footwalls and structural highs, e.g. basement highs (e.g. Brennand et al., 2009) (Figure 1A). Despite that, the steady decline in hydrocarbon discoveries imply that other underexplored hydrocarbon plays in the region, are imminent.

The syn-rift plays of the northern North Sea comprise significant remaining exploration potential, at least at the Norwegian Continental shelf (Johnson and Fisher, 2009). For instant, in the UK sector, several hydrocarbon fields (e.g. Britannia field) are producing from wedge shaped syn-rift reservoir strata situated in the hanging walls of major tilted fault blocks (Evans, 2003) (Figure 1B). Similar wedge-shaped syn-rotational packages are identified on seismic data near several hydrocarbon fields in the Norwegian sector (e.g. Snorre, Statfjord and Brage fields); however, with few exceptions (e.g. well 34/7-15S at the Snorre field), they remain undrilled (e.g. Evans, 2003; Færseth and Ravnås, 1998; Ravnås et al., 2000; Ravnås and Steel, 1997; Ravnås and Steel, 1998). These clastic wedges in the hanging wall, which are sourced from the antecedent footwalls and comparable to reservoir rocks in the present-day pre-rift plays are placed up-dip from the source rock and against the fault planes, in some cases, even structural higher than the strata from the producing (successive) footwall highs. In addition, producing fields in the region have established the presence of charged footwalls, which makes the presumption

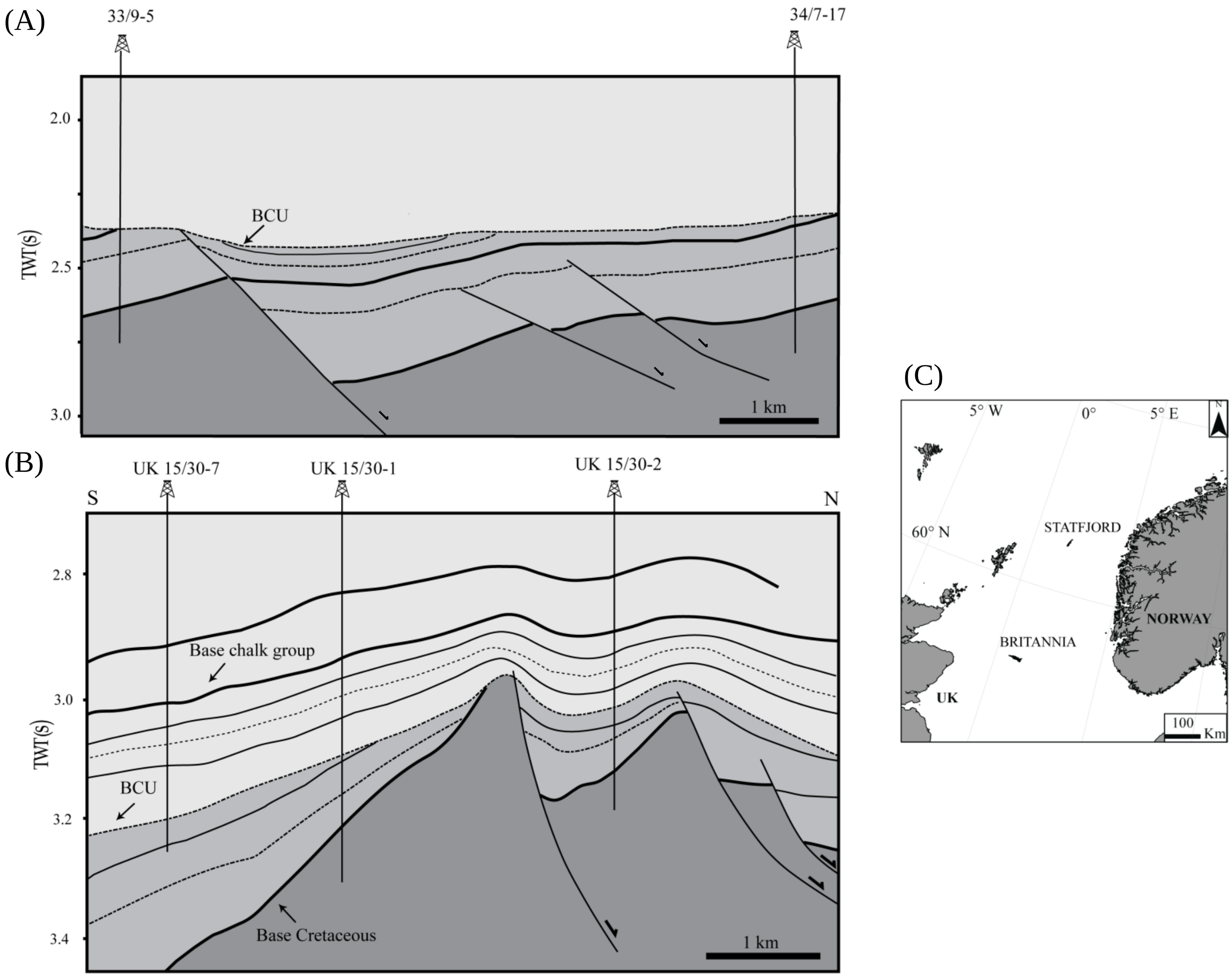


Figure 1 Schematic sketch of present-day exploration plays in the North Sea. (A) Pre-rift plays at the Norwegian sector on uplifted footwall highs example from the Statfjord field (modified after: Dawers et al., 1999). BCU = Base Cretaceous unconformity; TWT = two-way time. (B) Plays in the UK sector on terrigenous clastic wedges during late syn-rift deposition in the hanging wall from the Britannia field (modified after: Evans, 2003). (C) Map showing the location of the Statfjord field and the Britannia field.

of charged hanging walls an option, e.g. by source rock expulsion as described for the Brae field, (Karlsen et al., 2004).

To better understand if the observed late syn-rift clastic hanging wall wedges have a potential as new hydrocarbon plays in the Norwegian sector, a study of an up to scale outcrop analogue of rotated fault blocks in the Kalavrita-Diakofto region, situated in the Peloponnesus peninsula in southern Greece, was conducted (Figure 2). In terms of outcrops, the excellent exposure of seismic scale extensional faults in the region is considered to be among the most ideal locations to study modern analogues of rift structures (e.g. their 3-D geometry and tectonic controlled sedimentation) (Ford et al., 2013; Moretti et al., 2003). In addition, syn-rift clastic wedges dipping away from the fault in the hanging wall, and on top of the overlying pre-rift rocks are observed at several localities (Figure 2). These changes in sedimentation dip have been poorly studied, with the exception of the mapping of the north-dipping conglomeratic clastic wedge referred to as the Troulos fan (Ford et al., 2013), located west of the Dhoumena village (Figure 2). The Troulos fan is suggested to have occurred simultaneous with fault related folding and is interpreted as an isolated prograding alluvial fan sourced from the Dhoumena fault footwall (Ford et al., 2013). To give an input on the geometry, the volumetric and the processes responsible (Figure 3) for depositing these structures (e.g. deposited as a relay ramp fed fan; as a very late gravitational slump or deposited as late phase of syn-rotational faulting sedimentation), detailed field mapping of a north dipping conglomeratic wedge in the hanging wall of the Dhoumena east fault was conducted. This clastic wedge is located east (Figure 2) of the Dhoumena village and the Troulos fan.

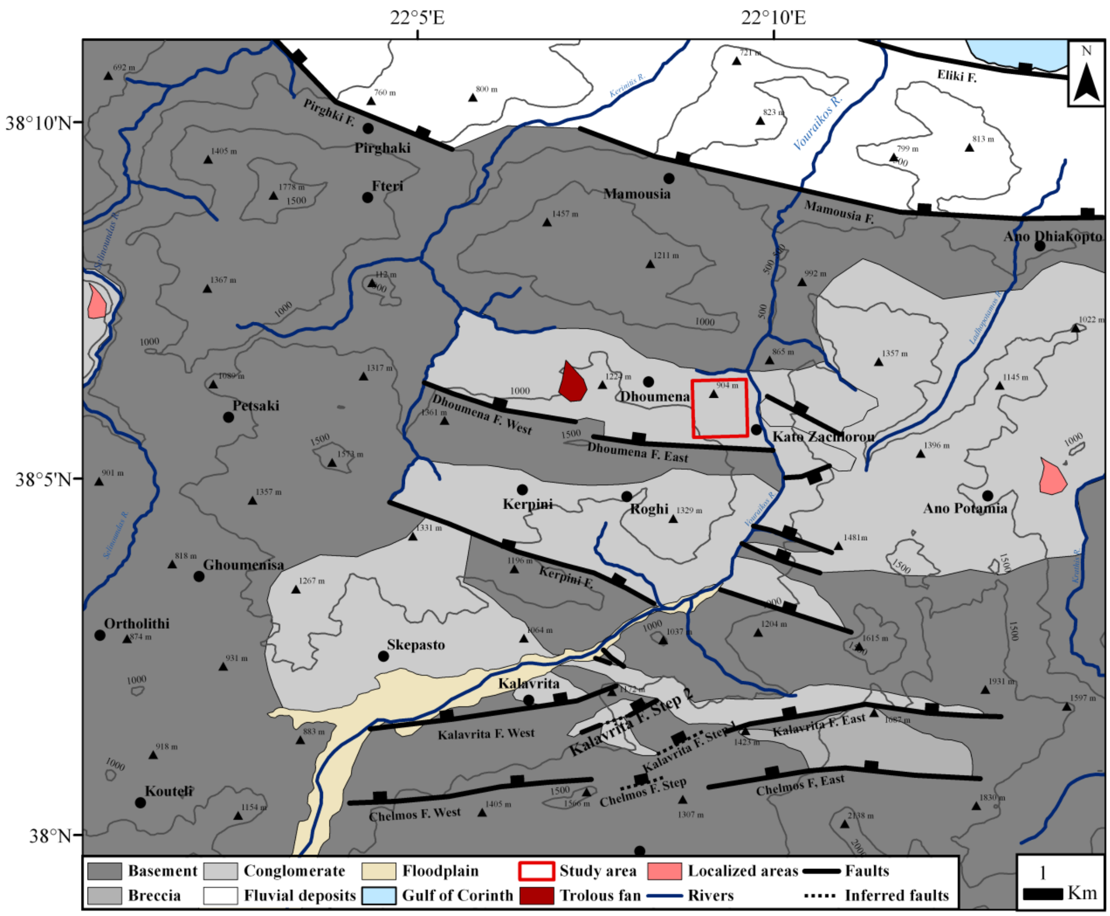


Figure 2 Field map showing the main faults and stratigraphy of the Kalavrita-Diakofto region. Boxed area represents the area of study. Localized areas of north-dipping syn-rotational strata, e.g. the Troulos fan, are displayed in red.

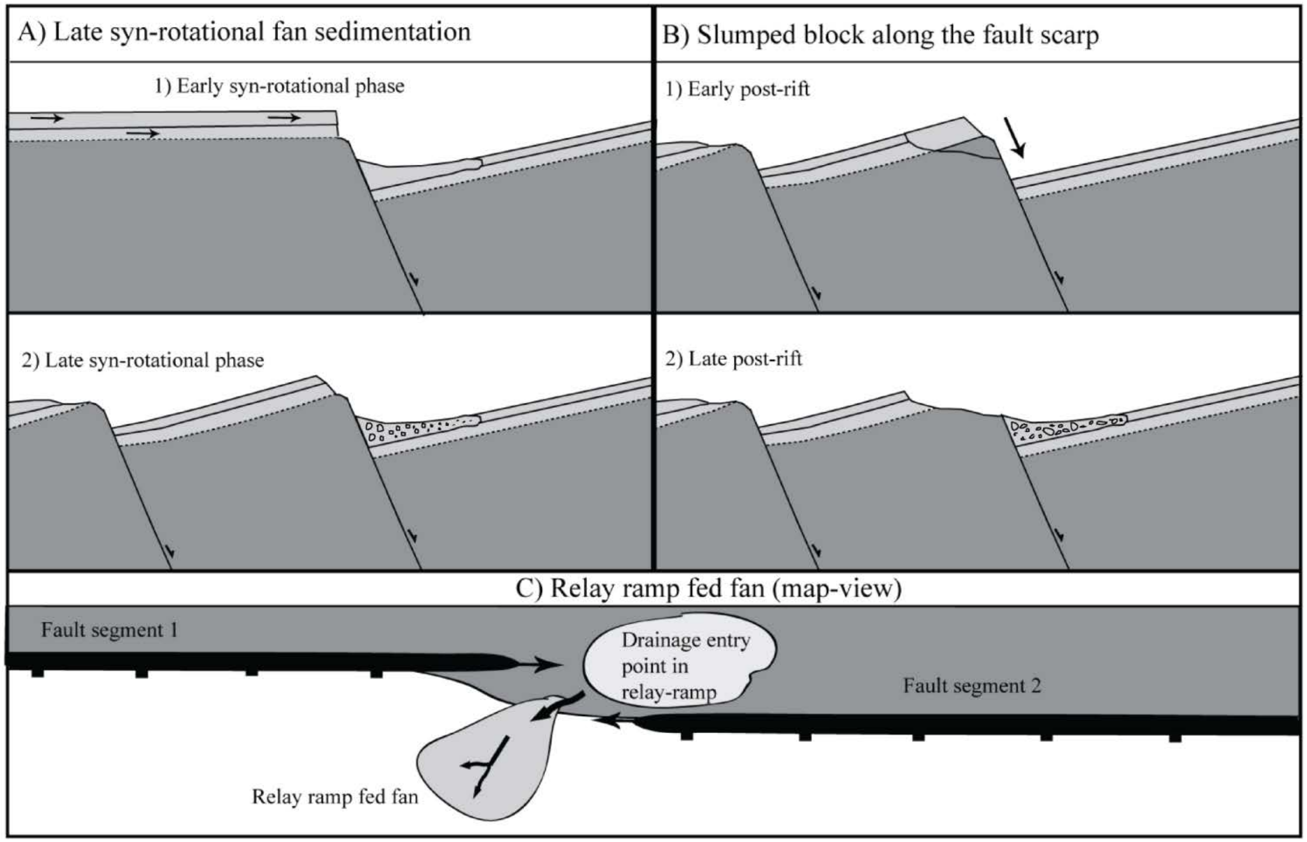


Figure 3 Schematic sketch indicating how terrigenous clastic wedges can be deposited. (A) Deposited during the last phase of syn-rotational faulting (modified after: Ravnås et al., 2000). (B) Deposited as a very late gravitational slumped block along the fault scarp (modified after: Ravnås and Steel, 1998). (C) Deposited as a relay ramp fed fan (modified after: Athmer and Luthi, 2011).

To integrate the lessons learned from the mapping of the syn-rift deposits in the Dhoumena east fault in Greece, and its application to subsurface data from the Norwegian continental shelf, the clastic wedge shaped syn-rift structure in the hanging wall of the inner Snorre fault, near the Snorre field was mapped, to further explore the syn-rift exploration plays in the North Sea region.

1.1 Colluvial Fan Classification and Deposition Mechanisms

It is suggested that observations of recent colluvial deposits, which are reported from mountainous regions and other topographically rugged terrains in virtually all climatic zones, from polar regions to the tropics, can act as small-scaled analogues of clastic marine petroleum rift reservoirs. In the northern North Sea region alone, the Jurassic reservoirs in the Helmsdale field, Claymore field, Ettrick field and Brae field can be observed under this perspective (Boote and Gustav, 1987; Harris and Fowler, 1987; Stow, 1985; Turner et al., 1987).

These colluvial fans show a wide variety of sizes, shapes and internal characteristics (depending on the dominant sedimentary processes) and are easily distinguished from alluvial fans, due to their characteristics products of avalanches processes (Blikra, 1994; Blikra and Nemec, 1998; Galloway and Hobday, 1996). In addition, the distinct features of colluvial systems differ from alluvial systems at several stages, among them the high gradient and the dominance of mass processes (Table 1). However, because of expansion of the feeder drainage area, colluvial fans can evolve into alluvial fans. Accordingly, colluvial deposits can represent an alluvial fan body core (Galloway and Hobday, 1996).

CHARACTERISTICS	ALLUVIAL FAN	COLLUVIAL FAN
Apex location	At the base of a mountain slope (valley/canyon mouth)	High on the mountain slope (at the base of ravine)
Catchment	Intramontane valley or canyon	Mountain slope ravine
Depositional processes	Debrisflow and/or waterflow (braided streams)	Avalanches, including rockfall, debrisflow, and snowflow; minor waterflow, with streamflow mainly in gullies
Depositional slope	Seldom more than 10-15° near apex, often less than 1-5° near the toe	35-45° near the apex, 15-20° near the toe
Geometamorphic setting	Mountain footplain or broad valley floor (footplain fan)	Mountain slope and its base (slope fan)
Grain size trend	Coarsest debris in the upper/apical zone	Coarsest debris in the lower/toe zone
Plan-view radius	Commonly up to 10 km, occasionally more than 100 km	Less than 0.5 km, rarely up to 1-1.5 km
Sediment	Gravel and/or sand, immature to mature	Mainly gravel, typical very immature

Table 1 Distinctive geomorphic and sedimentologial features of alluvial fans and colluvial fans (modified after: Blikra and Nemec, 1998).

Colluvium, which is variously, referred to as ‘talus’, ‘scree’ ‘debris slope’, ‘slope-waste deposits’ and ‘hillslope deposits’, are coarse grained and texturally immature slope-waste material deposited in the foot zone of a mountain slope or other topographic escarpments, brought there mainly by sediment-gravity processes (Blikra, 1994; Blikra and Nemec, 1993; Blikra and Nemec, 1998). Avalanches often dominate these highly episodic depositions of colluvial fans and are associated with mountain slopes of 15-45° (Bates and Jackson, 1987; Blikra and Nemec, 1993; Blikra and Nemec, 1998; Holmes, 1965).

The distinctive colluvial fan types deposited by rockfall/debrisfall, debrisflow, snowflow and waterflow processes are illustrated in the classification scheme in Figure 4. Rockfall dominated colluvial fans are among the steepest and shortest fans. Their steepness is controlled by the avalanche size and runout distance (Blikra and Nemec, 1998). In general, cohesive, high-viscosity dominated colluvial debrisflows fans are comprised of relatively broad gravel lobes and are typically steeper than watery or wet snow bearing fans. The latter fans are dominated by more mobile, lower-viscosity debrisflows, which commonly shows elongate scour-and-lobe features (Blikra, 1994; Blikra and Nemec, 1998).

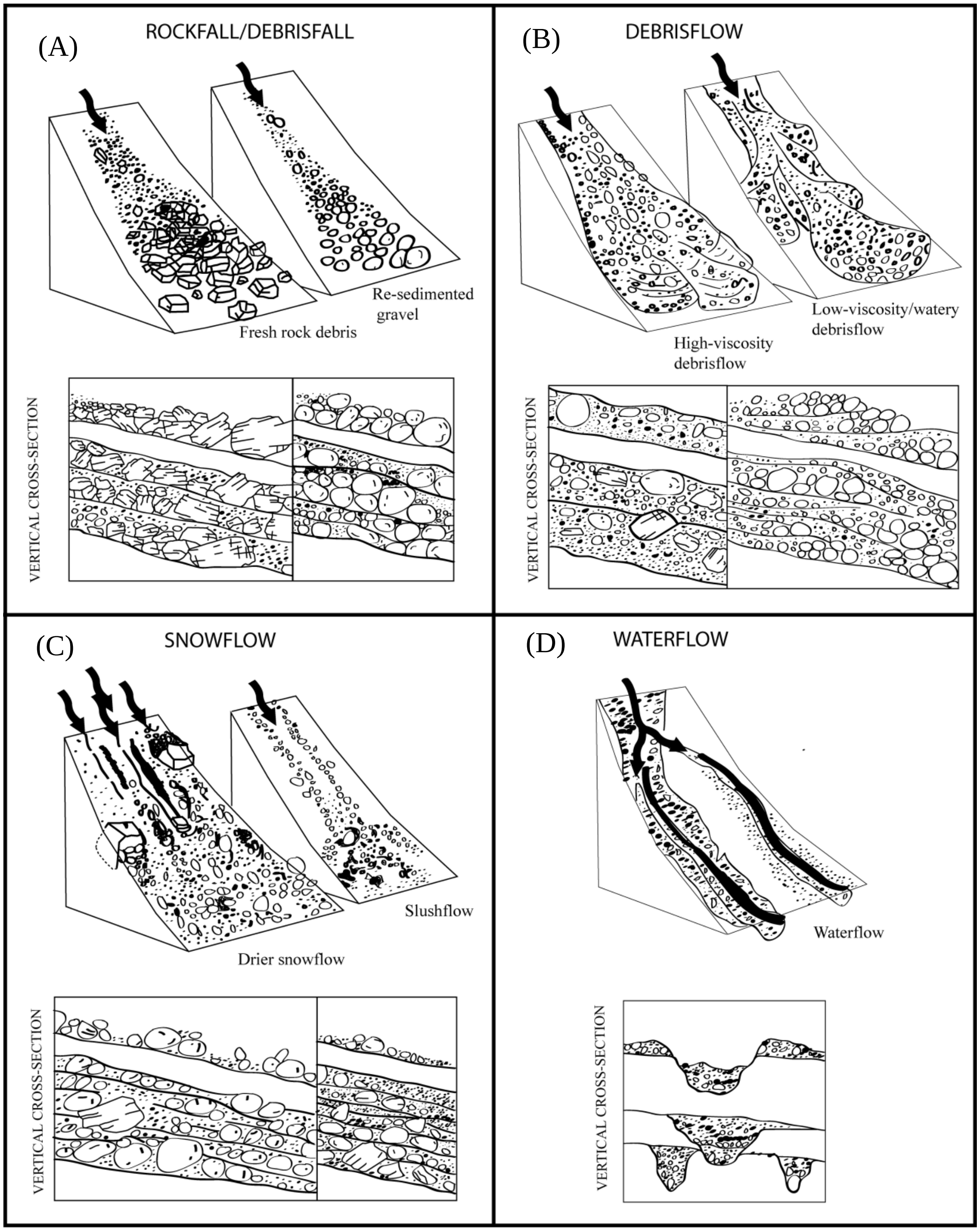


Figure 4 Schematic sketch of the geometry and internal structures of the distinctive colluvial fan types (modified after: Blikra and Nemec, 1998). Fans deposited by (A) rockfall/debrisfall, (B) debrisflow, (C) snowflow and (D) waterflow processes.

2. OUTCROP ANALOUGE – GREECE

2.1 Regional Context

The Kalavrita-Diakofto region is situated at the southern margin of the Gulf of Corinth in the Peloponnesus peninsula in Greece. It comprises an area of over 400 km^2 and is part of a rapidly extending WNW-ESE-trending graben, 105 km long and up to 30 km wide (Bastesen et al., 2009)(Figure 5). The regional rift activity of the young Corinth gulf is a consequence of back-arc spreading in the foreland of the Hellenic Trench (Doutsos and Kokkalas, 2001; Koukouvelas et al., 2005; Le Pichon and Angelier, 1979; Leeder et al., 2008). Extension is proposed to have initiated during the early Pliocene and continued until present-day (Bastesen et al., 2009). The rates of extension varies from east to west, with rates of 5 mm/yr to 15 mm/yr respectively (e.g. Moretti et al., 2003; Sorel, 2000).

2.1.1 STRUCTURES

The present-day displacement vectors in the Gulf of Corinth region are oriented N-S, forming a series of rotated fault blocks, controlled by an E-W striking normal fault system (Jackson and McKenzie, 1999; Morewood and Roberts, 2001) (Figure 5). The major faults in the area, with few exceptions, e.g. Tsivlos fault, trend between N086° and N112° and have exposed fault dips of 42° to 64° degrees. Because of juxtaposed pre-rift and syn-rift rocks along most of the fault length, the faults in the region are traced with high confidence from tip-point to tip-point (Ford et al., 2013). N-S lineaments, which are not fully understood, are suggested to be transfer faults or basement controlled structures, separating the different faulted blocks (Collier and Jones, 2004) (Figure 6). The active rift

(A)

(B)

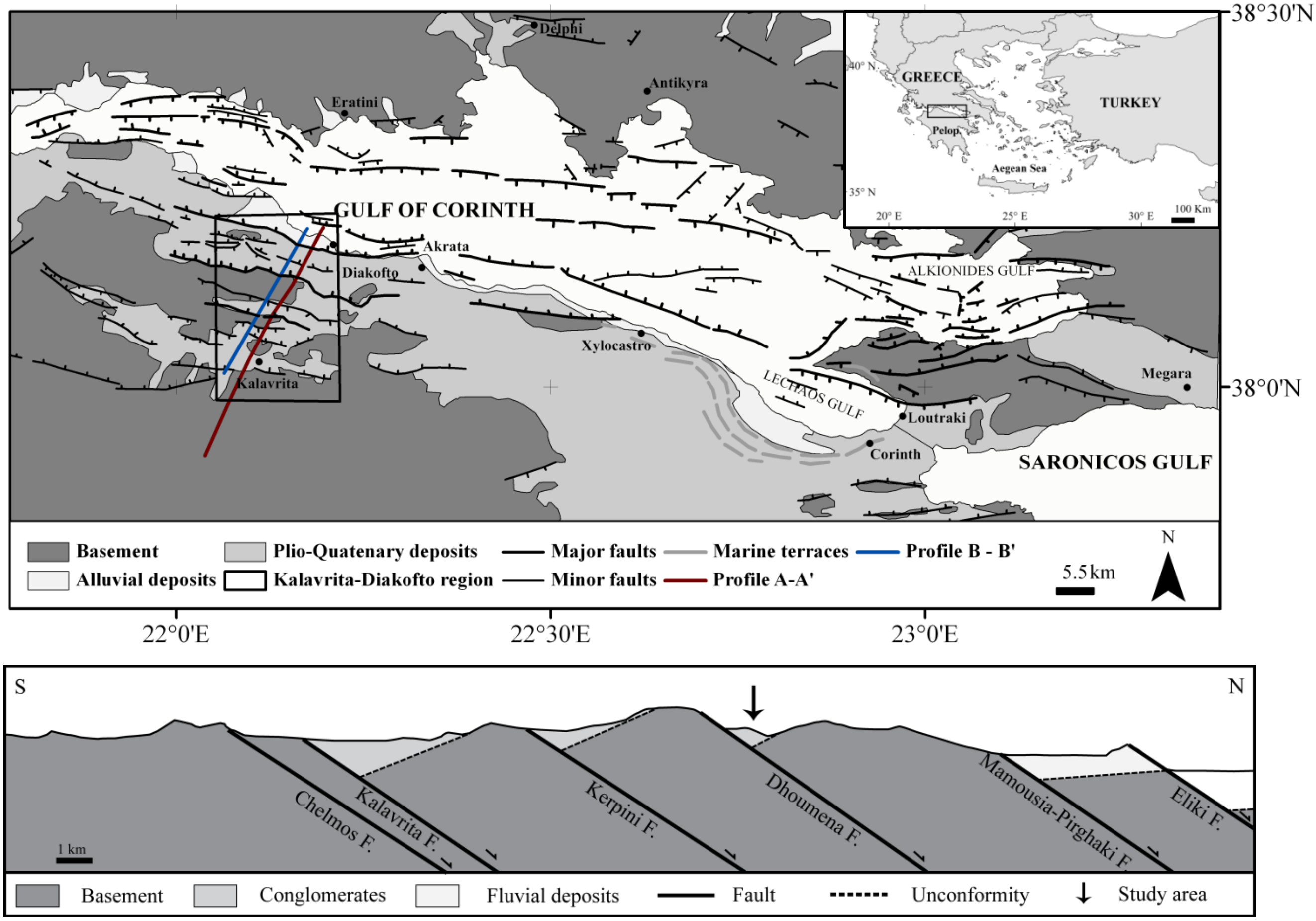


Figure 5 Map of the Gulf of Corinth area showing the main faults and onshore distribution of the Plio- Pleistocene sedimentary rocks (modified after: Moretti et al., 2003 and refrences therein). The location of the study area (Kalavrita-Diakofto region) is boxed, whereas the red line (profile A-A’) represents the regional cross-section in (B) and the blue line (profile B-B’) represent the cross-section in Figure 7. (B) Profile A-A’ showing the main structural framework of the region, from the inactive Chelmos fault in the south, to the active rift system at the margin of the Corinth Gulf in the north.

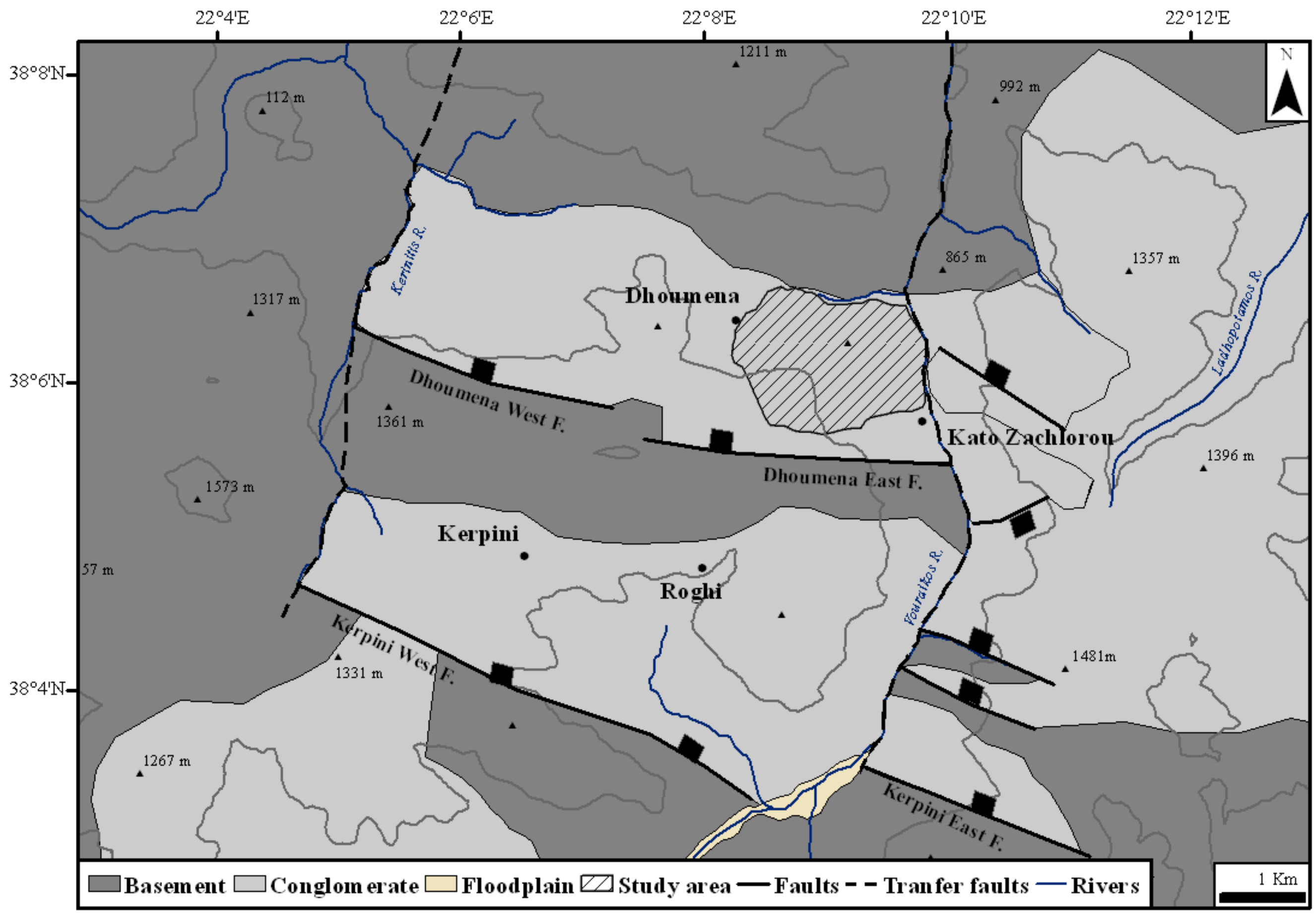


Figure 6 Close-up map showing the main faults and stratigraphy of the Kerpini to Dhoumena region. The geometry of the area studied is indicated by a stippled area. Transform faults, which separate the fault blocks are represented by dashed black lines.

faults are found along the present-day margins of the Gulf of Corinth, whereas the non-active, 4 to 7 km wide, rotated faulted blocks are found mostly to the south and represent scale analogues to many rifted blocks and hydrocarbon fields on the Norwegian continental shelf and other rift basins (Figure 5).

2.1.2 STRATIGRAPHY

In general, the stratigraphy in the region is quite simple and consists of Mesozoic lowgraded metamorphic limestones that are considered the basement, which are unconformable overlaid by Pliocene to Quaternary conglomerates and marl sedimentary rocks. These overlain rocks are interpreted as syn-rift sedimentation (Lower, Middle and Upper group) deposited in the half-graben space formed along the rotated faulted blocks (e.g. Backert et al., 2010; Ford et al., 2013; Ford et al., 2009; Ori, 1989; Rohais et al., 2007; Xypolias and Koukouvelas, 2001). The syn-rift rocks are mainly made of continental facies rocks, from colluvium, alluvium and fluvial rocks (Lower group) to the south, that grade into Gilbert deltas (Middle group) and marine environments (Upper group) towards the active part of the Corinth rift system (Dart et al., 1994; Ori, 1989). The syn-rift rocks from the Lower group generally dip around 20 degrees south in the rotated fault blocks, whereas strata from the Middle and Upper group dip around 5 degrees south; against the fault planes (Figure 5B). However, at some localized areas, syn-rift wedge shapes dipping north in very steep angles away from the fault plane, are observed. In addition, few evidences of growth strata are observed, suggesting that faulting and sedimentation were episodic rather than continuous.

2.1.3 EVOLUTION

The evolution of the western Corinth rift is not fully understood, therefore a variety of evolutionary models have been proposed (e.g. Flotté and Sorel, 2001; Ford et al., 2013; Ori, 1989; Sorel, 2000). In general, these models can be sub-divided into three main groups:

i. A simple northward-propagation system, with a progressive migration of the tectonic activity (e.g. subsidence, sedimentation, uplift and erosion) from south to north (e.g. Flotté and Sorel, 2001; Sorel, 2000).

ii. A two-phased evolution model, where the first slow phase (related to the deposition of continental and shallow water deposits), was surpassed by a fast second phase in the Late Pliocene (Ori, 1989). The latter still occurring phase is related to the shift in extension direction (to north-south).

iii. A complex three-phased evolution model, which suggest three phases of rifting and fault migration, with a step-wise increase in the extension rates (Causse et al., 2004; Ford et al., 2013) (Figure 7).

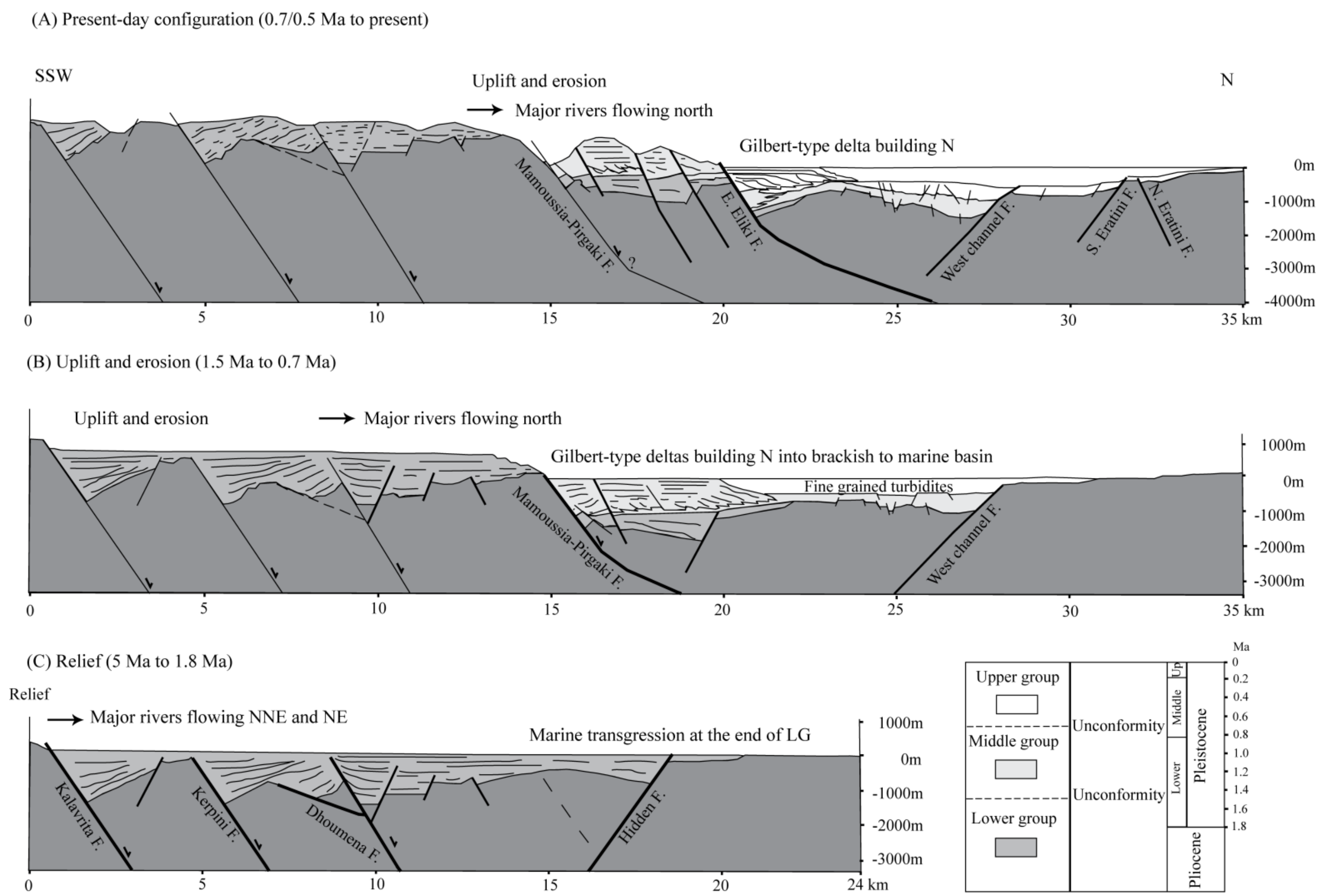


Figure 7 SSW to N cross-section (Modified after Ford et.al, 2013), showing the rift evolution. (A) The present day configuration. Location is indicated by a blue line (profile B-B') in Figure 5. (B) The evolution of the facies during uplift and erosion from 1.5 to 0.7 Ma. (C) During the deposition of the continental facies of the Lower group from 5 – 1.8 Ma.

2.2 Data and Methodology

2.2.1 DATA

The outcrop data consist of marked GPS locations, outcrop descriptions, measurements of flow direction and dips. In addition, a Petrel session containing a DEM surface overlaid by a 1:50 000 map of the Kalavrita- Diakofto region was used to build a 3-D model for volumetric calculations (Figure 8).

2.2.2 METHODOLOGY

A full field campaign (summer 2012 and spring 2013) where the general 3-D composition, from the geometry to the internal components of the steeply dipping conglomerate wedge shape in the Dhoumena east fault, was studied. Field methods consist of mapping the basement-conglomerate contact, take dip measurements across the wedge shape, measure flow directions, describe pebble sizes, facies, and look for depositional events. A 3-D geological model was constructed in the Petrel Schlumberger software, using the geological field map as input data. The volumetric of the studied clastic wedge was calculated based on the volume observed and the assumption of a porosity of 20% and a water saturation of 40%.

2.3 Observations

2.3.1 GEOMETRY

The NE-facing hanging wall scarp of the Dhoumena fault, host a short (ca. 1.75 km long) and steep gravelly clastic wedge, with a fan shaped geometry, i.e. smaller at apex (in the south) and wider at the base (in the north) (Figure 9). The apex is located at approx. 1200

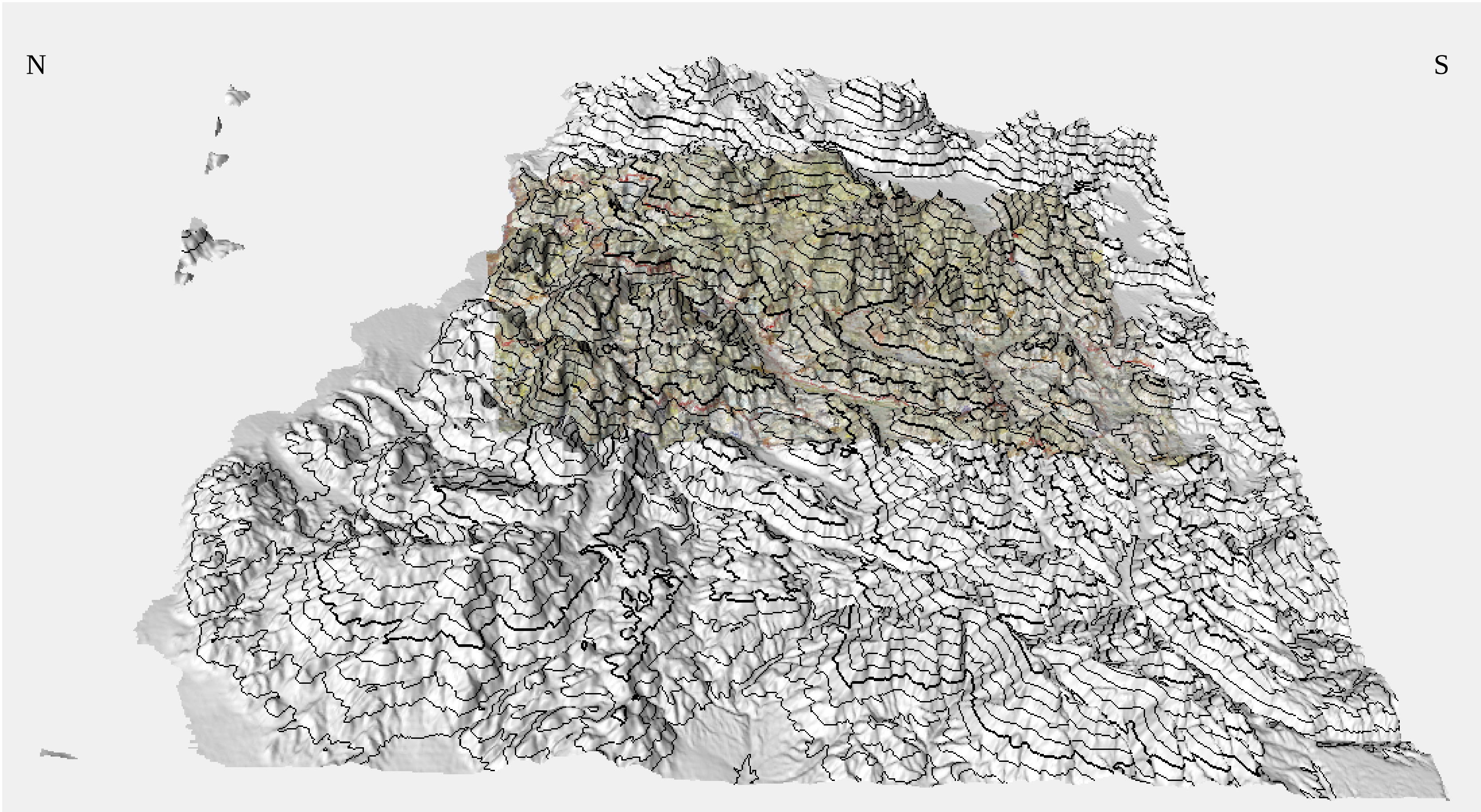


Figure 8 3-D view of the Petrel session, showing the DEM surface (VE = 3) that is overlaid by a map of the Kalavrita-Diakofto region.

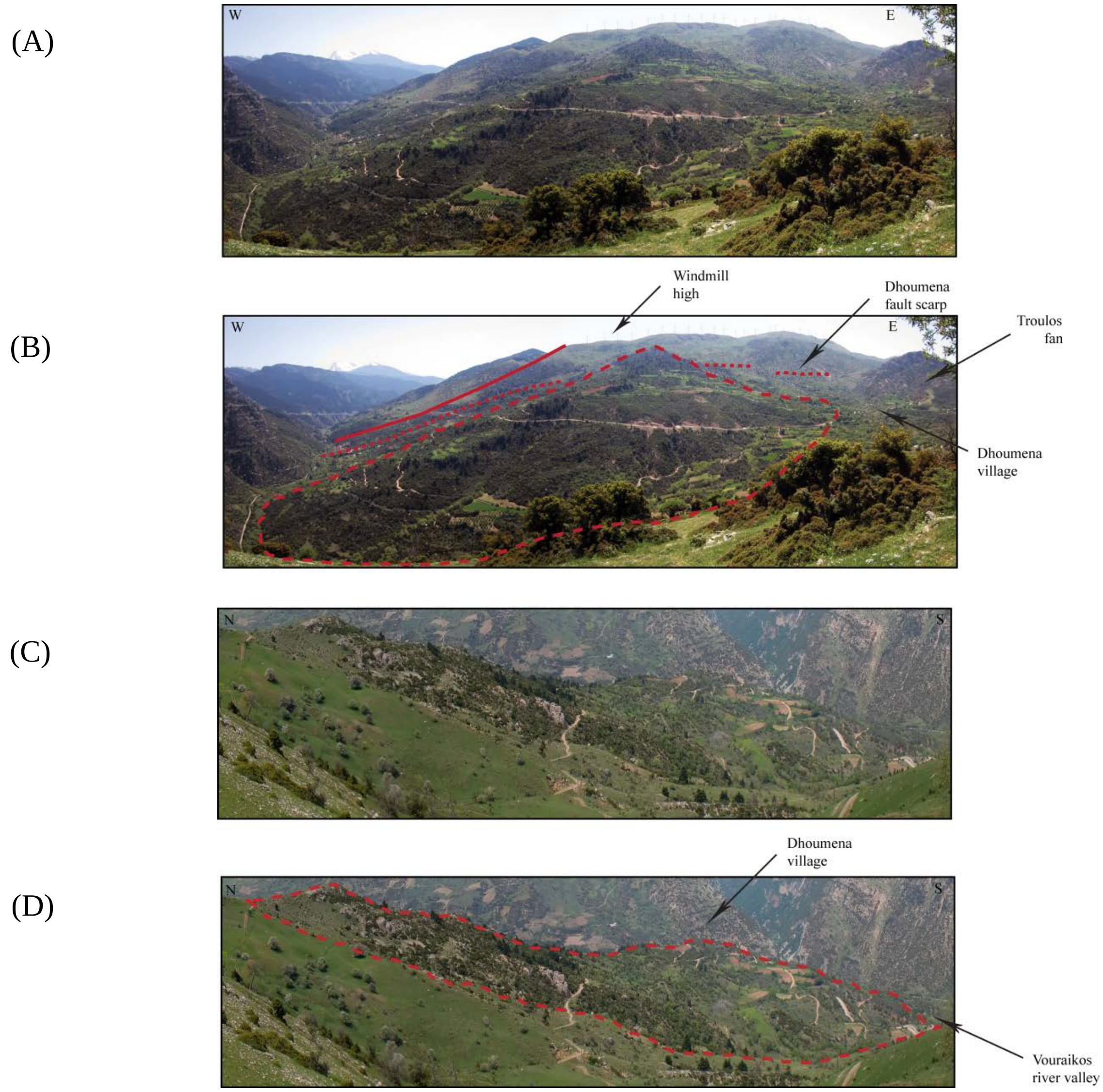


Figure 9 (A) Un-interpreted overview photograph of the studied clastic wedge. (B) Interpreted overview photograph showing the fan shaped geometry (red dashed line) of the studied north-dipping wedge situated in the hanging wall scarp of the Dhoumena fault. Red dotted lines indicate the Dhoumena fault segments, while the red line represents the Kerpini unconformity. In addition, the Troulos fan and the Dhoumena village are displayed. (C) Un-interpreted photograph of the studied wedge from the side, taken at the windmill high. (D) Interpreted photograph showing the geometry of the studied wedge indicated by a red dashed line. For reference the location of the Vouraikos river valley is indicated.

m.a.s.l., while the toe is at 600 m.a.s.l. In Figure 9, a red dashed line marks the outline, which represents the contact between the conglomerates and the underlying basement rocks. The plan-view radius length of the studied wedge shape is in the range of 1 to 1.2 km.

2.3.2 DIP MEASUREMENTS

The wedge shape generally has a NE dip direction. However, as indicated in Figure 10, a trend of NW dipping rocks along the western side of the wedge, from the apex down towards Dhoumena village, is observed. In addition, there are localized areas of non-consistent dip directions, mostly situated on the eastern side of the wedge close to the apex and in the middle part of the clastic wedge. The reason for these latter variations could be uncertainty in the measurements itself, most likely related to the difficulties in detecting layering within the quite massive conglomerate rocks. In addition, the condition of the quite heavily vegetated outcrops is very poor. The dip measurements varies from quite low, e.g. 4º, to 27º, which is still considered to be within the level of deposition of colluvial fans (Blikra and Nemec, 1998). In general, the dips are highest near the apex and decreases down toward the toe. However, the variations on dip could be related to the conglomerates angle of response, due to changes on grain-size. In general, the areas with largest pebble size correspond to areas of greater dips. The average dips, together with pebble size, are indicated in Figure 10.

2.3.2 FACIES

The rocks studied are separated into four main facies: facies 1: marl (Figure 11); facies 2: cemented conglomerates (Figure 12); facies 3: un-consolidated and poorly sorted conglomerates (Figure 11) and facies 4: consolidated and sorted conglomerates (Figure 13). The distribution of the facies together with the maximum pebble size observed is

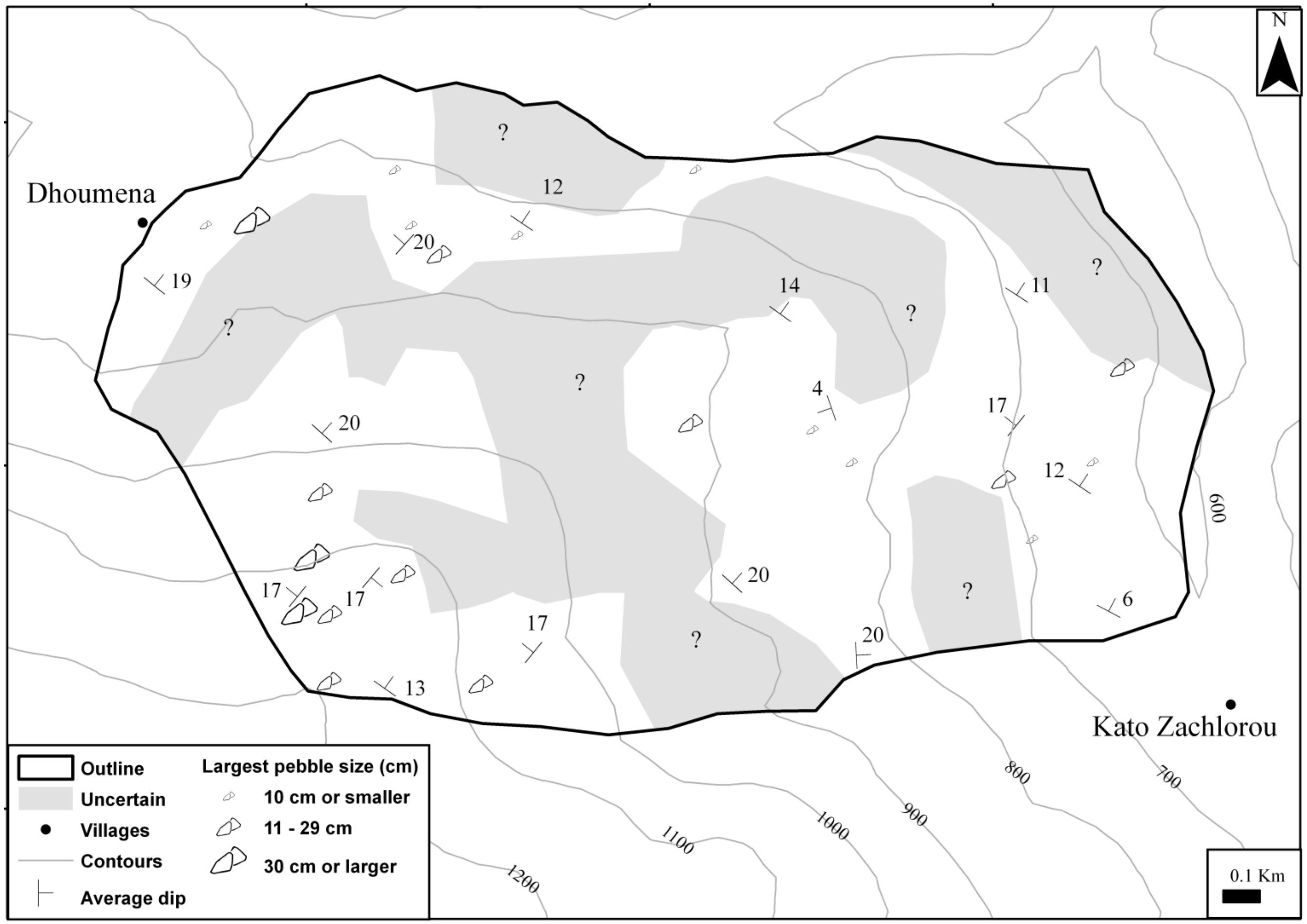


Figure 10 Map summarizing the average dips measured in the field, displayed together with the largest pebble size observed. In addition, contour intervals of 100 m are displayed.

(A)

(B)

Figure 11 (A) Un-consolidated and poorly sorted conglomerate channel, with a NW flow direction, eroding into the marl facies (black dashed line). Erosional depth of 8 m. Clast of re-sedimented conglomerates, with diameters up to 50 cm, are observed and indicated by a black circle. This indicates redeposition of large existing blocks (consolidated) and high energy. (B) Map showing the location situated close to the Dhoumea village.

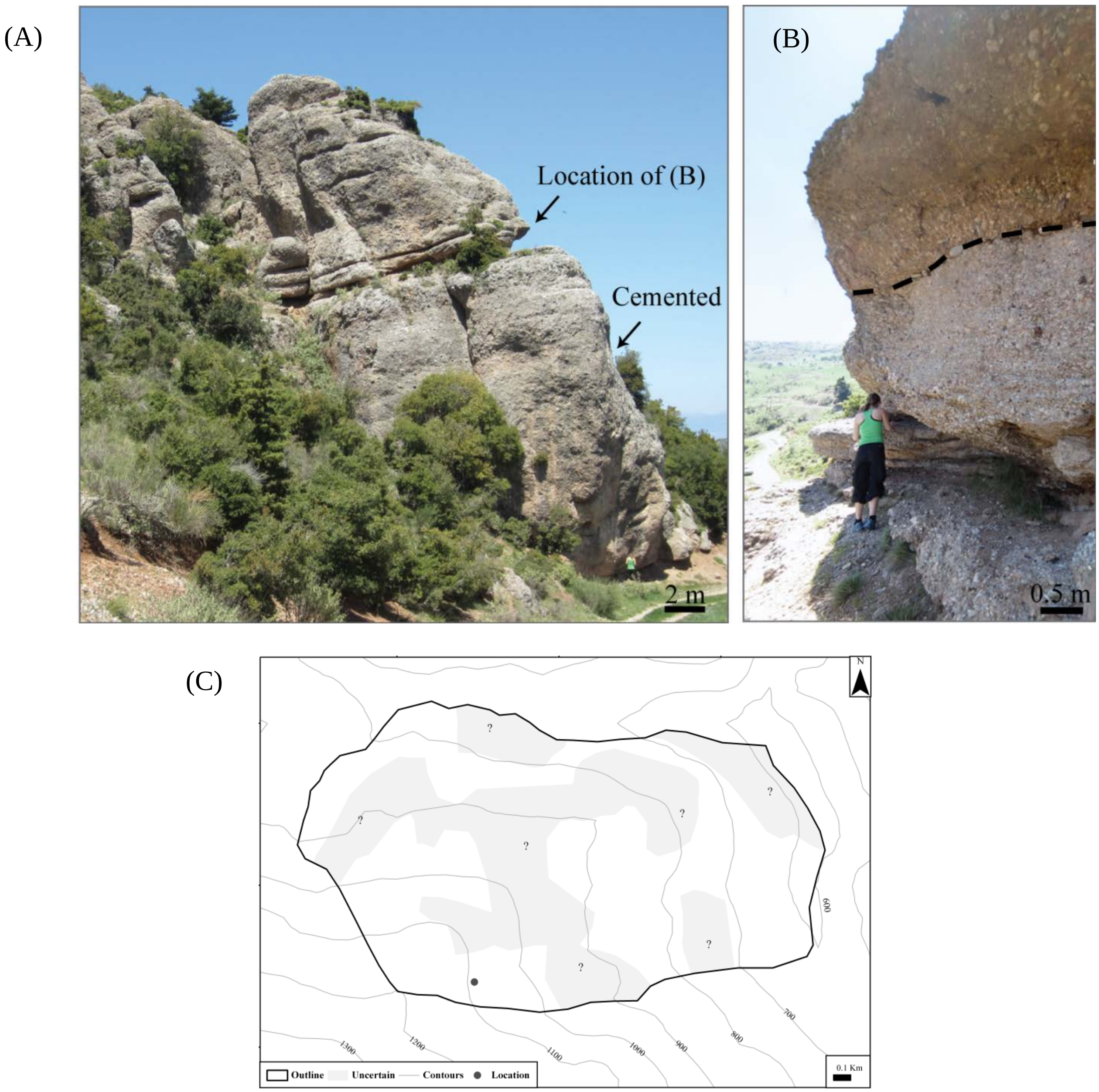


Figure 12 Cemented block located near the apex. (A) Overview image of the block, showing the cemented base. (B) Close-up of the upper part of the block, consisiting of well sorted conglomerates with a coarsening upward trend. Erosional surface (black dashed line) and minor channel incisions are observed. (C) Map showing the location of the block studied.

(A)

(B)

Figure 13 Conglomerate channel (black dashed line) eroding into the marl facies. Erosional depth is 1.5 - 2 m. Conglomerates are consolidated with an overall fining upward trend. (B) Map showing the location.

indicated in Figure 14. The proximal area of the studied wedge shape consists mainly of cemented conglomerates. Towards the middle area of the studied wedge shape, marly facies found mostly together with unconsolidated conglomerates dominates. The more distal area consists of matrix supported consolidated and sorted conglomerates. In addition, at many locations observations of well-cemented rocks that overlay poorly cemented ones are made. In general, with the exception of locations with occurrences of facies 3 (where boulders with a diameter up to 50 cm, consisting of re-sediment conglomerates are observed), the maximum pebble size decreases from the apex towards the toe, indicating a decrease in energy in this direction as the sedimentation gets more distal.

2.3.3 INTERNAL STRUCTURES

Internal structures of the clastic wedge observed include low energy lenses (Figure 15) and paleo-erosional surfaces, with indications of scour and fill processes, interpreted as channels (Figure 16). The conglomerate channels observed erodes into the marl facies with erosional depths of up to 8 m (e.g. Figure 11). The changes in incision depth, which are interpreted as changes in energy, are indicated by the size of the flow arrows in Figure 17. In addition, the linear relationship between the maximum pebble size and the channel height is indicated in Figure 18. The main flow directions of the channels are towards the northwest (on the western side) and northeast (on the eastern side). In addition, eastwards flows are observed at the middle part of the clastic wedge (Figure 17).

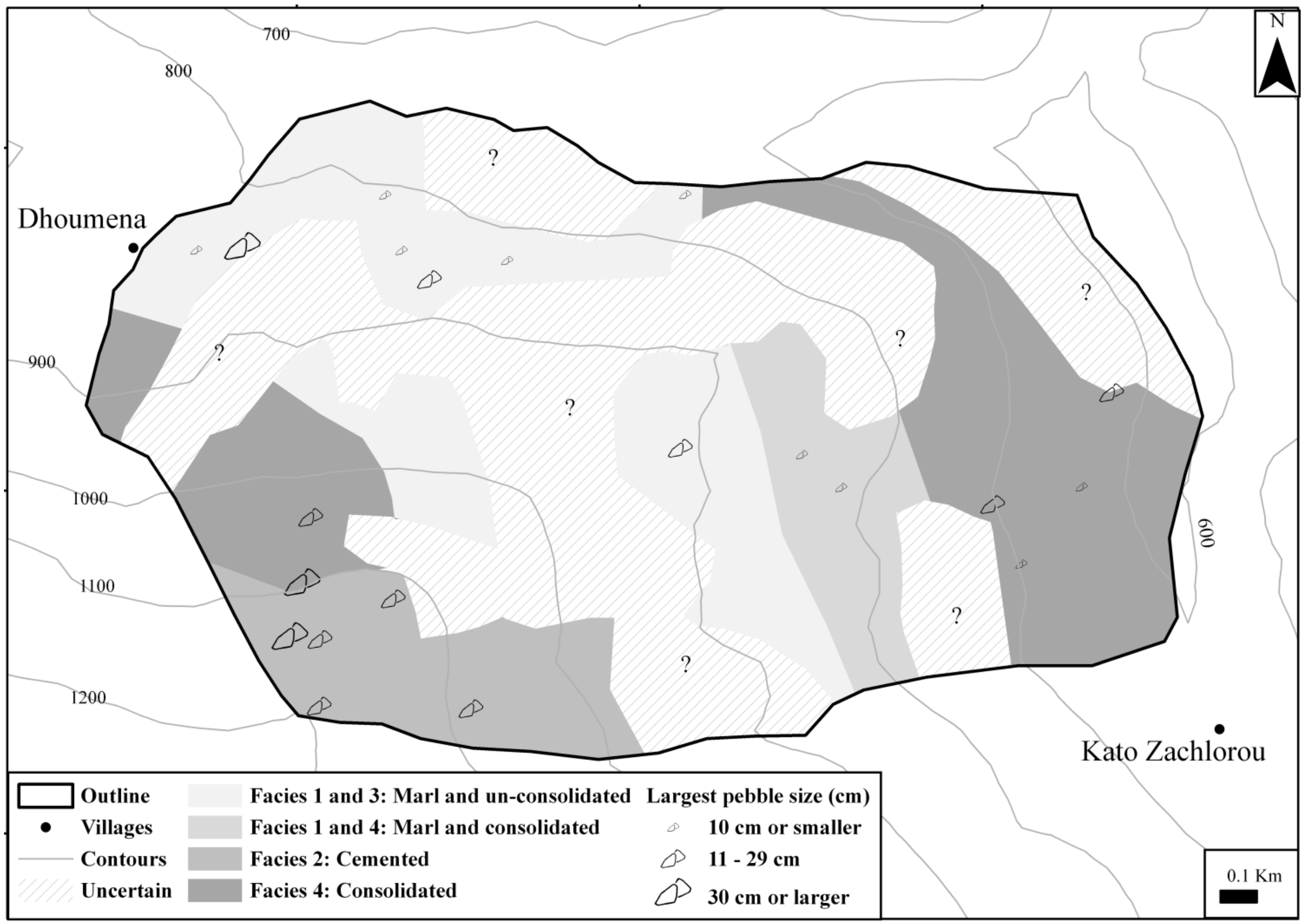
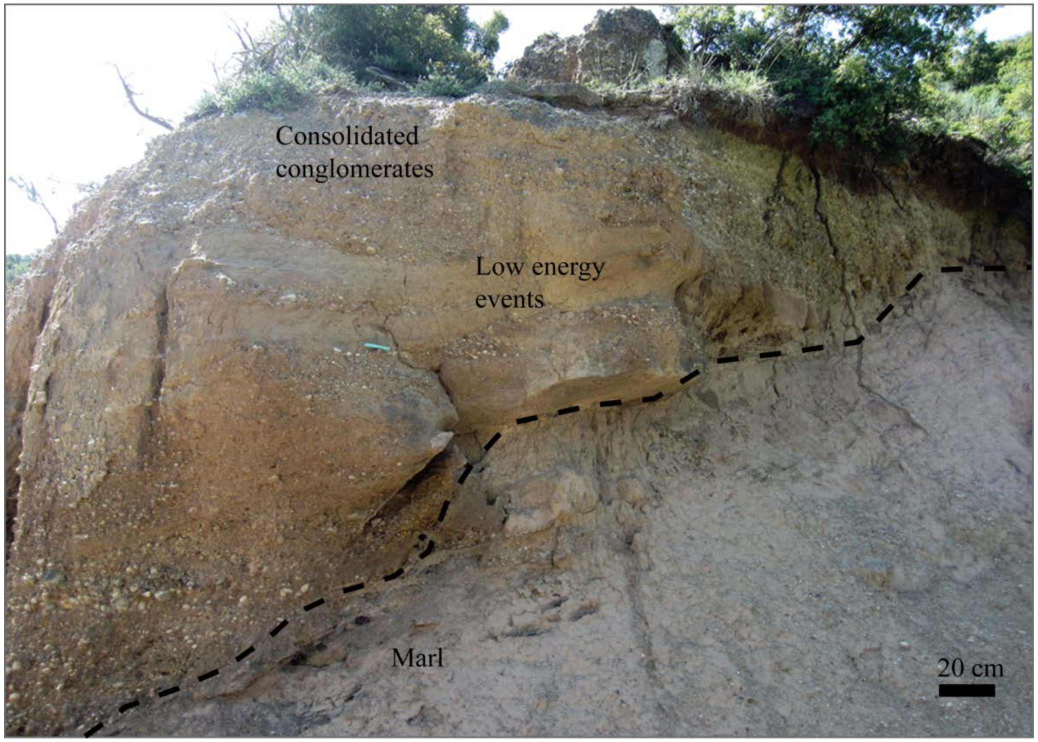


Figure 14 Map summarizing the main facies observed in the conglomeratic wedge shape. Facies 1: marl; facies 2: cemented conglomerates; facies 3: Un-consolidated and poorly sorted conglomerates and facies 4: consolidated and sorted conglomerates. In addition, the largest pebble sizes observed at different localities are displayed.

(A)



(B)

Figure 15 (A) Consolidated coarsening upwards conglomerate channel eroding into the marl facies (black dashed line). Erosional depth is 0.5 - 1 m. Low-energy lenses striking SW are observed in the 18°NE dipping block. (B) Map showing the location.

(A)

(B)

Figure 16 (A) Well-rounded and consolidated conglomerates. Paleo-erosional surfaces, with indications of scour and fill processes, are observed and represented by black dashed lines. (B) Map showing the location.

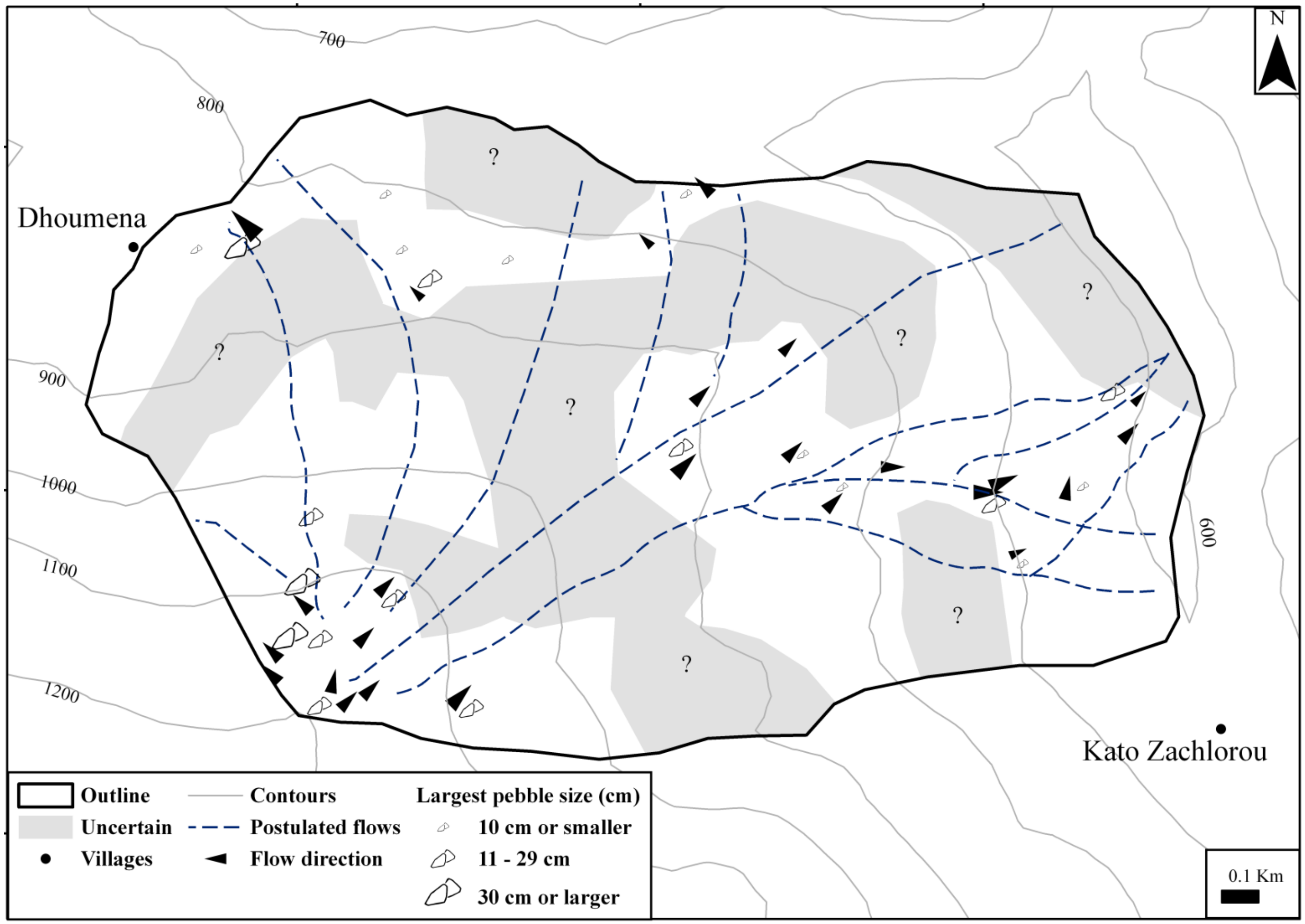


Figure 17 Map summarizing the channel directions measured in the field. The size of the flow arrow represents the size of the channels. In addition, the postulated flow patterns for the channels are displayed.

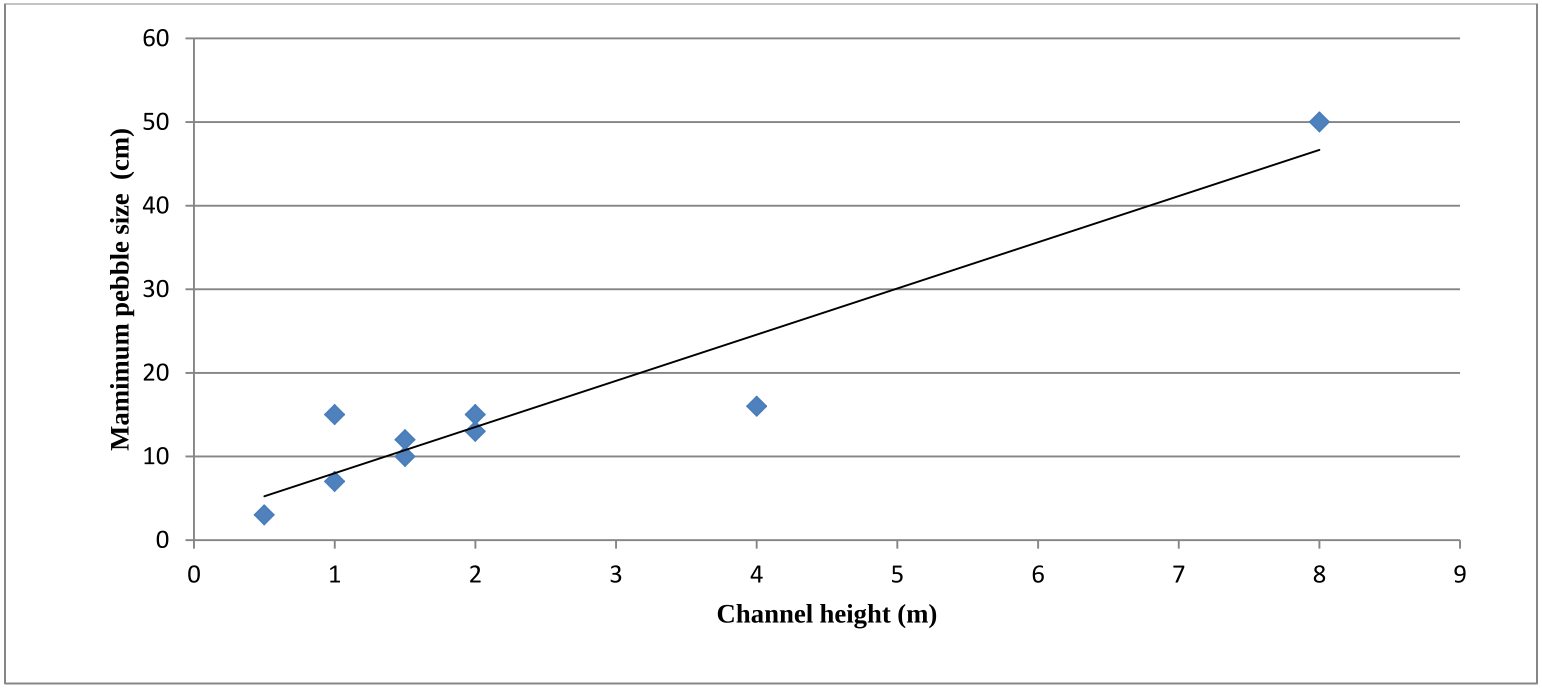


Figure 18 Graph showing the maximum pebble size vs. channel height, together with the linear trend line.

2.3.4 PROFILES

Figure 19B shows the smooth longitudinal morphometric profile along the main axis of the clastic wedge studied. The slope profile shows a concave-upward trend from 14° inclination near the toe to 31° at the apex, which corresponds to the depositional slopes observed for postglacial colluvium in western Norway (Blikra and Nemec, 1998). In addition, cross-profiles for the proximal, middle and distal area of the clastic wedge are given, with locations of surface observations, such as channels and facies.

The proximal cross-profile (Figure 19C) is smooth, with its highest elevation towards the central part. Facies observed mostly consist of well-cemented conglomerates, with occurrences of consolidated conglomerates at the western flank. Three observations of channels with erosional depth of up to 2 m are observed, all within the cemented conglomerates.

The middle cross-profile (Figure 19D) shows an irregular profile, with successions of minor ridges and depressions (up to 10 m), with its highest elevation point (of 1000 m.a.s.l.) close to the main axis of the clastic wedge. At the western flank, a prominent debris-flow channel (with an erosional depth of 8 m) is observed. However, most of the wedge surface has an extensive cover of vegetation, which makes it difficult to determine facies changes.

The distal cross-profile (Figure 19E) shows four occurrences of depressions with depths of 5 - 10 m, which are observed at horizontal distances of 75m, 500m, 1025m and 1940m from the western flank of the wedge shape. Most of the surface along the distal cross-profile are heavy vegetated or fields, making it difficult to describe the changes in facies.

(A)

(B)

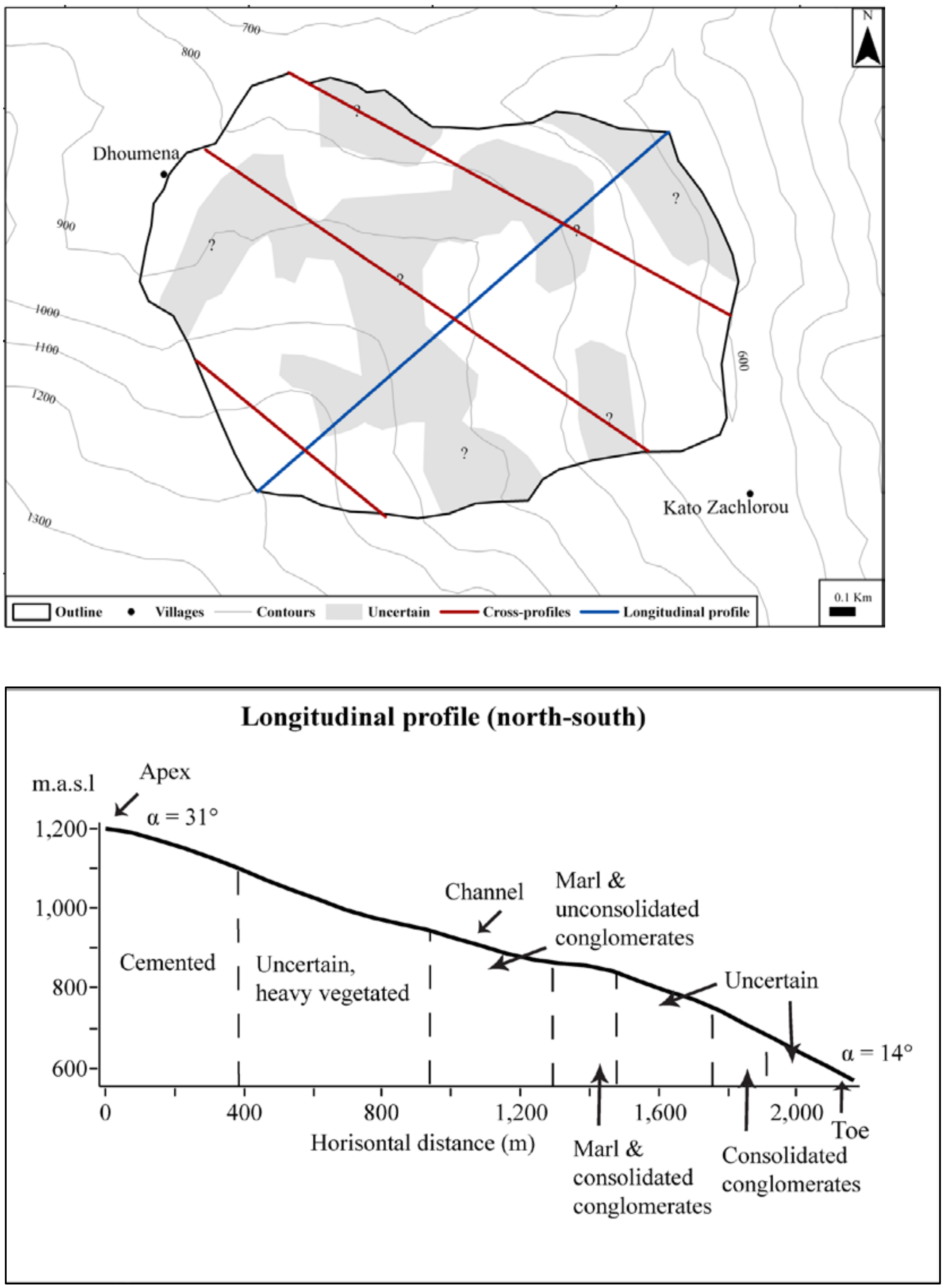
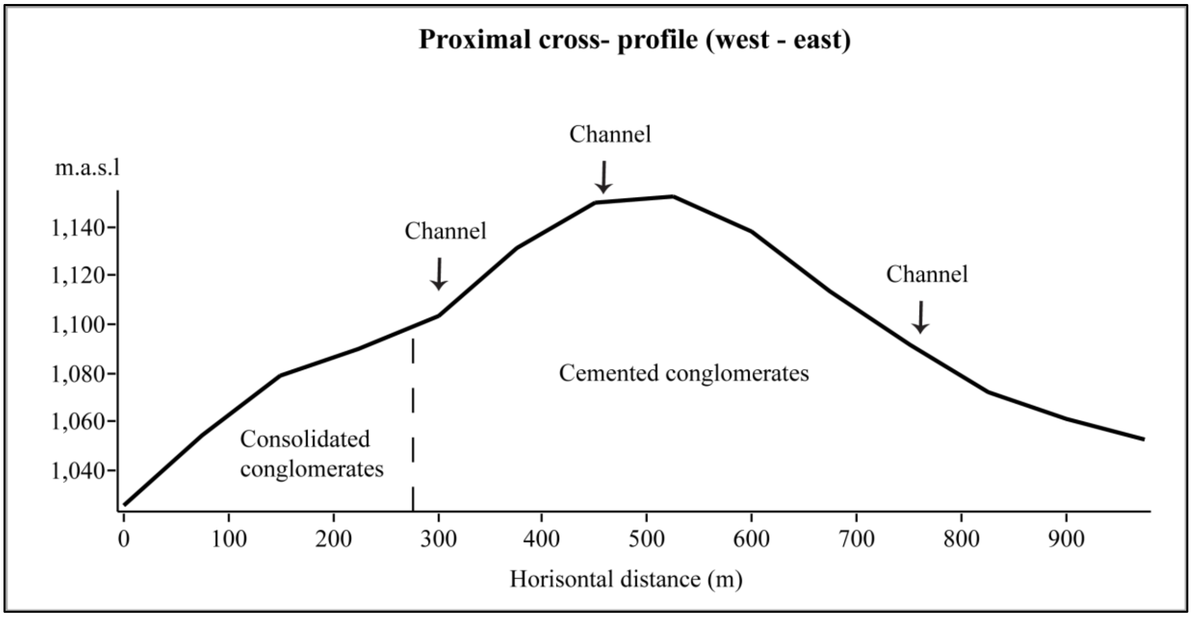


Figure 19 (A) Location of the profiles. Blue line represents the longitudinal profile, whereas red lines represent cross-profiles (B) Longitudinal metamorphic profile along the main axis of the wedge shape.

(C)



(D)

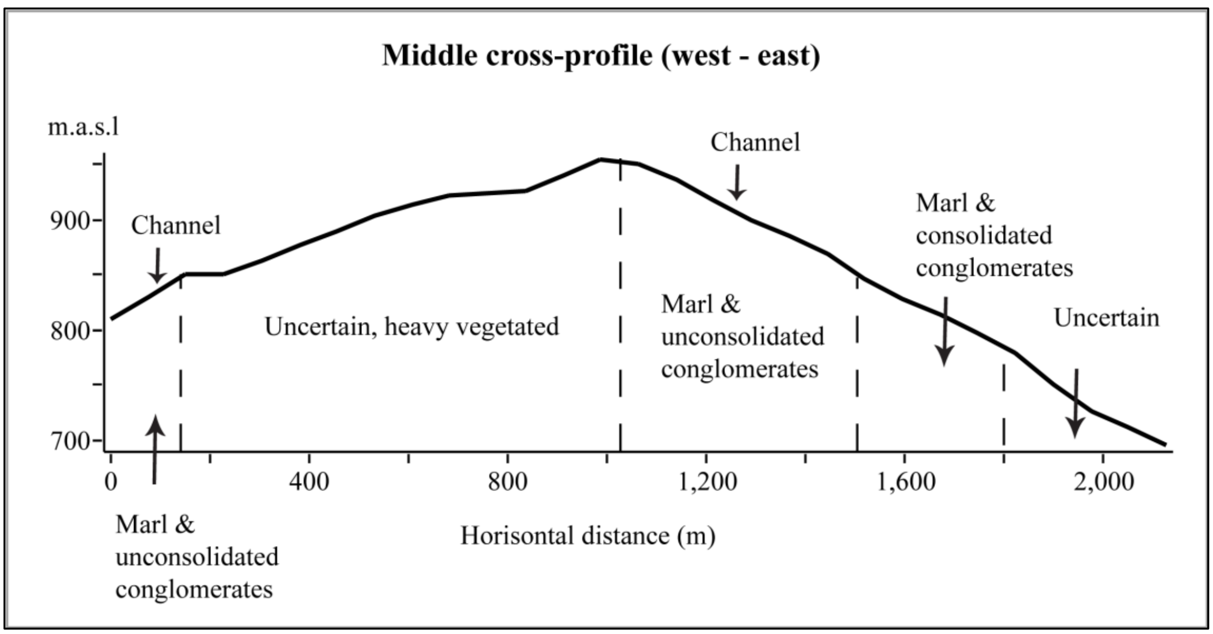


Figure 19 (C) Proximal cross-profile of the studied wedge. (D) Middel cross-profile.

(E)

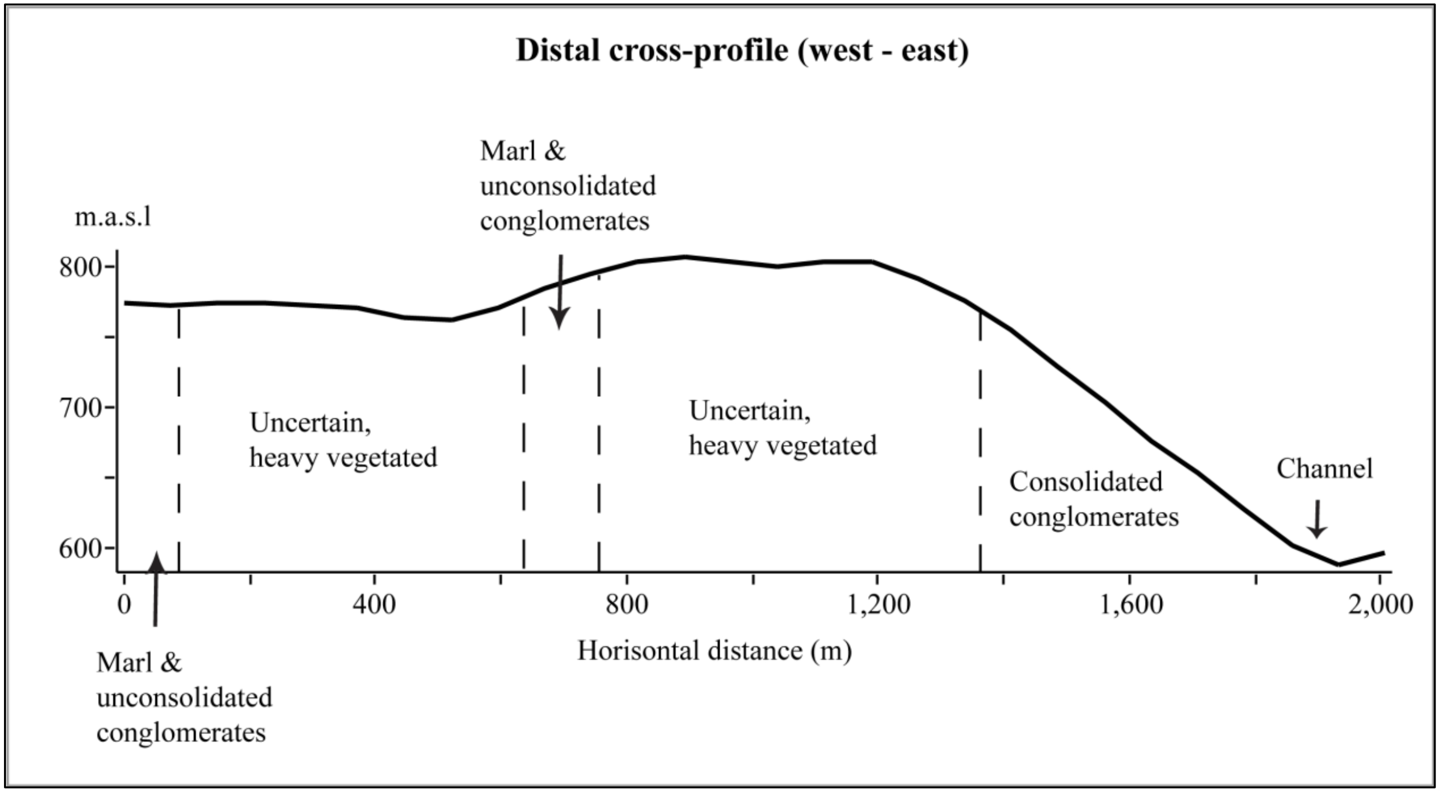


Figure 19 (E) Distal cross-profile of the wedge shape, showing surface observations of channels and facies.

However, with the exceptions of the uncertain areas, marl is observed along the entire profile. One channel, with erosional depth of 1 - 2m, is observed at the eastern flank of the wedge shape.

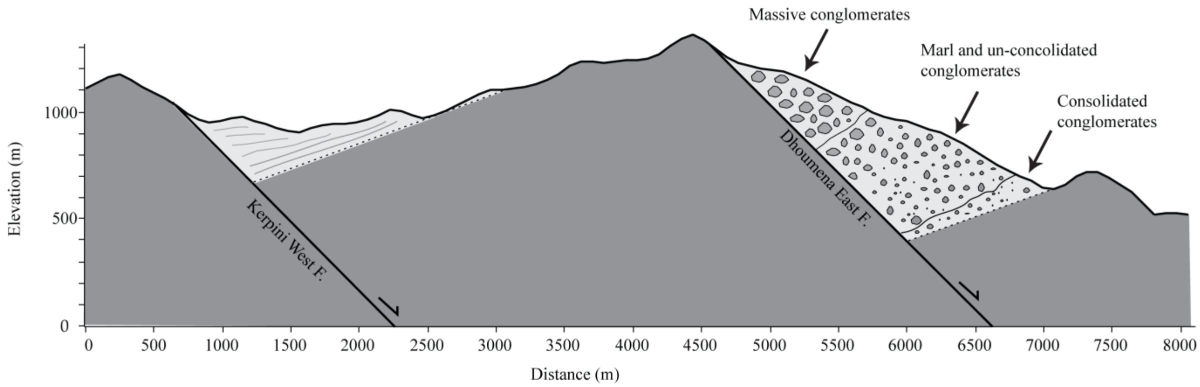
A SW-NE profile showing the relationship and the stratigraphy in the Dhoumena and Kerpini fault blocks is indicated in Figure 20. The Kerpini fault block, which is situated antecedent (in the south) of the Dhoumena fault block, have not been studied in detail. Therefore, no indications of internal characteristics for the Kerpini fault block are given. However, mapping of the unconformity and measurements of dip directions for both the unconformity and the fault, have been conducted.

2.3.5 FAN CLASSIFICATION AND DEPOSITIONAL MODEL

Field observations, such as the fan-shaped geometry, consistent dip directions, low energy events and channels with a flow direction from the apex and northwards towards the toe; suggest that the studied clastic wedge is a fan. To determine the type of the fan situated in the hanging wall of the Dhoumena east fault, the classification schemes from Blikra and Nemec (1998) are used. Firstly, based on the geomorphic and sedimentological features (Table 1), the fan is considered a colluvial fan, rather than an alluvial fan, derived from the following:

- The apex is located high on the mountain slope at 1200 m.a.s.l
- The depositional setting of the fan is considered the mountain slope, with a slope inclination of 31° near the apex and 14° near the toe.
- The plan-view radius is in the range of 1 – 1.2 km, which is close to the maximum radius observed for colluvial fans.

(A)



(B)

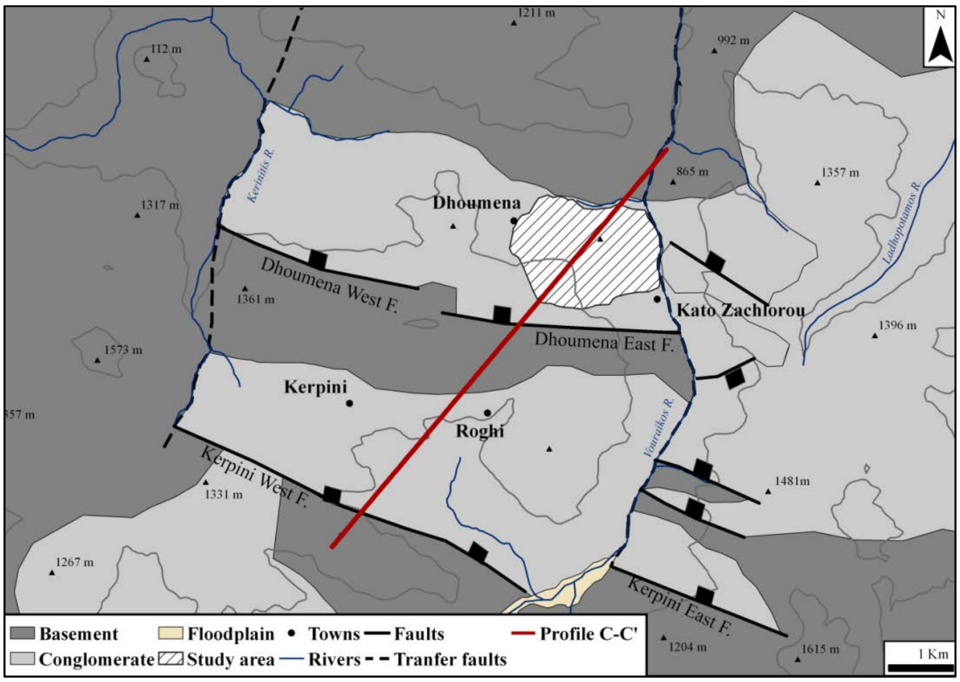


Figure 20 SW-NE cross-section (C-C’) showing the stratigraphy in the Dhoumena and Kerpini fault blocks. Changes in facies and pebble size are indicated in the north-dipping conglomeratic wedge studied in the Dhoumena east hanging wall scarp. Black lines represent faults, whereas the dotted black lines represent unconformities. (B) The location of profile C-C’ is indicated by a red line.

- The sediments observed are gravelly and mainly immature, as described for colluvial fans.

To determine the distinct type of colluvial fan observed in Greece, one would ideally have studied a vertical succession (from the toe to the apex) of the fan. However, due to heavy vegetation, studies like this are very hard to define within the area of study. In addition, there is a problem related to sedimentation and stratification of the well-cemented and poorly cemented conglomerate rocks. At first glance, one might suggest that the poorly cemented rocks are more recent deposits, than the well-cemented ones. However, in many locations well-cemented rocks overlay poorly cemented ones. The reasons for this could be related to different sources or timing of sedimentation.

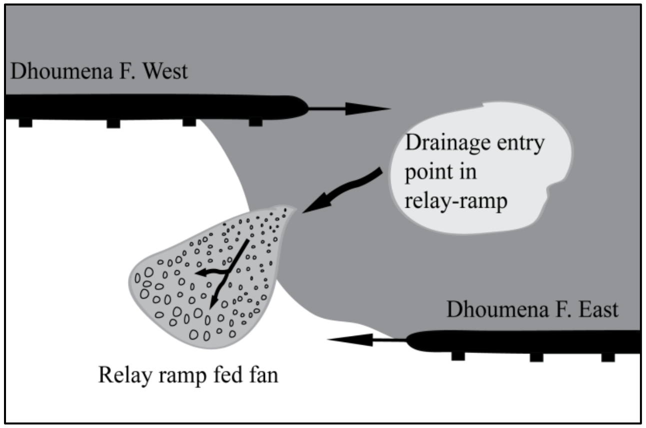
The matrix-supported rocks studied, shows an overall coarsening upward trend with sub-rounded to rounded pebbles, therefore the wedge shape studied is considered a high-viscosity debrisflow fan. However, observations of scours, suggest a more channelized deposition, which is more common for waterflow fans. This suggests that the colluvial fan studied had a two stage development trend involving an early stage dominated by cohesive, high-viscosity debrisflow (consisting of broad and matrix supported lobes) and a later stage of more mobile lower viscosity waterflows (that shows channel and scour features). However, the changes in process have not been studied in detail and are therefore only postulated tentatively.

Initially, three possible models for deposition of the studied fan were proposed:

a) N-S lineaments in the area resulted in an E-W trending relay-ramp along the Dhoumena fault. In this case, sediments from the Kerpini fault block or from the Dhoumena footwall were sourced down the relay-ramp as a fan (Elliott et al., 2012) (Figure 21). Based on field observations, this model is considered the most likely one. Firstly, the geometry observed is fan-shaped. Secondly, fault segments referred to as the Dhoumena east and Dhoumena west faults are identified in the field (Figure 9). In addition, the Dhoumena east fault is located near the fan apex.

b) The fan deposited during the late phase of syn-rotational faulting, sourced from the Dhoumena fault footwall, previous to rotation of the block to the south (Kerpini fault block) (Figure 22). For this model to be likely the sediments need to maintain its depositional dip, which indicate that the Dhoumena fault was in the last phase of activity or inactive during and after deposition of the fan as shown in Figure 22. However, according to this model the rocks studied initially had a dip of approx. 35 – 40° degrees, which is at the edge of the maximum frictional angle, which for debrisflow colluvial fans is given as 40° degrees (Blikra et al., 1989). In addition, if this is the case, it implies that the rotated fault block south of the Dhoumena fault, i.e. Kerpini fault, had not formed during this time, resulting in sediment by-pass from the Kerpini fault block during the last phase of rifting. As the Kerpini fault block rotation initiate, during the late syn-rotational faulting phase, the gateway for sediment by-pass closed and ended the sedimentation in the Dhoumena fault half graben. In addition, for this model one need to consider the original vs. the final deposition angle, i.e. since the Kerpini block was not faulted, the initial pre-rotation angle was higher.

(A)



(B)

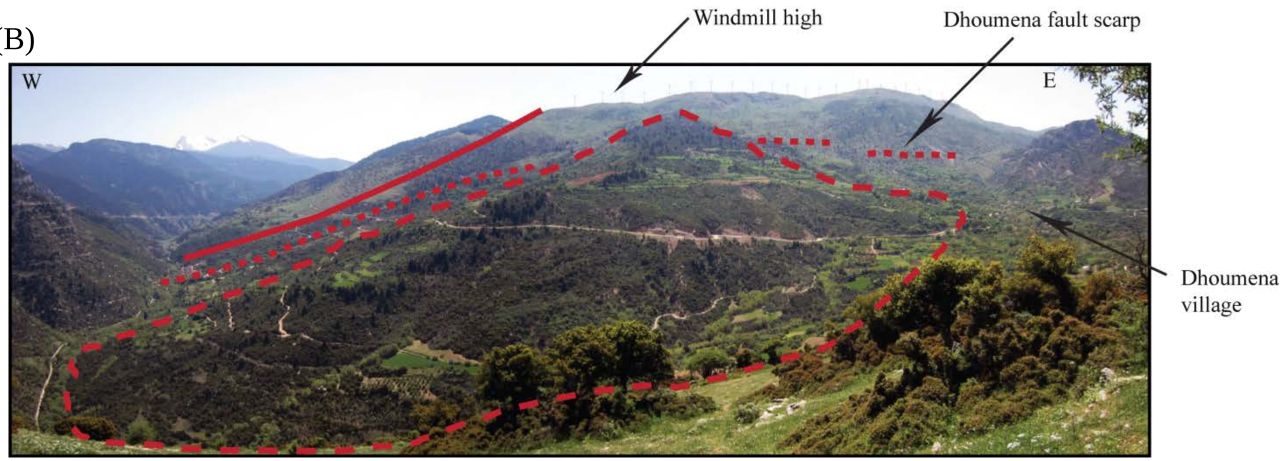
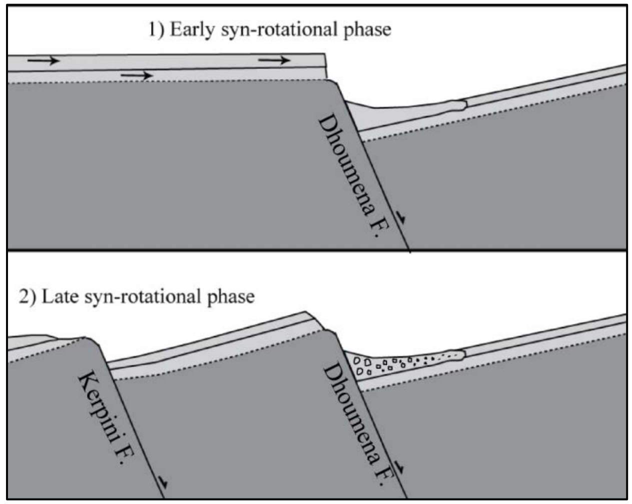


Figure 21 Proposed model a), which suggest that the studied conglomeratic wedge shape in the hanging wall of the Dhoumena east fault was deposited as a relay-ramp fed fan (A) Schematic sketch of the model (Modified after Athmer and Luthi, 2011). (B) Outcrop analysis. Red dotted lines represent the Dhoumena fault scarps, the red line represents the Kerpini unconformity and the red dashed line represents the fan outline.

(A)



(B)

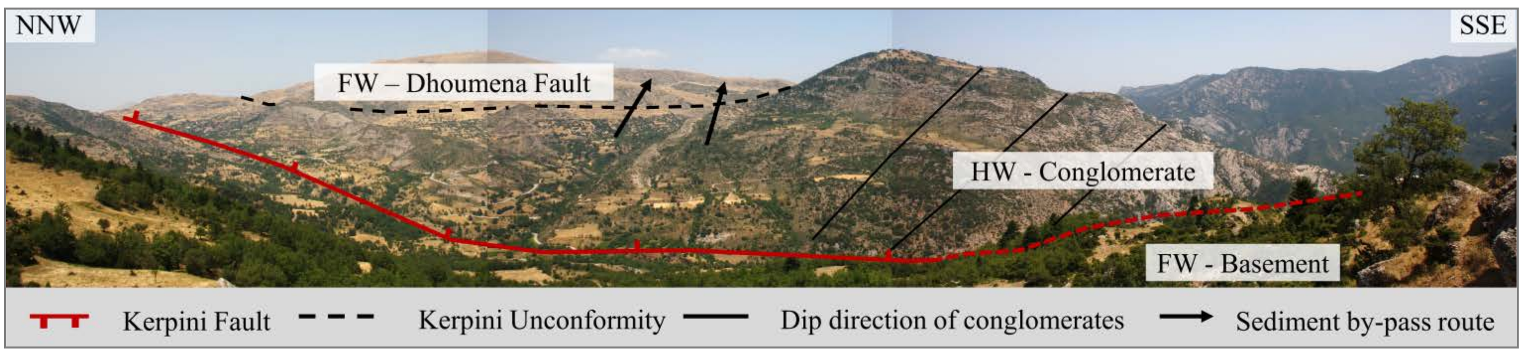


Figure 22 Proposed model b), which suggest that the conglomeratic wedge shape studied is a fan sourced from the Kerpini fault block previous to fault block rotation. (A) Schematic sketch of the model (Modified after Ravnås and Steel, 1998). (B) Outcrop analysis.

c) A slumped block along the fault scarp of the Dhoumena fault and footwall, during the post-rift (Figure 23). According to this model, one would expect the conglomerates to be unorganized blocks with no indication of flow, and a more chaotic shape. In addition, one expects to see little evidences of depositional features. However, field observations, shows low energy lenses, channels and a more organised system with consistent flow directions and dips. Together with the fan shaped geometry, this makes the model more unlikely.

2.3.6 VOLUMETRICS

The 3-D volume (Figure 23) of the studied clastic wedge was calculated to be between 1 km^3 and 1.3 km^3. Converted to oil equivalents, with a porosity of 20% and a water-saturation of 40%, this represents a volume of 18 to 24 mmboe. Volumes calculated are comparable to several hydrocarbon fields, e.g. Hannay, Saltire and Highlander, in the UK sector, which have estimated reserves of 8 – 20 mmboe in the Lower Cretaceous deep-water clastic plays (Garrett et al., 2000).

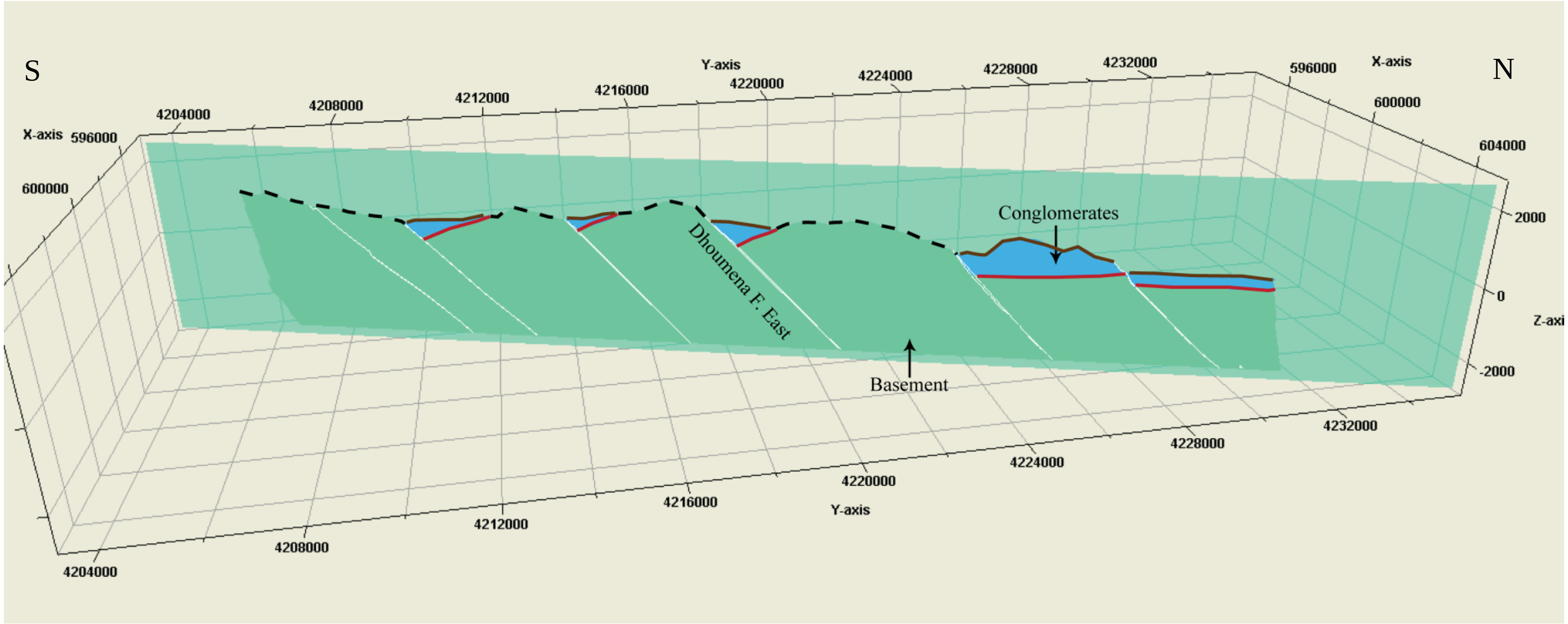
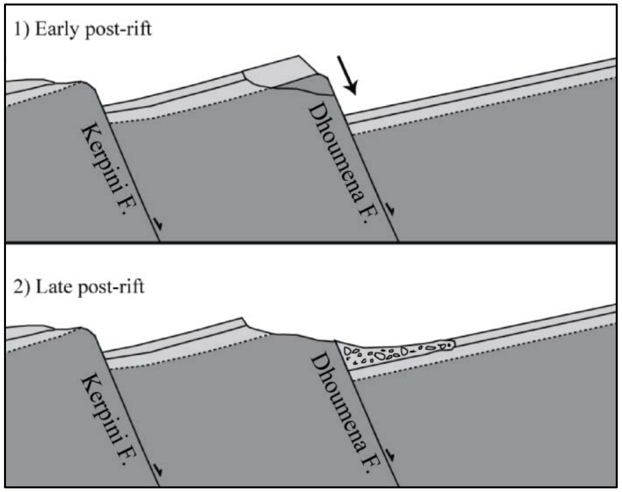


Figure 23 Cross-section from the 3-D geological model, with indications of the input surfaces used for volume calculations. The simple volume calculations were conducted using the volume below surface (surface) operation, with the input parameters: DEM surface as the top surface (indicated by brown lines), merged unconformity surface as the base surface (red lines), and the imported shapefile of the outline as boundary. Black dashed lines represent areas where the top and base surface matches.

(A)



(B)

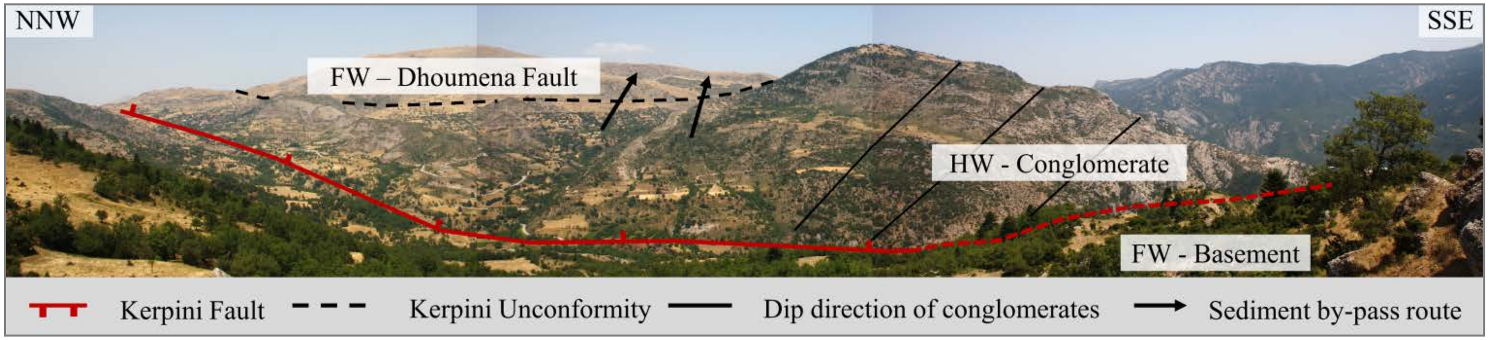


Figure 24 Proposed model c), which suggest that the studied conglomeratic wedge shape was deposited as a slumped block along the fault scarp of the Dhoumena east fault, during the post-rift phase. (A) Schematic sketch of the model (Redrawn and modified after Ravnås and Steel, 1998). (B) Outcrop analysis.

N

3. SUBSURFACE STUDY – THE SNORRE FIELD

3.1 Regional Context

The Snorre field, which is a part of the prolific hydrocarbon province on the western margin of the Viking Graben, is situated in the Tampen Spur area in the Northern North Sea (Figure 25). The westward tilted Snorre half-graben is situated at the southern extension of the Snorre Fault block, between the Statfjord East and Visund Fault blocks (Figure 25). The development of the Snorre fault block is described as a five-phased (Figure 26 A-E) tectono-stratigraphic evolution process, which occurred during the Middle Jurassic to the Early Cretaceous (Ravnås et al., 2000). In general, by the late Bathonian to Early Oxfordian, the drowning of the Brent Group and the deposition of the Heather Formation, ascribed to slightly increase in extensional rates, occurred across the gently tilted and submerged fault block topography (Figure 26A). As the rotation accelerate in the Late Oxfordian, the footwall crest was exposed, and the segmentation of the Tampur Spur into distinct half-graben sub-basins occurred (Figure 26B). Renewed rotation, footwall uplift and its erosion, and the infilling of the hanging wall throughs characterize the late rotation climax in the Kimmeridigian - Volgian times (Figure 26C). In the late syn-rotational phase (Ryazanian) the peneplanation and drowning of the footwall highs occurred (Figure 26D) and by post- Ryazanian, tectonic quiescence predominates, representing the drowning and draping (of limestone) on the fault block terrain (Figure 26E).

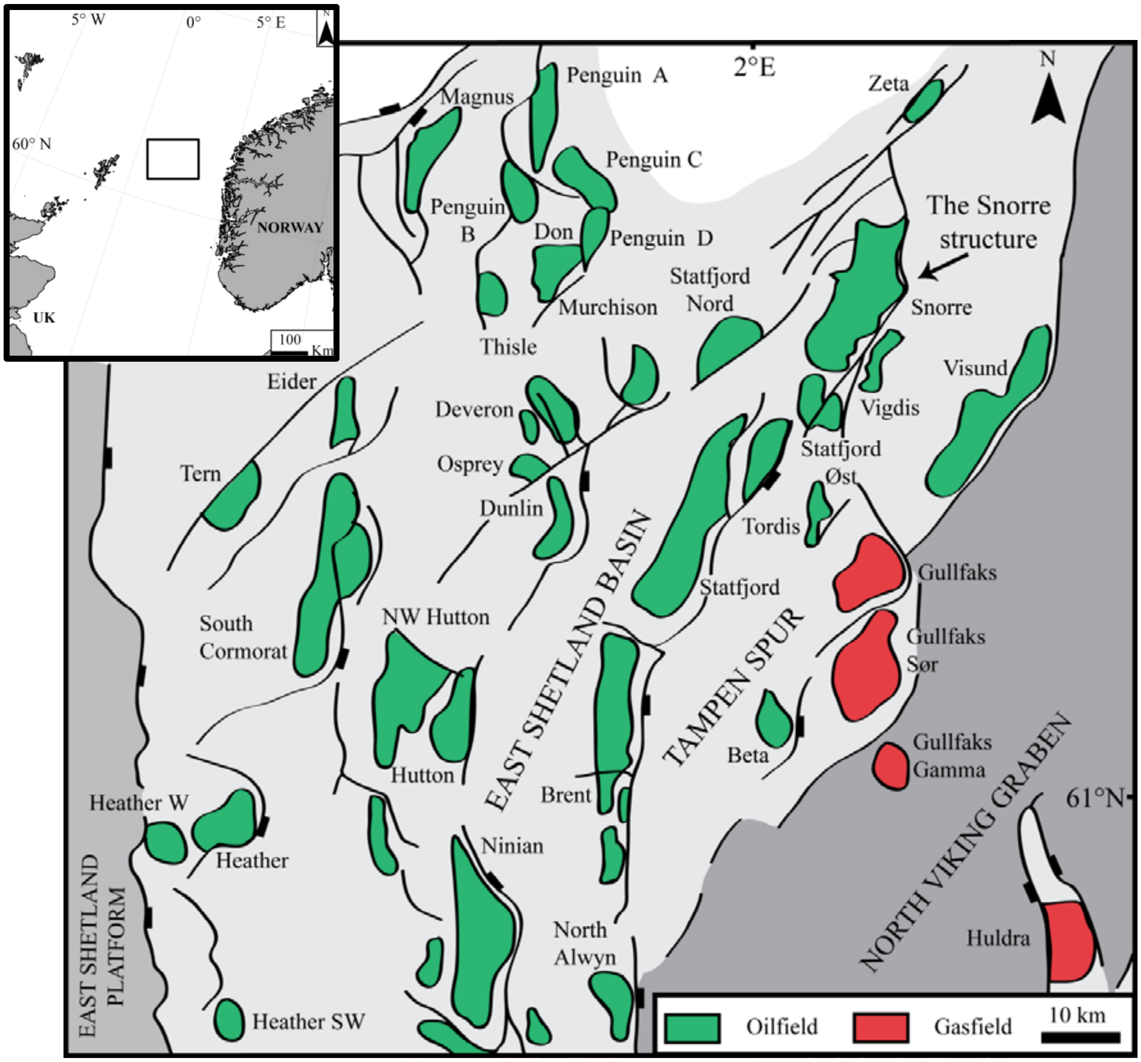


Figure 25 Geographic location of the Snorre structure (represented by a black rectangle) and the main oil fields in the East Shetland basin (modified after Evans, 2003).

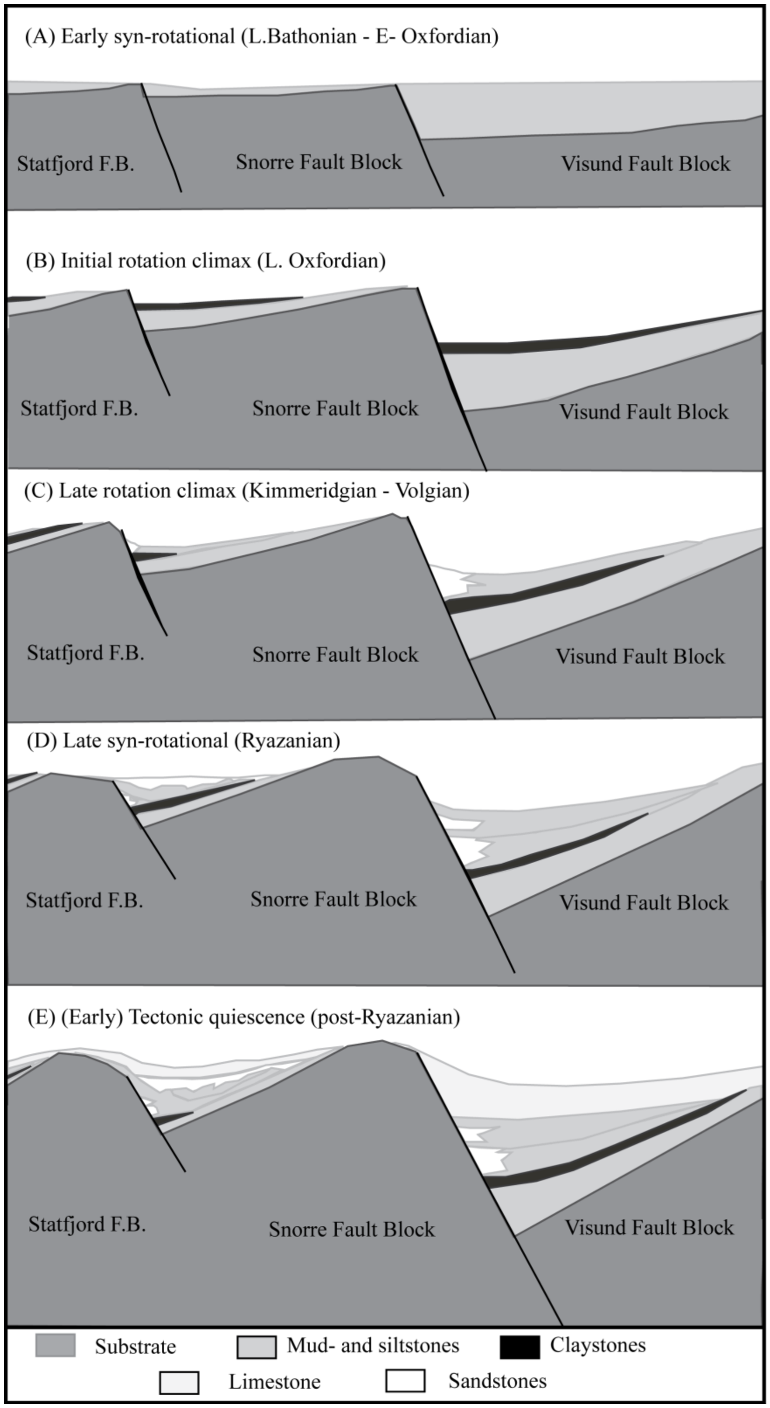


Figure 26 The evolution of the Statfjord, Snorre and Visund fault blocks (Ravnås et al., 2000) during: (A) the early syn-rotational phase. (B) Initial rotation climax. (C) Late rotational climax. (D) Late syn-rotational and (E) the tectonic quiescence.

3.2 Data and Methodology

3.2.1 DATA

A 3-D seismic time cube (SG9701), covering the Snorre and partly the Visund and Statfjord East fields in the northern North Sea, was used for seismic interpretation. The survey was shot for Norsk Hydro Production AS in 1997 and covers an area of 1800 km^2. The outline of the survey together with field locations and the wellbores used in the interpretation are indicated in Figure 27. The well density in the hanging walls within the area of seismic cover is low. Therefore, mostly well information from wells located close to the wedge shape feature was used as a reference during the seismic interpretation. In total 4 wells with a variable suite of logs (e.g. gamma ray, resistivity and sonic), together with stratigraphic well tops (from NPD) have been used. Table 2 show the well information for the wells used. However, only one of the wells used, 34/7-15S, drilled the clastic hanging wall wedge.

3.2.2 METHODOLOGY

Seismic mapping of the top and base of a wedge shape feature located in the hanging wall of the Inner Snorre fault was carried out at an increment of 50 lines, both in in-line and x-line, using the Petrel software from Schlumberger. Time structural maps (base and top) and a thickness map of the interpreted wedge shape were built. Simple volume calculations were preformed based on the observed geometry and the assumption of a porosity of 20% and a water-saturation of 40%. In addition, the inner Snorre hanging wall clastic wedge (of the late syn-rift) was compared to the Kalavrita model.

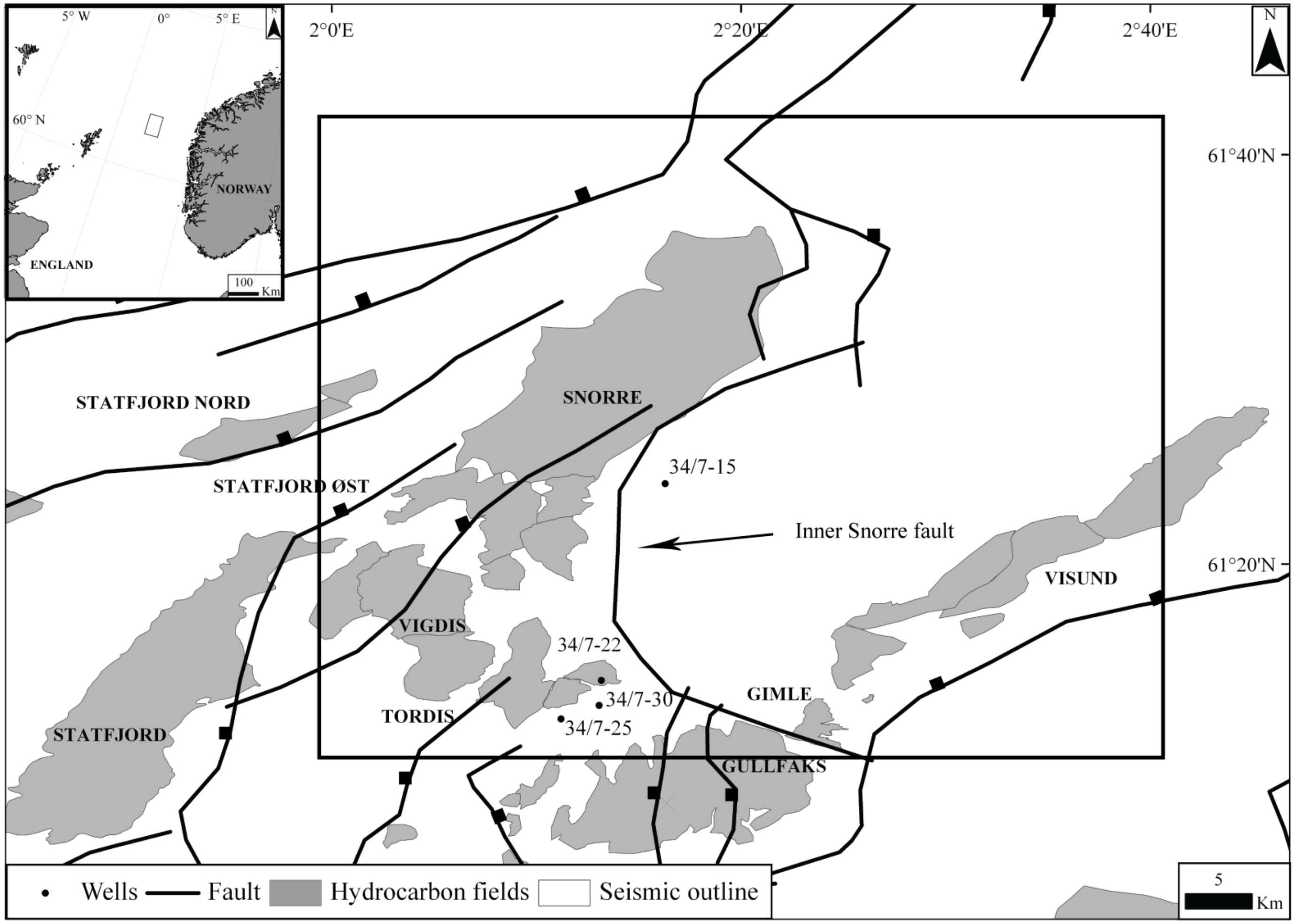


Figure 27 Outline of seismic survey (SG9701), displayed together with hydrocarbon fields, main faults and key wells.

Well	Year	TD (MD) [m]	Oldest rocks penetrated	Discovery	Reservoir
34/7-15S	1990	4646	Early Jurassic	No, oil shows	N/A
34/7-22	1993	2507	Early Jurassic	Yes, oil	Middle Jurassic sands
34/7-25S	1996	3235	Early Jurassic	Yes, oil	Late Jurassic sands
34/7-30SR	1999	2478	Middle Jurassic	No	N/A

Table 2 Well information

3.3 Observations

3.3.1 WELL CHARACTER

Well 34/7-15S, drilled in the hanging wall of the inner Snorre fault (Figure 28), penetrates the western flank of the clastic wedge studied. The low gamma ray response, consistent with sandy facies, shows a coarsening upward succession in the late syn-rift phase (Figure 28C). No other wells within the area of seismic cover, drilled the hanging wall wedges.

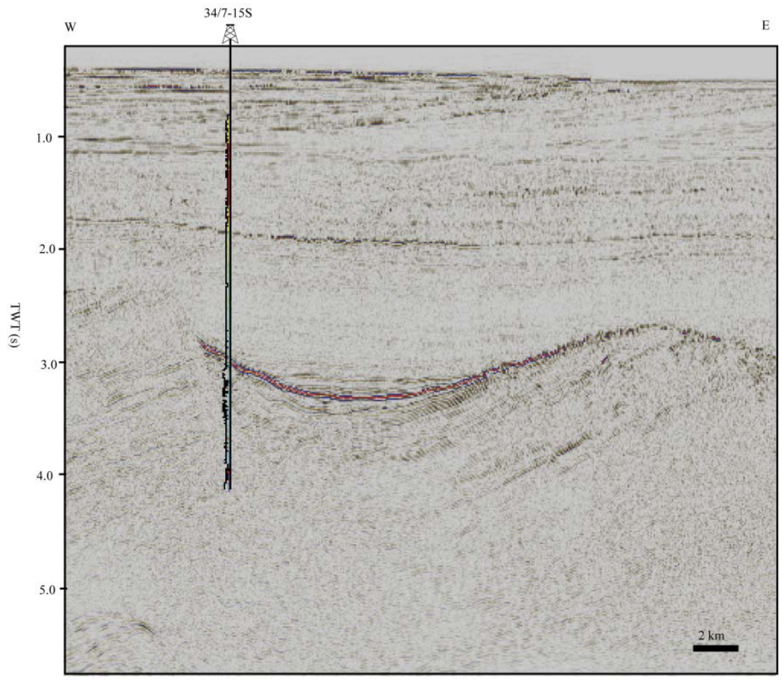
3.3.2 SEISMIC CHARACTER

The top of the late syn-rotational wedge shape is picked on a strong trough and represents strata from the Upper Jurassic, which is truncated by the Base Cretaceous unconformity (Figure 29). Internally, the wedge shape consists of chaotic reflectors that indicate changes on dip. These reflectors are downlapping on the internal unconformity and onlapping onto the syn-rotational strata (Figure 28).

3.3.3 STRUCTURAL CONFIGURATION

The structural maps reveal two main faults, the inner Snorre fault (trending N-S) and the Visund west fault (trending SW-NE) (Figure 30). The present-day structural low is situated in the northern part of the study area, as indicated in Figure 29. The thickness map (Figure 31) shows asymmetrical wedge geometry, where its maximum thickness (~900 ms) is located in the northern part of the study area adjacent to the inner Snorre fault and is interpreted as late syn-rotational strata. The thin part (~100 ms), which is interpreted as distal late-syn-rotational strata, is located in the eastern part of the study area (Figures 29 and 31).

(A)



(B)

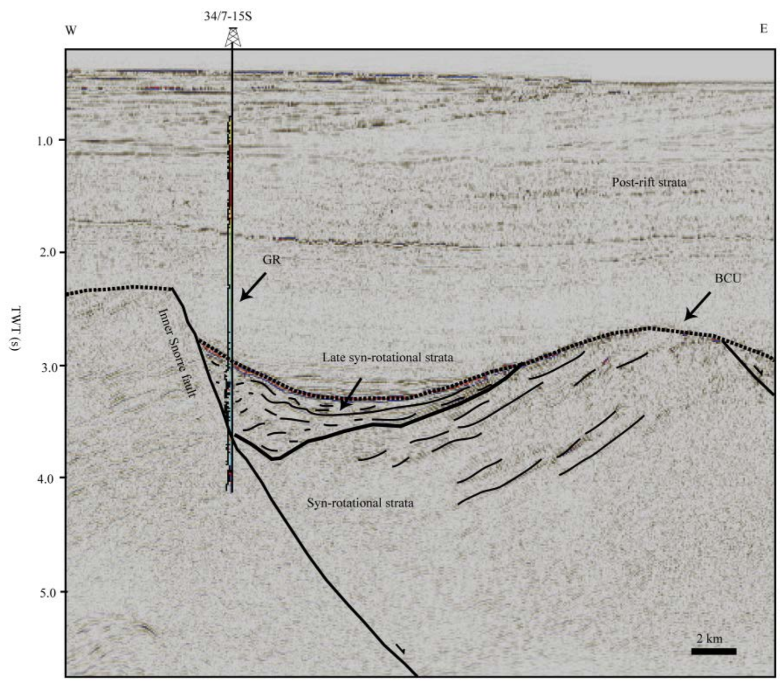


Figure 28 (A) Un-interpreted W-E seismic line. (B) Well 34/7-15S on interpreted W-E 3-D seismic line from the Snorre field. Chaotic reflectors mostly dipping away from the fault indicates changes on dip. TWT = two-way time; BCU = Base Cretaceous Unconformity.

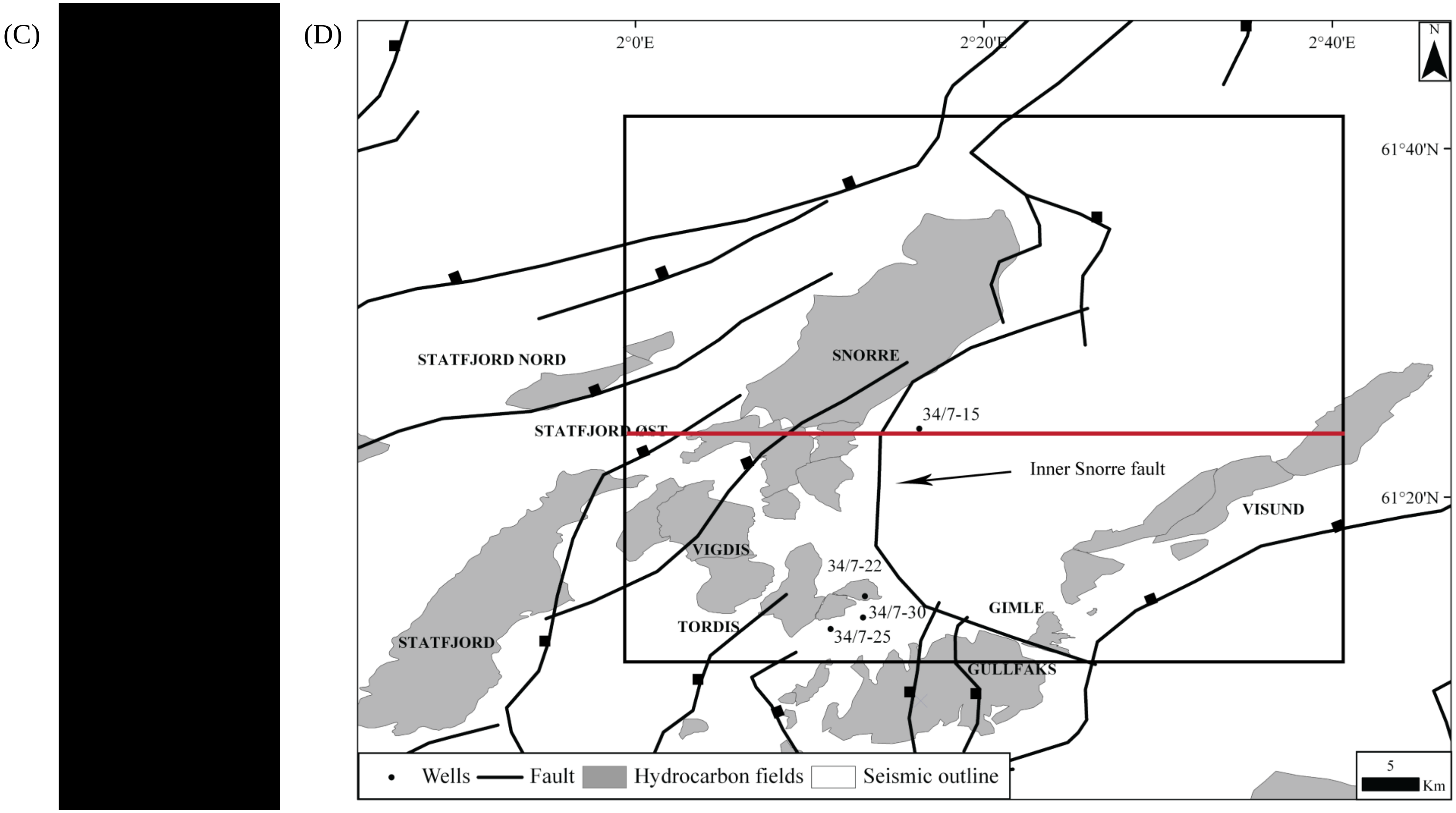
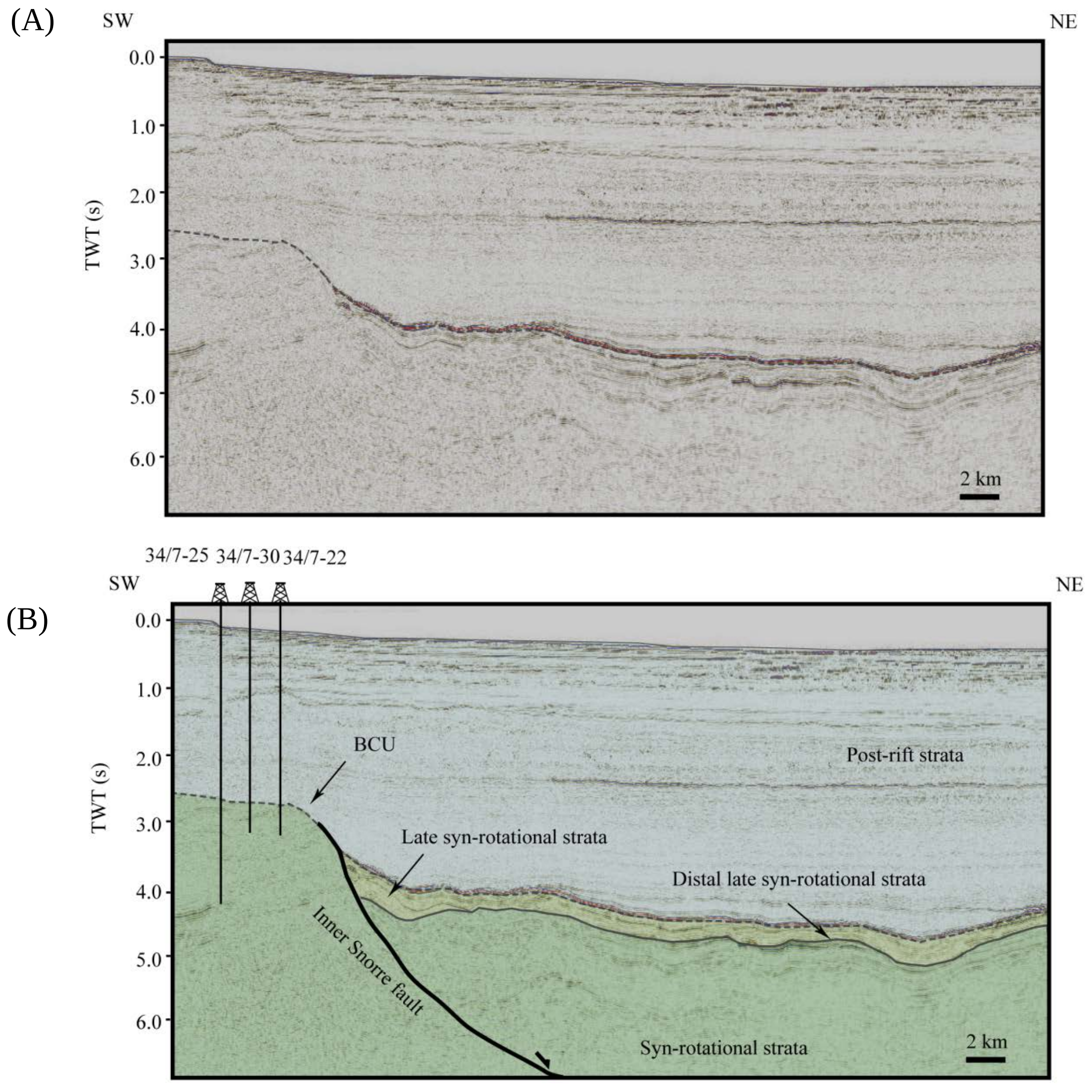


Figure 28 (C) Well-log character of well 34/7-15S showing the different sequences interpreted, which indicates that the wedge shaped strata drilled contains sandyfacies with a coarsening upward succession in the late syn-rift phase. (D) Location map. Red line represents the interpreted seismic line.



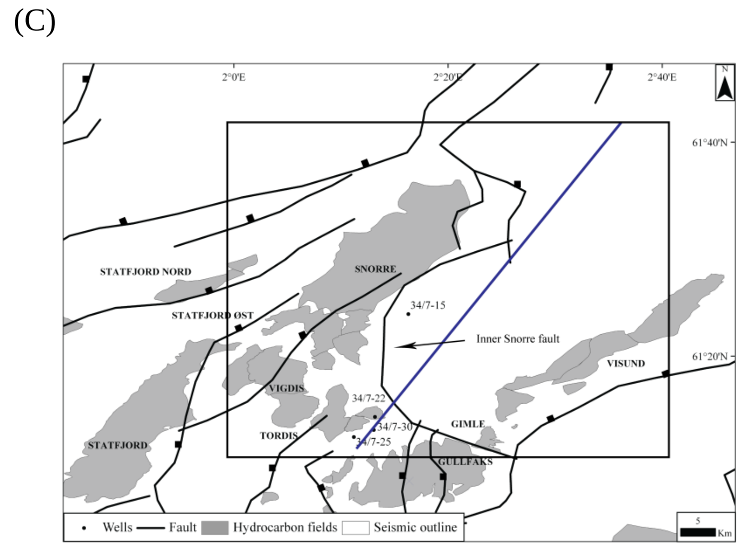
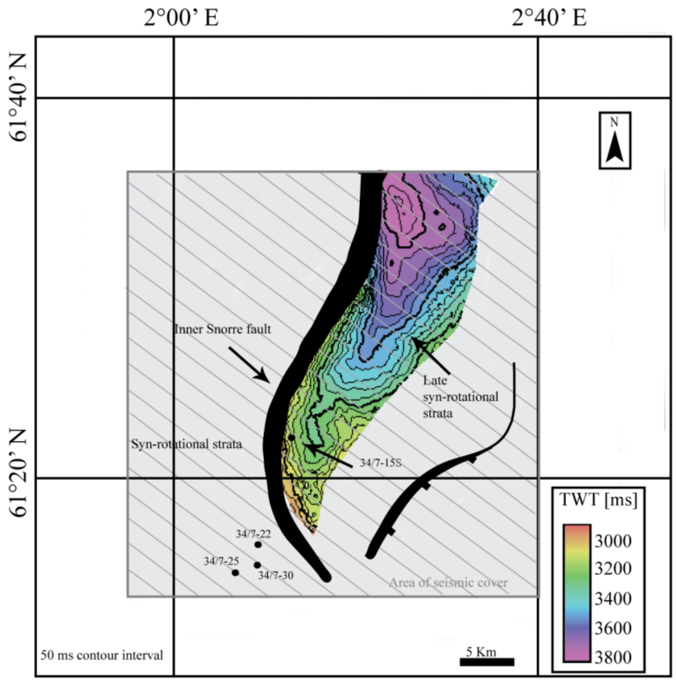


Figure 29 (A) Un-interpreted three-dimensional SW-NE seismic line from the Snorre to Visund fault block. (B) Interpreted three-dimensional SW-NE seismic line showing the inner Snorre fault, drilled wells and the stratigraphy. BCU = Base Cretaceous unconformity; TWT = two-way time. (C) Location of the interpreted line.

(A)



(B)

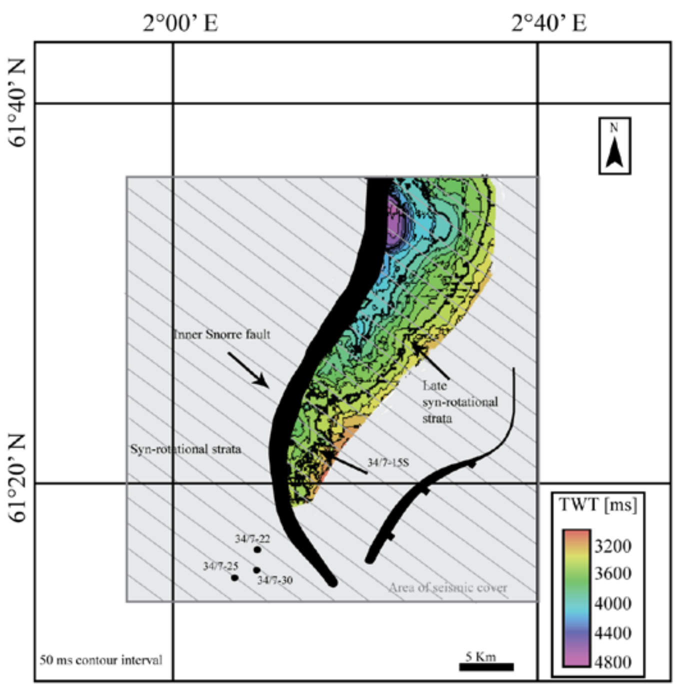


Figure 30 Time structural map of the (A) the top and (B) the base of the wedge structure, displayed together with wells and interpreted faults. TWT = two-way time.

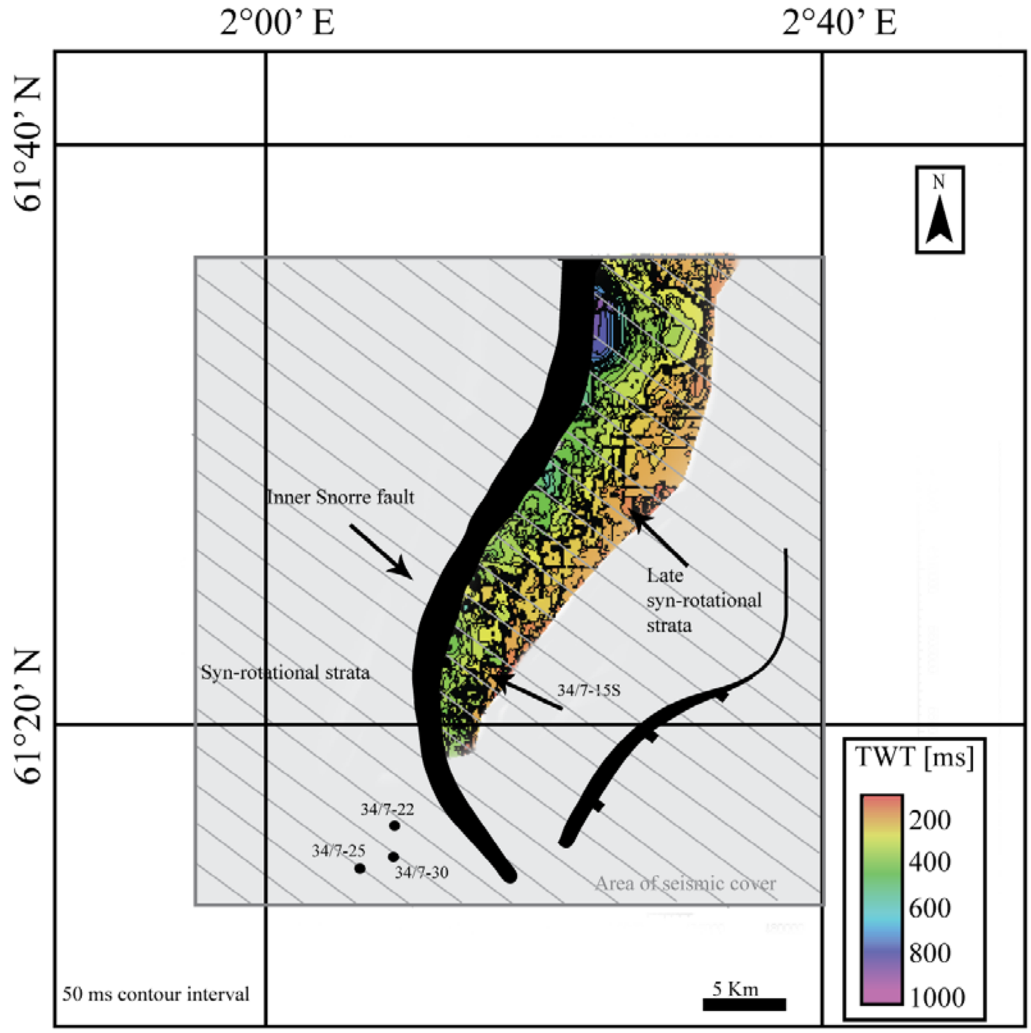


Figure 31 Time thickness map of the wedge sequence, displayed together with wells and interpreted faults. TWT = two-way time.

The clastic wedge is placed up-dip from the source rock and against the fault plane, with a throw of 500 m from the uplifted footwall where the Snorre field is located. In addition, a part of the clastic wedge is placed at the same structural level as the adjacent producing footwall high from the Visund field (Figure 28). By postulating the OWC from the adjacent footwall high, one can assume that part of the studied structure is oil filled (Figure 32).

3.3.4 INTERPRETATION

Based on well information (from NPD) the well penetrating the late syn-rotational wedge strata was abandoned in 1990, as a dry hole with oil shows. Even though this specific well was dry, it did not penetrate the highest part of the structure. In addition, the fault displacement on the inner Snorre fault is very large (minimum displacement of 500m). As a result, the studied wedge shape is situated deeper than the OWC. Therefore, similar wedge shaped structures in the region with comparable reservoir properties and less fault displacement, could still be producible. The calculated volumes of 0.6 to 0.64 km^3, assuming a porosity of 20% and a water saturation of 40 %, representing 11-12 mmboe could be attractive plays for smaller oil companies in Norway.

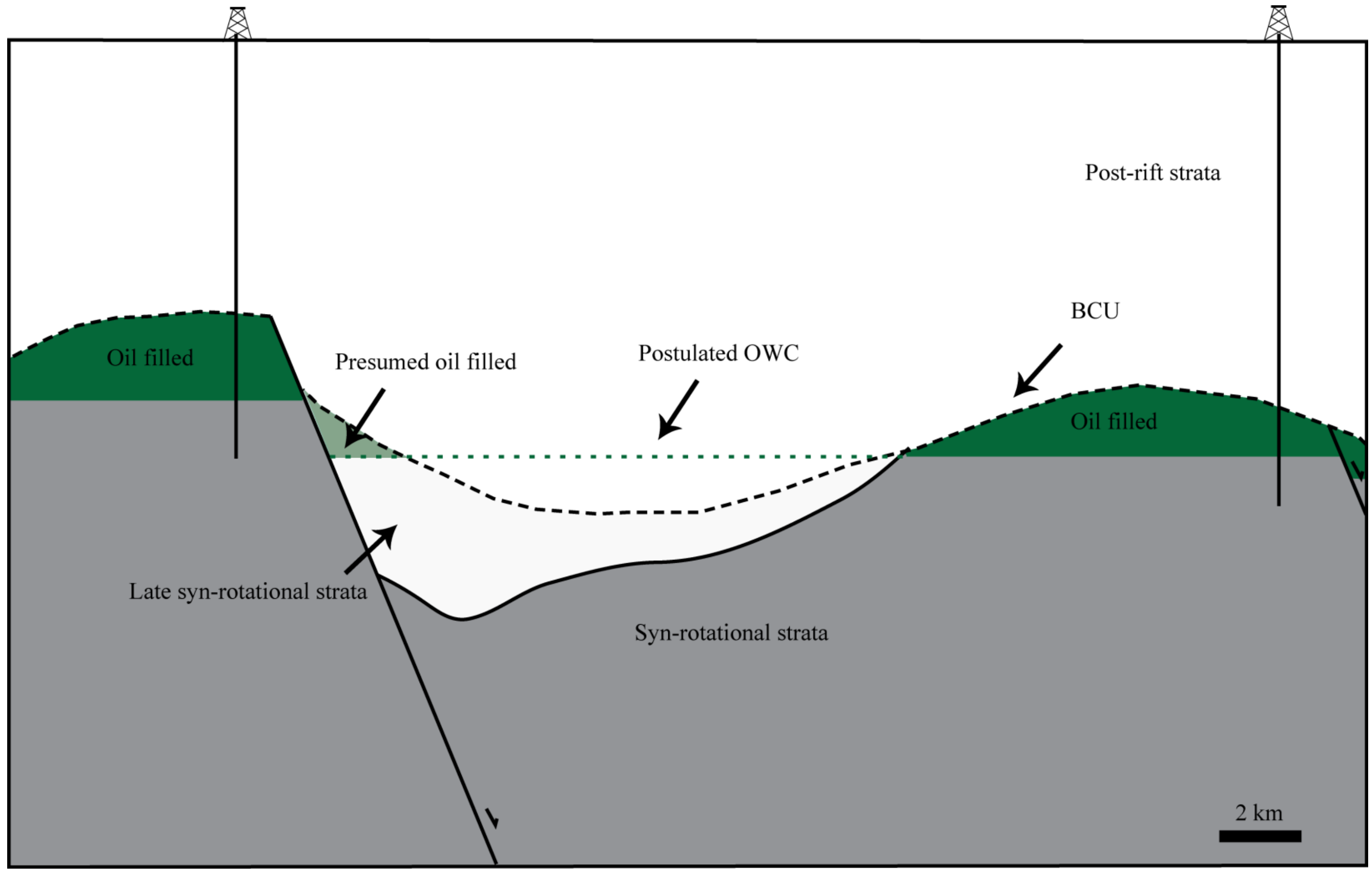


Figure 32 Schematic sketch indicating the OWC, the postulated OWC and the wedge studied on seismic. The wedge is placed structurally higher than the adjacent footwall. Therefore, it is suggested that the studied structure is partly oil-filled.

4. DISCUSSION

4.1 North Sea vs. Kalavrita Clastic Wedges - Similarities and Differences

Outcrop analysis can provide a better understanding of sedimentation and filling architectures in rift systems, e.g. the Norwegian Continental Shelf. To further investigate how the outcrop data can be applied to the subsurface; a comparison of the observed clastic wedges (North Sea and Kalavrita region) is given in Table 3.

4.1.1 SIMILARITIES

i. Changes on dips

   For the fan studied in Greece, changes on dip are represented by quite consistent NE dip directions measured in the field, against the fault planes. Corresponding changes on dips are observed in the subsurface fan in the hanging wall of the inner Snorre fault (based on chaotic reflectors). However, here the fan shows more chaotic dips, with no specific dip direction.

ii. Structures

   Both the studied fans are situated in the hanging wall of normal faults (against the fault planes) and have comparable throw displacements in the range of 500 – 800 m.

iii. Geometry and volumetrics

   The studied fans represent large stratigraphic units (of 12-24 mmboe), which are comparable in size and geometry.

iv. Facies variations and grain-size trend

   Both the studied fans, shows a coarsening upward succession. Therefore, the Corinth rift fan is a suitable analogue for 3-D geometry and facies variations.

CHARATERISTICS	**GREECE**	**NORTH SEA**
Dip	Changes on dip, mostly NE dip directions	Chaotic changes in dip
Deposition	Relay-ramp fed	Late syn-rotational sedimentation
Sediment	Gravelly conglomerates with a coarsening upward succession	Sandyfacies with a coarsening upward succession
Volumetrics	18 – 24 mmboe	11 – 12 mmboe
Structures	Fan in the hanging wall of normal faults	Fan in the hanging wall of normal faults
Geometry	Fan-shaped	Fan-shaped
Age	Pliocene- Quaternary	Jurassic – Lower Cretaceous
Fault throw	800 m	500m

Table 3 Comparison of the wedges studied in the Kalavrita and the North Sea region.

4.1.2 DIFFERENCES

i. Sediments and reservoir properties

The Corinth rift fan consists of gravelly conglomerates, whereas the subsurface fan consists of more sandy-facies. Therefore, the Corinth rift fan is not a good analogue related to the stratigraphy and reservoir properties.

ii. Depositional model

Analysis of the data obtained in the field resembles interpretations from many hydrocarbon fields on the Norwegian Continental Shelf, e.g. the Snorre field. Here the late phase of syn-rotational faulting (Figure 22) resulted in a localized fan shape against the fault plane, where the source of sediments is considered to be the footwall, prior to footwall rotation (Færseth and Ravnås, 1998). However, the outcrop study of fan deposition in rotated fault blocks in the Corinth rift system in Greece indicate that the fan deposition occurred as a relay-ramp fan, fed from the footwall (most likely during the late faulting phase). Relay-ramps are not observed within the area of seismic cover. However, the 3-D seismic survey used, might be too small to see relay-ramps. It is suggested that related to model of deposition, the fan studied in the Corinth rift system, might not be that applicable.

4.2 Petroleum Significance

The North Sea region possesses an active petroleum system, demonstrated by the amount of oil that is produced daily from fields in the Norwegian and UK sector. However, drilling the discoveries of Jurassic to Lower Cretaceous wedges situated in the hanging walls of major faults, are mostly restricted to the UK sector and include fields such as the Scarpa, Captain, Claymore and Britannia fields in the Moray Firth area (Evans, 2003). These Lower Cretaceous reservoirs, in the UK sector, have estimated reserves of approximately 1.6 BBOE, which are mainly dominated by deep-water clastic plays, especially from the Britannia field (650 mmboe) and the Captain field (339 mmboe) (Garrett et al., 2000). Minor hydrocarbon fields, e.g. Hannay, Saltire and Highlander, have estimated reserves of 8 – 20 mmboe, which are comparable to the calculated volumes (11 – 12 mmboe) for the studied subsurface wedge situated close to the Snorre field. Given the already existing infrastructure in the North Sea region and a successful petroleum system, these late syn-rotational wedges (with good reservoir properties), could be attractive plays (at least for smaller oil companies), in the Norwegian sector.

4.2.1. Play-Fairway Analysis

Play-fairway analysis of these syn-rift plays put the controlling factor on reservoir, top seal and hydrocarbon charge.

4.2.1.1 Reservoir

Sandstones were deposited in the North Sea region in response to the diachronous rifting process, which resulted in thick and laterally restricted fan shaped sand-bodies, partly enchased in organic rich muds (Johnson and Fisher, 2009). This correlates to the facies observed in well data for the studied wedge shape in the Inner Snorre hanging wall (Figure 28). However, fields producing from similar wedge-shapes in the UK sector are situated within the East Shetland platform, with the Britannia field at the eastern flank. Therefore, the drilled wedges, with the exception of the Britannia sandstone member (at depths of 4000 – 4200m), are situated at quite shallow depths (1000 - 2000 m) at least compared to similar wedge shaped structures in the Norwegian sector (e.g. close to the Snorre field), within the Viking Graben, at depths of 3000 - 3500m. Strata buried at greater depths could result in more cemented strata that are less producible. However, in the UK sector they successfully drill and produce from the Britannia sandstones member, which indicates a preservation of porosity at great depths. For strata within the grabens, this preservation of porosity (with depths that exceed 3900m), is suggested to be related to the significant overpressure observed in the region (Johnson and Fisher, 2009).

4.2.1.2 Trap

The clastic wedge observed is located in a large and relatively simple, tilted fault block structure (between the Snorre and Visund fields). The trap style is considered an up-thrown fault closure, related to the rotated fault block, which is observed on seismic data (e.g. Figure 29). However, the trap could also involve a stratigraphic pinch-out of the submarine fan and reservoir truncation of the Base Cretaceous Unconformity (Figures 28 and 29).

4.2.1.3 Source Rock and Migration

The Upper Jurassic source rock (e.g. the Spekk and Heather formation) is well established as a good source rock within the area of study. The studied wedge structure is placed up-dip from the mature source rock and the hydrocarbon migration is considered to be short distant.

5. CONCLUSION

1. The clastic wedge in the Kalavrita region is interpreted as a colluvial fan, deposited by debris-flow slope-waste sedimentary processes.
2. The clastic wedge observed in Greece, which is suggested to have been deposited as a relay-ramp fed fan, can act as an outcrop analogue for hydrocarbon reservoirs in the Northern North Sea. However, this only applies for the structures and volumetrics, and does not include the stratigraphy.
3. Late syn-rift deposits, even though they have small volumes, are an attractive play, considering that they are placed next to fields producing from the footwall high and thereby are situated close to existing facilities.
4. Facies with good reservoir properties are observed in the clastic wedge, situated in the adjacent hanging wall of the Snorre field. However, it is too deep for OWC, so there were no discoveries. In addition, these good reservoir properties do not apply to the steeply gravelly fan observed in the hanging wall of the Dhoumena east fault.
5. Volumetrics for the two studied clastic fans are calculated to be between 11- 28 mmboe, which are comparable to reserves estimated for Lower Cretaceous clastic wedges in producing UK hydrocarbon fields, e.g. the Hannay field.

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