# TECTONIC EVOLUTION AND STRUCTURAL STYLES OF DEFORMATION OF SOUTHERN KAKAP BLOCK, WEST NATUNA BASIN, INDONESIA

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**Indonesia, West Natuna Basin, Kakap**

Resumen *Evolución tectónica y estilos estructurales de deformación del sector sur del bloque Kakap, cuenca de West Natuna, Indonesia*
La cuenca de *West Natuna*, Indonesia, sufrió un activo tectonismo en un período de tiempo relativamente corto. Fue afectada por distintos episodios extensivos desde el Eoceno tardío hasta el inicio del Oligoceno Inferior. Dos megasecuencias de *syn-rift* registran estas etapas. Se asocian con hemi-grábenes generados por fallas de rumbo ENE-WSW y NW-SE, de alto ángulo, que involucran al basamento y buzan hacia el norte. Sobre estos depósitos syn-extensionales se reconoce un extenso intervalo con espesores homogéneos. Este evidencia el inicio de un período con una tasa de extensión menor durante el comienzo del Oligoceno Tardío. La inversión tectónica comienza promediando el Oligoceno Tardío y continúa hasta el Reciente. La inversión no tuvo una distribución homogénea. Se concentró en el sector oriental, donde la extensión inicial fue mayor. La compresión invirtió las estructuras extensivas previas, generando pliegues por propagación de falla asimétricos, de gran escala. La inversión de una falla extensional conjugada a los segmentos principales fue responsable del cambio de vergencia de las estructuras a lo largo del rumbo. La inversión más intensa se reconoce en la parte superior de la primer megasecuencia compresiva, que tuvo lugar durante el Mioceno Medio superior. Estos depósitos fueron erosionados en las crestas de los anticlinales por una discordancia regional, la cual fue posteriormente plegada, indicando la existencia de una etapa compresiva posterior. Los niveles correspondientes al Mioceno Tardío y Plioceno que suprayacen a esta discordancia representan la segunda megasecuencia compresiva, conformada por estratos de crecimiento suavemente plegados.

## INTRODUCTION

West Natuna basin is located in SE ASIA, in the Natuna Sea, between peninsular Malaysia and Borneo, west offshore of the Indonesian Natuna Island (Fig. 1).
This Tertiary basin underwent great tectonic activity during a quite short period of time. To unravel its evolution, a 600 $km^2$ 3D survey (Fig. 1) has been interpreted and analysed. The involved area is placed within the Kakap Block, which is on the centre to north-western sector of the West Natuna basin.

## SE ASIA TECTONIC FRAMEWORK - SUNDALAND BASINS ORIGIN

West Natuna Basin is located on the southeast corner of the Eurasian plate, within the Sundaland geological province (Fig. 2). The Sundaland and the basins within it are characterized by being floored by continental crust.
This sector of the Eurasian plate is bounded on the west and south by the Indian-Australian plate through a subduction zone (Fig. 2).
The eastern boundary also corresponds to an active margin, which relates the Phillippine Sea plate with the Eurasian plate (Fig. 2).
The Indian-Australian-Eurasian's Benioff zone is dipping eastwards west of Indochina, and northwards south of Sumatra and Java islands, which developed as island arcs (Fig. 2). Subduction on the Eurasian-Philippine Sea plate's boundary has west polarity (Fig. 2).
The collision between India and Eurasia that took place between 45 and 50 Ma (Tapponnier et al., 1986; Dewey et al., 1988; Peltzer & Tapponnier, 1988; Harrison et al., 1992; Le Pichon et al., 1992 and Hall, 2002) produced the extrusion of Eurasia through a series of main strike-slip faults (Fig. 2).
The presence of regional faults with lateral displacement has been pointed out by numerous authors (Fig. 2). They are interpreted to cause transtension and the associated opening of sedimentary basins in the Sundaland during the Tertiary (Peltzer & Tapponnier, 1988).

WEST NATUNA BASIN STRUCTURE

The whole evolution of the basin occurred during the Tertiary and continues to present.

West Natuna Basin shows signs of continuous tectonic activity from the very beginning and all through its history. It began in an extensional kind of setting (rifting) and was tectonically inverted later on.

The change from extensional to compressional setting occurred in a relatively short period of time, due to major global plate’s reorganization. The latter stage produced the generation of many hydrocarbon-bearing positive structures across the basin (Fig. 1).

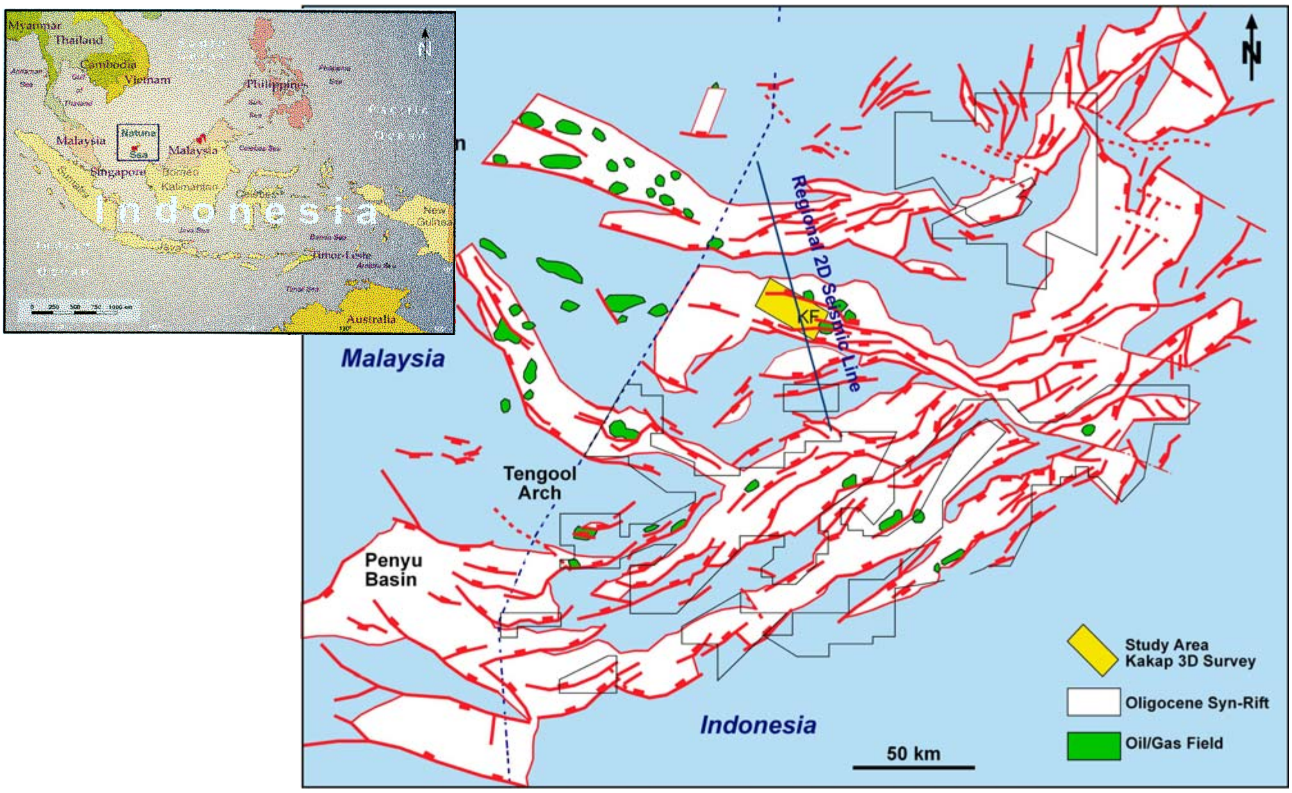


Figure 1: West Natuna Basin is located in the West Natuna Sea (left-hand side), SE Asia, within the Indonisian shelf, where water depths are not greater than a hundred meters. Map of West Natuna Basin (right-hand side) showing the most important structure trends. Locations of the study area (in yellow) as well as hydrocarbon fields (in green) around the basin are included. Modified from Shawn (1997).

A regional structural analysis of the West Natuna Basin has been done in the past by different authors. McClay & Bonora (1998) recognised two major fault trends in the region: a northeast-southwest trend and a northwest-southeast one (Fig. 1), which have been active causing multi-episodic deformation.

The first trend is common on the southeast half of the basin, while the second one (northwest-southeast) is commonly observed on the northwest half of West Natuna Basin, where the study area is located (Fig. 1).

These faults, mainly planar-domino style, generated half-grabens as the basin started extending in the Late Eocene. The latter structures underwent tectonic inversion soon after the extension stage, in the upper Late Oligocene.

Tectonic inversion was responsible for the occurrence of inversion growth anticlines. They typically show steep forelimbs and gently dipping back limbs. Wedge-shape geometries are also common in both syn-extensional and syn-inversion deposits (Cooper & Williams, 1989).

WEST NATUNA BASIN STRATIGRAPHY

A description of the lithostratigraphy that comprises West Natuna Basin sedimentary record is outlined in Figure 3.

Sundaland basement's rocks are igneous, sedimentary and metamorphic, Mesozoic and Palaeozoic in age (Hall, 2002).

Overlying an erosive unconformity on the basement, Eocene and Oligocene sedimentation occurred in lacustrine systems, where fluvio-deltaic bodies prograded into lakes.

In the Early Miocene, a change took place in the region. The Barat Formation shows shales deposited in marine conditions. They represent the begging of sedimentation on a large shallow embayment. Shallow marine deposition would continue in the sedimentary record up to Recent.

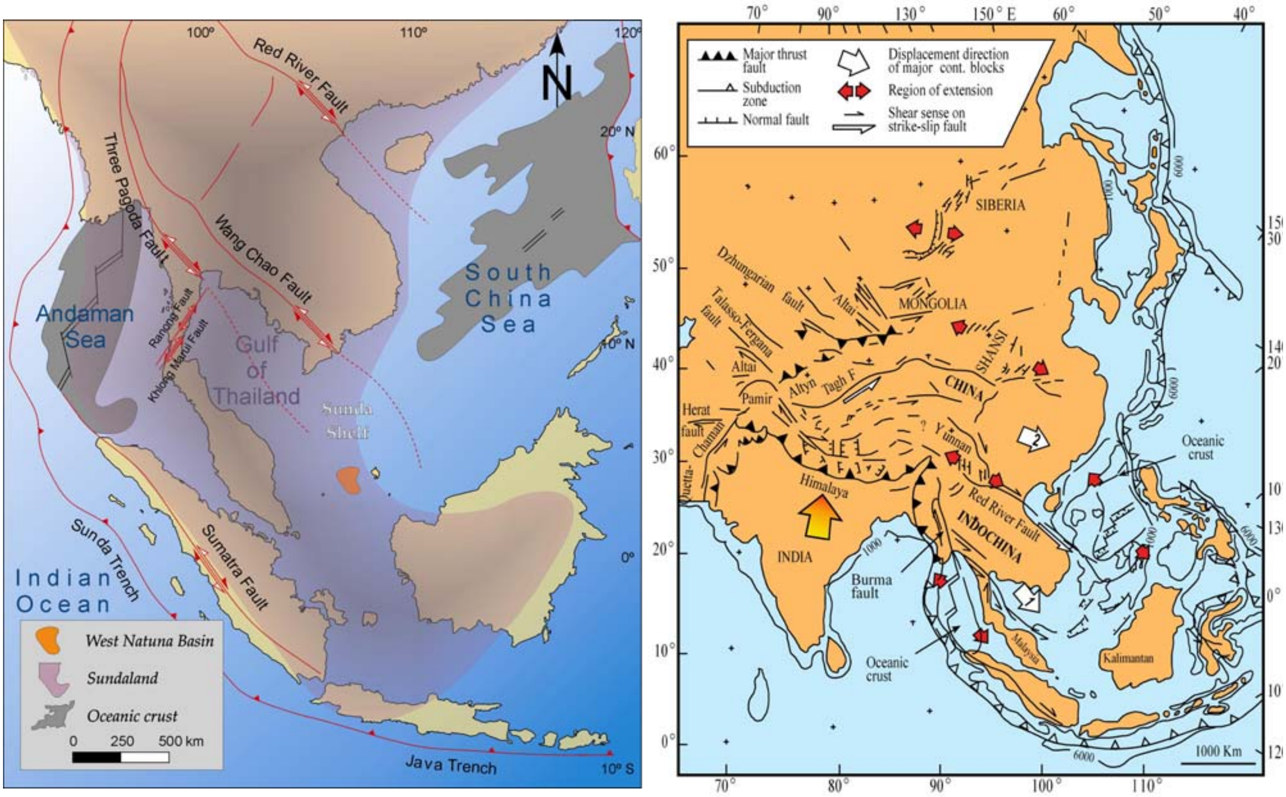


Figure 2: West Natuna Basin (in orange) is located within the Sundaland geological province (left-hand side), which is underlain by continental crust. Plate tectonic boundaries are shown by subduction zone and major faults in SE Asia are also displayed. Tectonic map of the region (right-hand side). Extrusion of Eurasia due to India collision at 45-50 Ma could be responsible for the origin of many basins in the Sundaland geological province. Major lateral displacement faults are shown. Modified from Peltzer & Tapponnier (1988).

A regional angular unconformity, the Muda unconformity, is observed in the register in the early Late Miocene. Overlying it, Muda Formation was deposited. It consists of fine sediments, deposited in a shallow marine to estuarine environments.

It is worth noticing that many lateral changes are expected to occur within the basin.

Since, for instance, Late Eocene-Oligocene sediments were deposited in different half-grabens (sub-basins) and during the Miocene major faults were tectonically inverted, generating great differences in water depth in short distances.

Figure 4 shows a chronostratigraphic chart indicating the tectonic evolution of southern Kakap block.

Two main extension stages have been interpreted. Syn-rift A, which shows minor pulses, and Syn-rift B megasequences.

A period of tectonic calm, where thermal subsidence occurred, was interpreted as either a Late syn-rift or Post-rift, being recorded by the Upper Gabus Member (Fig. 4).

Inversion started in the upper Late Oligocene/early Lower Miocene, and continues into present time. Two inversion-related megasequences have been interpreted, Syn-inversion A and Syn-inversion B megasequences.

A folded regional unconformity, known as Muda, acts as a boundary between them.

Muda Unconformity

A basin-wide unconformity developed in between the Middle and Late Miocene (Fig. 5). This hiatus is represented by an erosive surface, which truncated most of the positive structures of West Natuna Basin (Fig. 5).

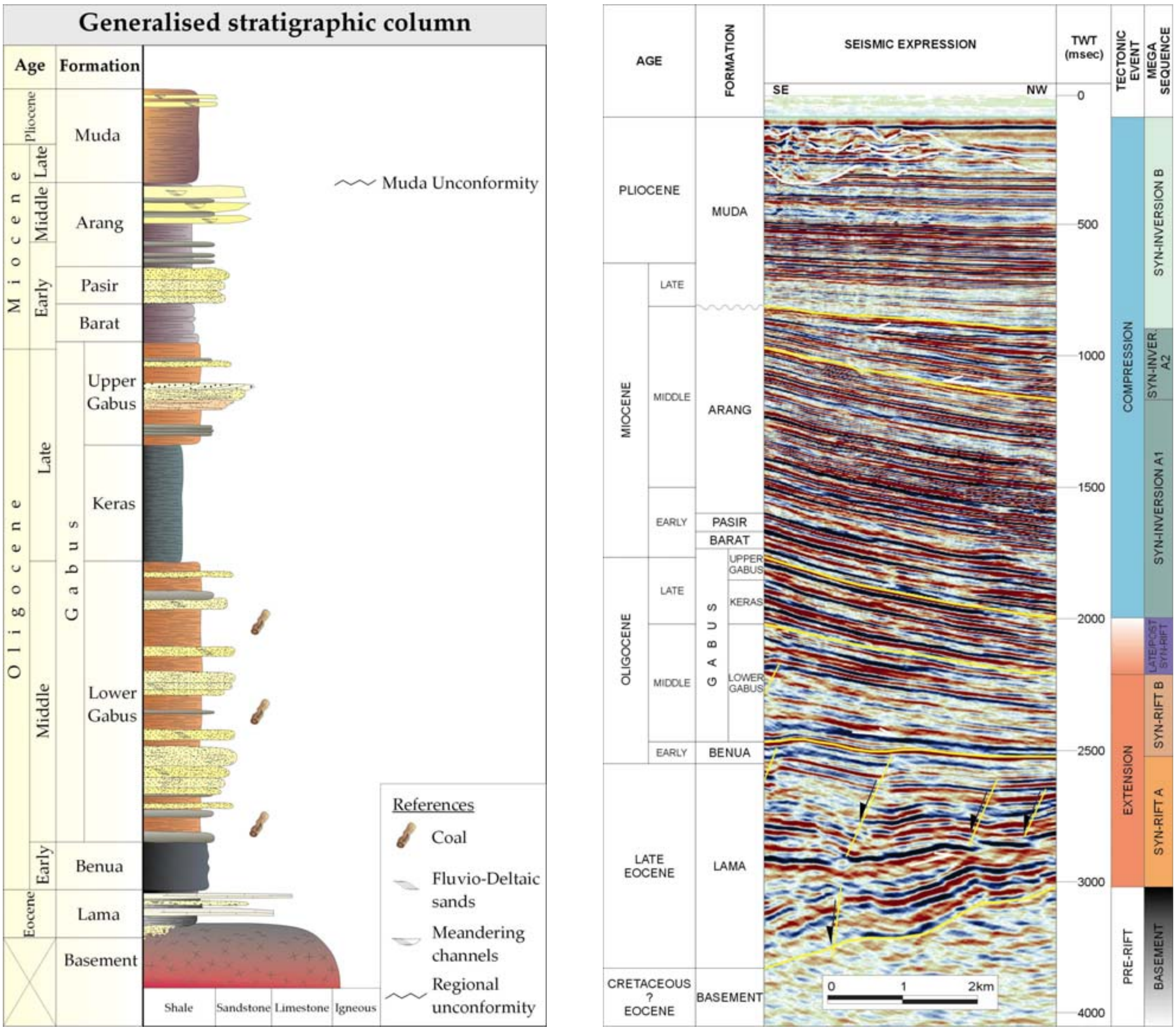


Figure 3: Generalised stratigraphic column of West Natuna Basin (left-hand side). Note that sedimentation during Eocene and most of the Oligocene occurred on continental environments of deposition, while during Miocene it turns into a marine marginal kind of sedimentation. The right-hand side figure shows the seismic expression of the different interpreted megasequences and their related tectonic.

Folded beds were eroded away by the Muda unconformity, which is also deformed, comprising an open fold, evidencing that inversion went on after that event (Fig. 5).

Truncated underlain structures are much more tightly folded, indicating that maximum deformation occurred before this erosive event (Fig. 2).

SOUTHERN KAKAP BLOCK STRUCTURAL ARCHITECTURE

Deformation in the area was firstly accommodated by Late Eocene WSW-ENE and NW-SE extensional faults which comprised a segmented half-graben (Fig. 6).

Principal inverted extensional fault segments can be observed on Figure 6, on the southern side of the study area. They are northwards-dipping ENE-WSW and NW-SE trending faults that joined as propagated further.

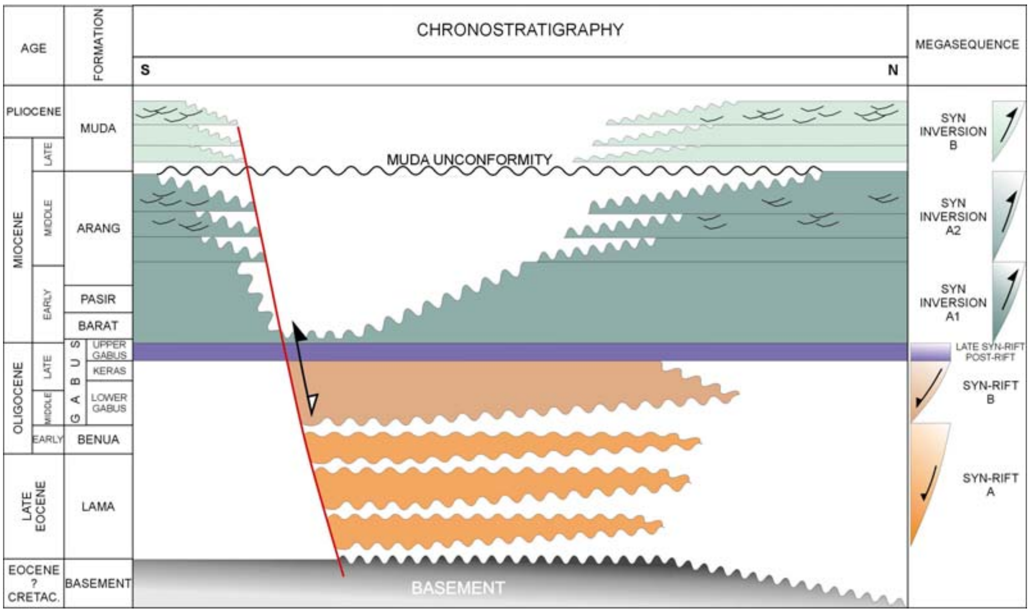


Figure 4: Chronostratigraphic chart showing the tectonic evolution of southern Kakap block.

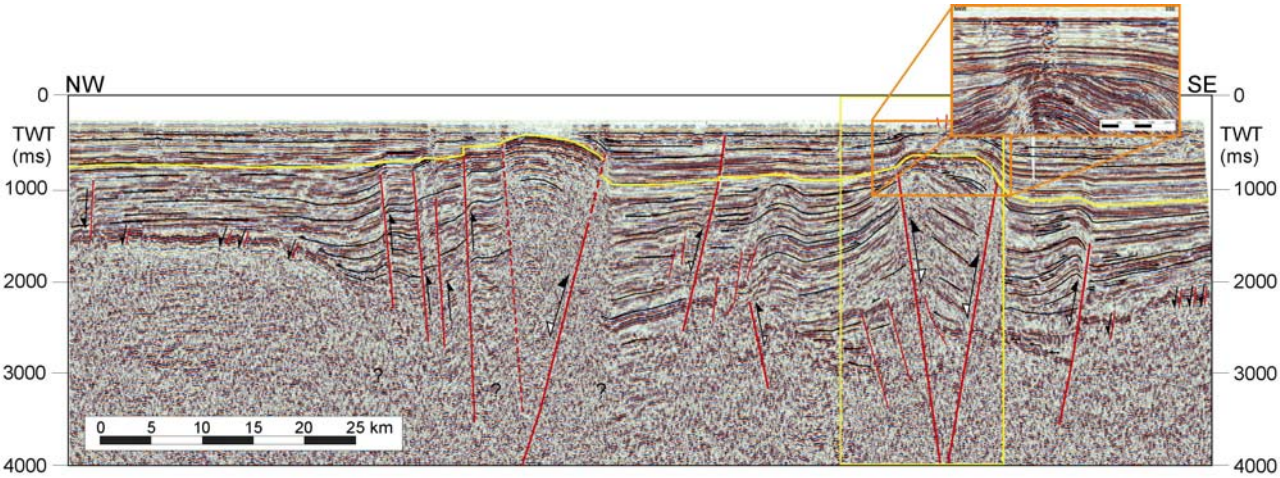


Figure 5: Regional 2D line in a NW-SE direction (location in Figure 1). The Muda unconformity (yellow line across the region) is a basin-wide unconformity; it cuts the hinges of the main inversion anticlines (orange box shows a closer view) and stays conformable on lower sectors. Study area highlighted by a yellow box.

A southwards-dipping inverted fault can be observed on the eastern side of the study area. The latter was responsible for a flip in vergence of the inverted half-graben.

Compression was accommodated by inversion of these fault segments. Therefore, the resulted anticline follows their trends.

Even though tectonic inversion was strong, top basement did not reach the null point, remaining in net extension (Fig. 6).

SEISMIC EXPRESSION

Figure 3 shows the defined Megasequences and their respective seismic pattern. On the left-hand side the lithostratigraphic column is also shown. The different boundaries are delineated by a yellow line.

Basement is recognized by the blurred imaging of the seismic information.

Syn-rift Megasequences display a divergence of the horizons towards the main fault (towards the southeast in this case), implying an increase in thickness of the megasequence towards that direction.

Late Post-rift Megasequence is recognized by the parallelism of the seismic horizons and the good imaging of the comprising layers. Inversion-related megasequences also show divergence of the layers, though outwards the main faults, increasing their thickness away from the hinge of the inversion structures.

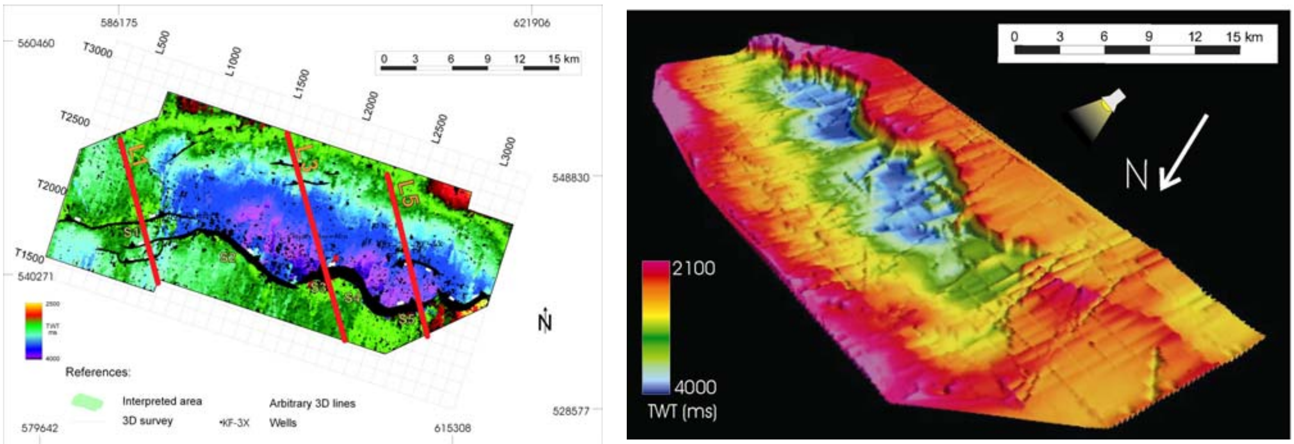


Figure 6: Top basement time structure map (left-hand side) of the 3D survey area. Reddish and greenish colours indicate structural highs, while bluish ones show deep areas. Red lines L1, L3 and L5 show the location of Fig. 7, 8 and 9 respectively. Top basement 3D view (right-hand side). Despite the tectonic inversion, the half-graben geometry can still be observed.

## STRUCTURAL ANALYSIS

Thick-skinned deformation affected the study area. Initial extension created a major half-graben, formed by sub-planar, northwards dipping faults. Later compression and consequent shortening was accommodated by inversion of this previous structure, which acted as weakness zones, involving the basement in the deformation.

Three representative arbitrary lines L1, L2 and L5, perpendicular to fault segments S1, S3 and S5 (location in Figure 6), are displayed in Figures 12, 13 and 14 in order to show the main structural characteristics of the study area.

Tectonic inversion of major fault segments resulted in the generation of a large scale fault-propagation fold. It typically has a gently dipping back-limb and a steeper forelimb. Its hinge line is curved, parallel to the trend of the ENE-WSW and NW-SE inverted faults.

A flip in polarity of the main positive structure is caused by the presence of a conjugate inverted fault (Fig. 9).

A relationship between the initial extension and later inversion has been noticed. Extension on the east was stronger than on the west side of the study area, and so happened with subsequent inversion.

## SOUTHERN KAKAP BLOCK TECTONIC EVOLUTION

Understanding the tectonic evolution of this area is the main objective of this piece of work. In order to unravel it, 600 $km^2$ of 3D seismic information in time has been analysed. Since unconformities and major structural features (such as fold symmetry, relative thicknesses, apparent throw, etc.) would not change drastically by depth converting the seismic, it was considered not essential to produce this conversion for the purposes of this work.

The involved area has undergone a complex tectonic history that included periods of extension followed by later tectonic inversion. Extension probably started on the Late Eocene (Fig. 4). Syn-rift A deposits filled the accommodation space generated by the half-graben created by northwards-dipping extensional faults.

Figure 10 display how thicknesses were more important in the hanging-wall (north), close to the faults, than in the footwall (South, in red), where thicknesses tend to be constant. Extension during this stage was very mild on the west (Fig. 7).

Another extensional phase began in the Middle Oligocene. This time extension also reached the west side, evidenced by the wedge geometry of Syn-rift B deposits (Fig. 7 and Fig. 11). A depocentre was located on the east side, where sedimentation occurred in a graben (Fig. 9 and Fig. 11).

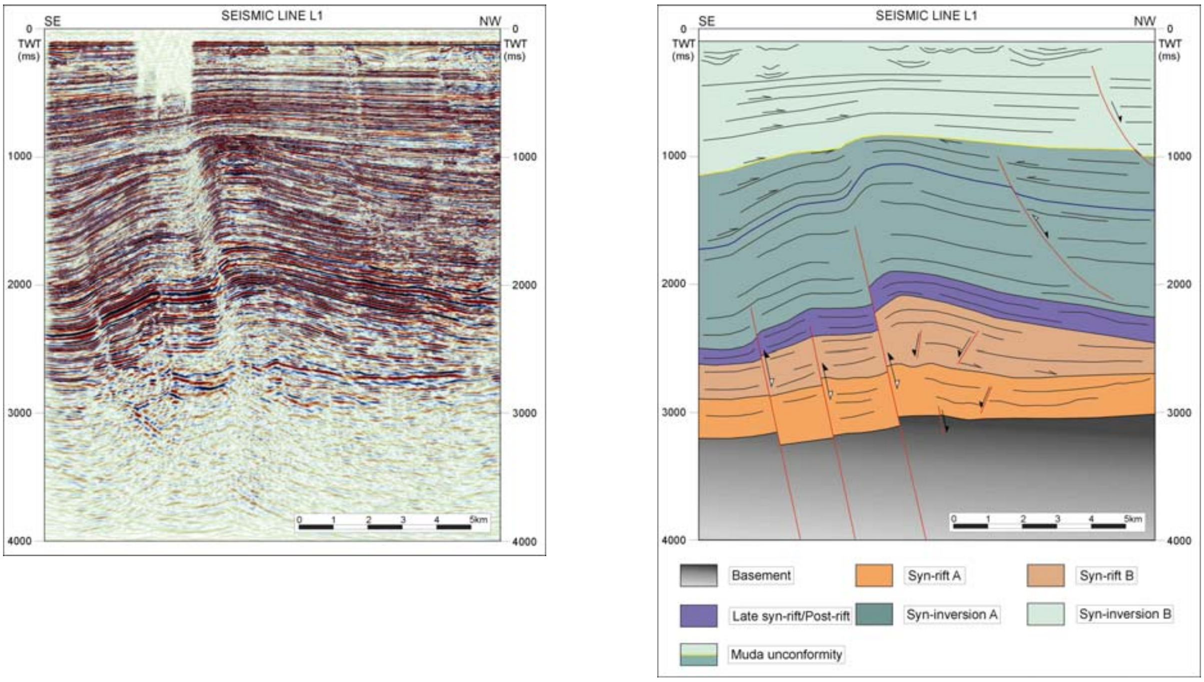


Figure 7: Arbitrary seismic line L1 and its interpretation. Three planar southwards-dipping domino faults generated fault-propagation folds when inverted. Vergence of the structure is clearly towards the south. First extensional stage was very mild, while second one, whose deposits show wedge geometry, was stronger. Most northern fault was more active. The upper part of Syn-inversion A (A2), and Syn-inversion B show well developed growth strata. Muda unconformity is mildly folded.

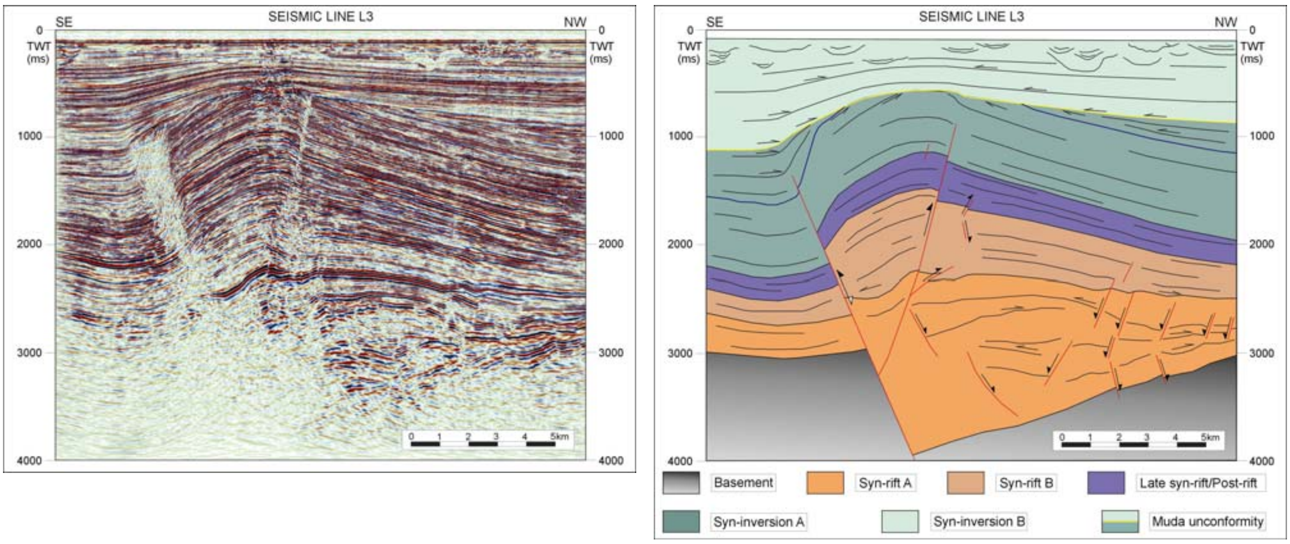


Figure 8: Arbitrary seismic line L3 and its interpretation. A major southwards-dipping inverted fault generated a large scale inversion anticline. Syn-rift A and B megasequences thicken towards the main inverted fault. Inversion of these deposits produced typical harpoon geometry. A back-thrust developed, producing a fault-propagation fold with opposite vergence. Muda unconformity, which is quite folded, truncates tighter folded underlain beds. Overlaying deposits (Syn-inversion B) are less deformed. Estuarine channels can be observed near the sea bottom.

During the upper Late Oligocene extension rate decreased dramatically or stopped (Late syn-rift/Post-rift), being accommodation space passively infilled. Therefore, the whole area underwent homogenous sedimentation (Fig. 12).

Compression started in the most upper Late Oligocene (Syn-inversion A1). This initial stage was quite mild, and was stronger on the east (Fig. 13), shown by out the fault thickening packages and unconformities (Fig. 9). Muda unconformity eroded away great part of these deposits on the east side.

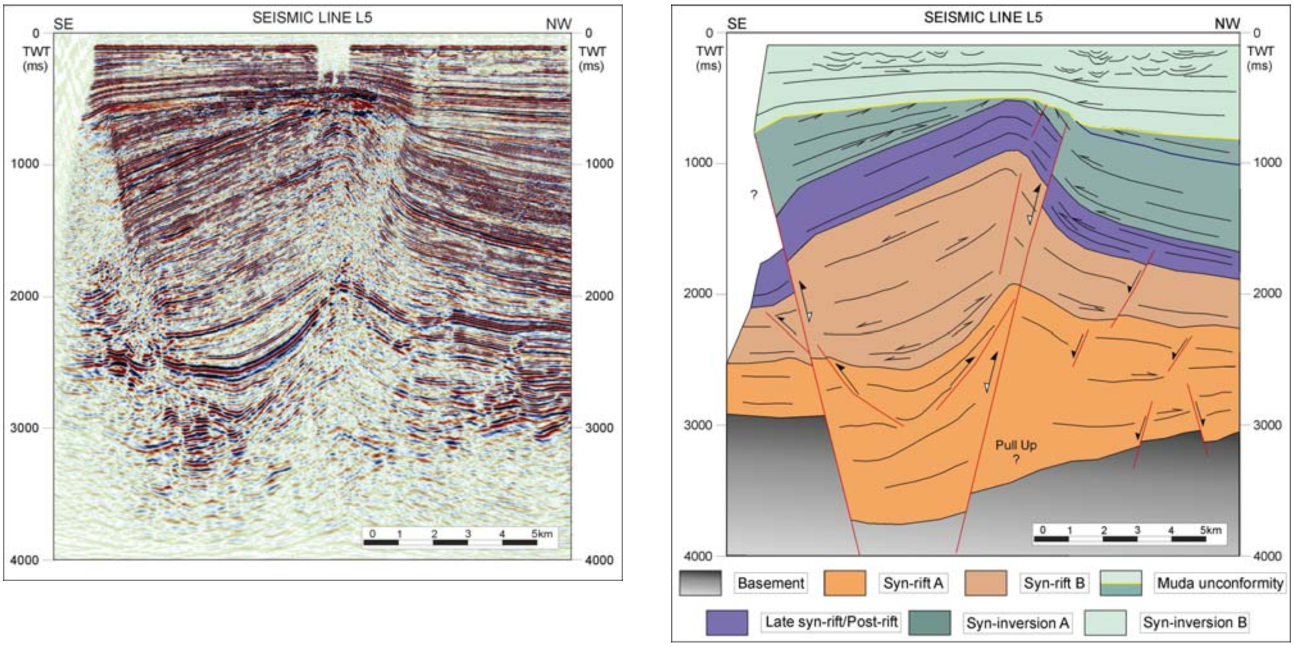


Figure 9: Arbitrary seismic line L5 and its interpretation. The presence of a southwards-dipping conjugate sub-planar fault produced a flip in polarity of the main anticline. Though Syn-rift A deposits have wedge geometry (indicating that extension prevailed on the southern fault), Syn-rift B beds have been deposited in a graben setting, while both faults were active. Inversion on this sector was stronger, and so was the erosion produced by the Muda unconformity.

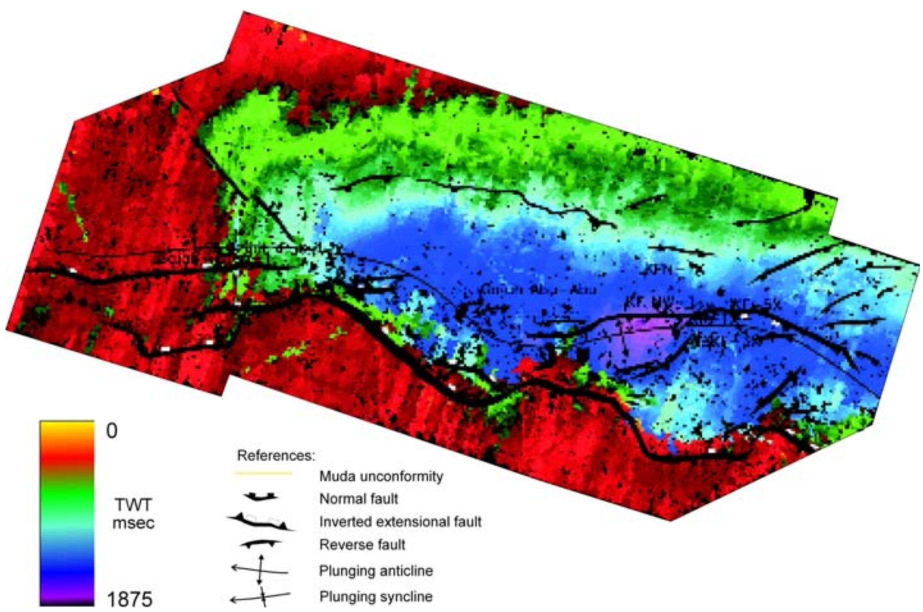


Figure 10: Syn-rift A time thickness map with main interpreted structures.

In the Middle Miocene the strongest compression and consequent tectonic inversion occurred (Syn-inversion A2). Deposits clearly thicken outwards the main structure (Fig. 14), though it should be noticed that Muda event eroded away most of these growth strata on the east side. Thicker packages can be found on the forelimb of the major inversion anticline, were two depocentres formed.

Muda unconformity developed during the upper Middle Miocene and lower Late Miocene. It truncated the tightly folded finge of the main structure (Fig. 7 and Fig. 8).
This regional unconformity was right after deformed by compression (Fig. 9), which continued up to recent times. Syn-inversion B deposits grew away from the hinge line of the main structure (Fig. 15).
Collapse faulting occurred quite recently on the west side. These faults do not show great signs of inversion.
Through a series of different block diagrams of the study area the tectonic evolution for the eastern and western sector of the southern Kakap block is shown in Figure 16.

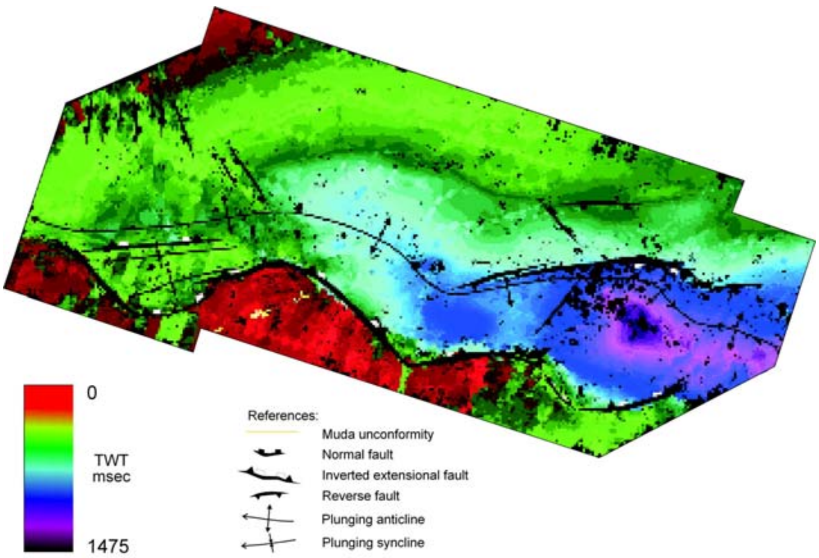


Figure 11: Syn-rift B time thickness map and interpreted structures.

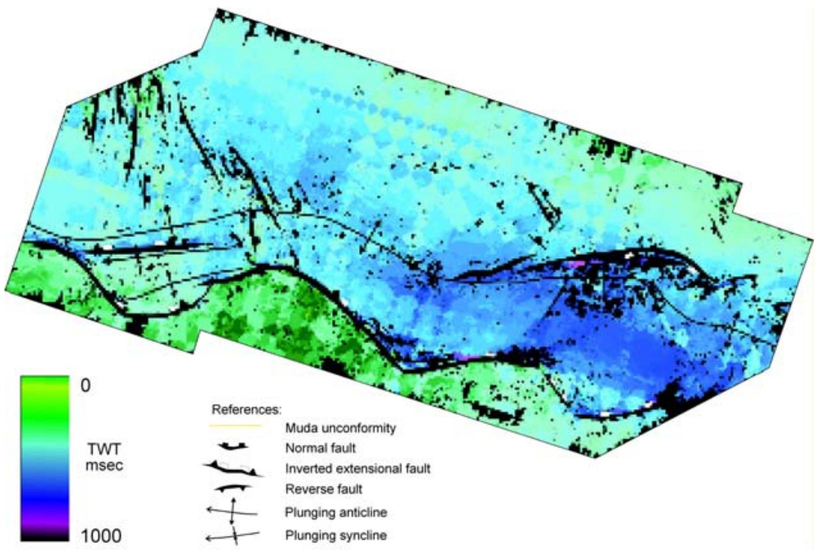


Figure 12: Late Syn-rift/Post rift time thickness map

CONCLUSIONS
Thick-skinned deformation affected the study area.
A half-graben was originally formed by separated ENE-WSW and NW-SE fault segments. These segments joined afterwards.
Tectonic inversion of the initial extensional structures produced a large scale anticline which bends following the trends of the adjacent fault segments.
Inversion structures are typically fault-propagation folds. They show harpoon geometry of the inverted syn-extensional beds. Anticlines have a gently-dipping back-limb and a steeply-dipping forelimb.

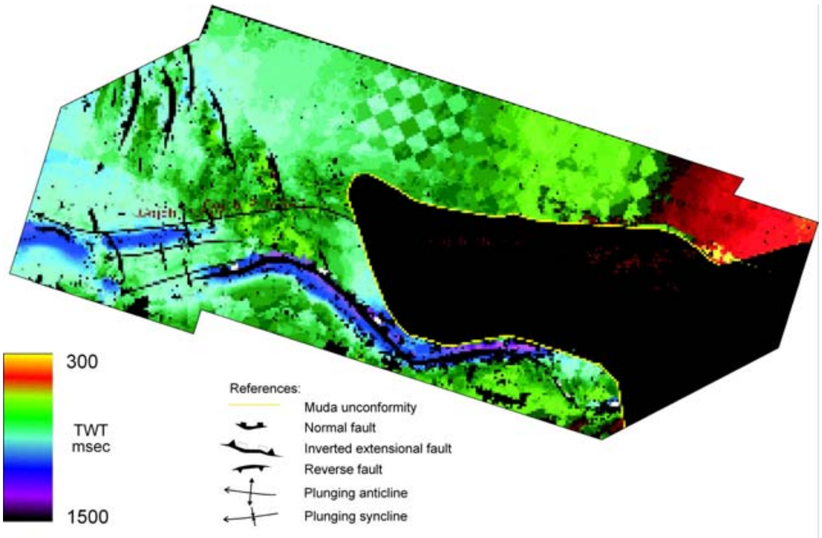


Figure 13: Syn-inversion A1 isochron map.

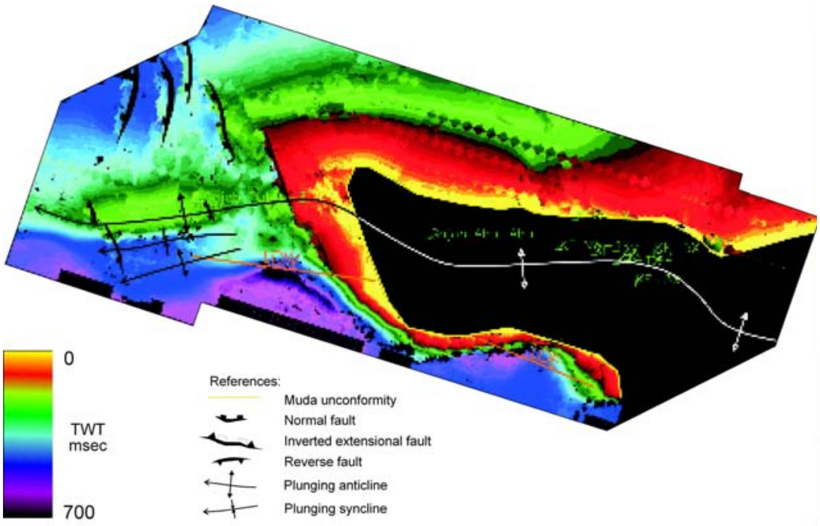


Figure 14: Syn-inversion A2 time thickness map.

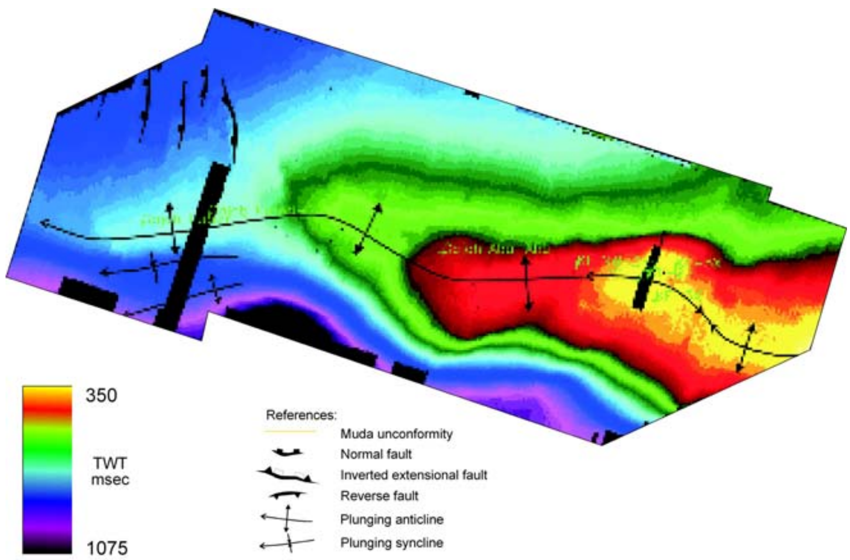


Figure 15: Syn-inversion B isochron map.

Extension probably began during the Late Eocene by different pulses shown by minor unconformities within Syn-rift A Megasequence.
The end of the Syn-rift A in the upper Early Oligocene is determined by an extended unconformity recognisable by the presence of on-lapping reflectors in the whole study area, which marks the beginning of the Syn-rift B megasequence. Extension that produced these deposits occurred during the Middle Oligocene. During the lower and middle Late Oligocene extension stopped or diminished dramatically and as a result the Late syn-rift/Post-rift megasequence's deposits are quite constant in thickness.

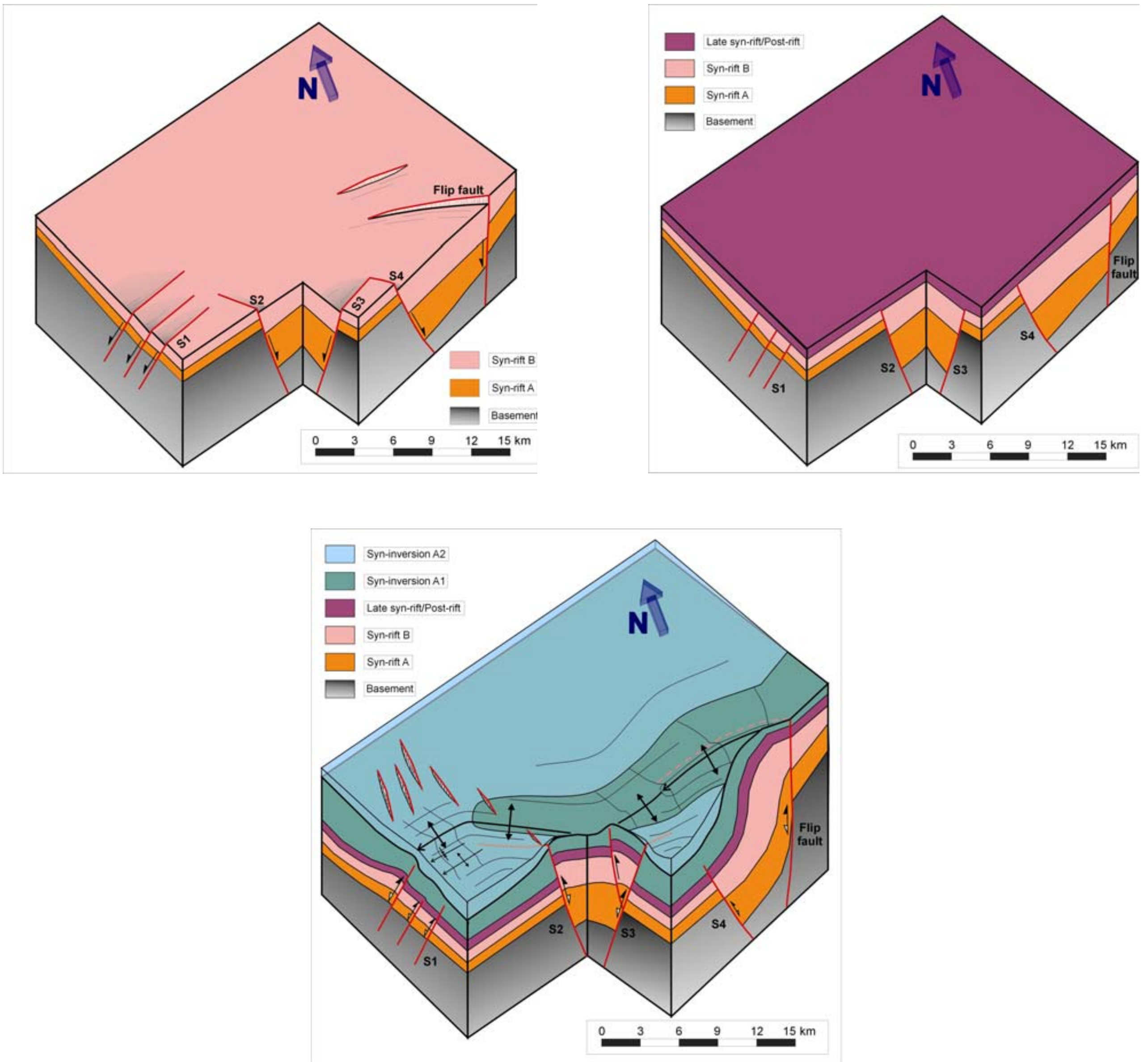


Figure 16: Block diagrams showing the tectonic evolution of the region. Notice that the western sector underwent both less initial extension and later milder tectonic inversion compared to that occurred on the eastern side of the study area. Location of fault segments can be observed in Figure 6.

Inversion started in the area in the upper Late Oligocene (Syn-inversion A megasequence) but its greatest pulse began in Middle Miocene (Syn-inversion A2), when most of the deformation occurred. The latter stage took place by pulses, marked by the presence of growth strata where several unconformities developed.
On the Late Miocene a folded regional unconformity (Muda unconformity) marks the onset of the Syn-inversion B megasequence, which continues up to very recent, though with smaller uplift rates.

Both extension and inversion were stronger on the east side of the area and the opposite is observed on the west side.
A flip on the vergence of the main inversion anticline is associated with the presence of an inverted extensional fault whose fault plane is conjugated to the fault segments related with the creation of the half-graben. On the sides, shortening produced by this fault is accommodated by back-thrusting.

ACKNOWLEDGEMENTS
Silvia's help and support allowed me to go through this piece of work. I would like to thank PremierOil for providing the data used in this work and authorizing the publication of this paper. Richard Backhouse kindly helped to gather all the necessary information. AAPG Grants in Aid economically supported this MSc. project. Royal Holloway College Professors Chris Elders and Ken McClay made this work possible through wise advising. I would also like to express gratitude to Salvador Minniti and Tomás Zapata, who helped me through valuable observations, and Chevron Corporation for allowing my presence in this technical event.

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