

STRUCTURAL EVOLUTION AND ITS CONTROL ON HYDROCARBON
POTENTIAL OF SOUTHERN KOZLUK (BATMAN),
SOUTHEAST ANATOLIA, TURKEY

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ANATOLIA, TURKEY**

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ABSTRACT

STRUCTURAL EVOLUTION AND ITS CONTROL ON HYDROCARBON POTENTIAL OF SOUTHERN KOZLUK (BATMAN), SOUTHEAST ANATOLIA, TURKEY

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The area of interest (Kozluk, Batman) is located on the foreland section of the Bitlis-Zagros Suture Zone and is characterized by several major oil fields. Recent oil discoveries have drawn attention to this region and necessitate detailed studies in order to develop existing reserves and better understand the hydrocarbon potential for future exploration activities. In particular, the role of structural elements, specifically recent strike-slip faulting, has formed the center of interest. The present study therefore has integrated and interpreted field observations, well sections, drilling data, well logs and 3-D seismic data to: (i) determine the deformation pattern (geometry and extend of faults, and related fracture networks) of the sedimentary succession deposited since the Late Cretaceous, and (ii) provide insights into the number, timing and mechanism of deformation phases; the effect, role and control of tectonic development on the stratigraphy and hydrocarbon potential are also evaluated. The region has been experiencing compressional deformation since early Campanian. The structural history of the region commenced by the formation of fault controlled sub-basin, in which organic-rich major source rock was deposited during Campanian. Early–Middle Miocene was started with a transgression and continued with deposition of Silvan Group sediments and characterized NE–SW- and NW–SE-trending faults. Upper Miocene corresponds to structural inversion from normal to reverse faulting of NW–SE-trending faults, accompanying the final collision of Arabian-Eurasian plates and development of Bitlis-Zagros Suture Zone. Last phase of deformation is marked by the reactivation of pre-existing structures as strike-slip faults. It is also demonstrated that the NW–SE- and NE–SW-trending faults played important role on hydrocarbon migration and accumulation along Upper Cretaceous reservoir rocks.

Key words: hydrocarbon, fault, 3-D seismic data, Kozluk (Batman), southeast Turkey

ÖZ

BATMAN İLİ KOZLUK İLÇESİ GÜNEYİNİN YAPISAL GELİŞİMİ VE PETROL POTANSİYELİNE OLAN ETKİLERİ, GÜNEYDOĞU ANADOLU, TÜRKİYE

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Çalışma alanı Bitlis-Zagros orojenik kuşağının foreland olarak adlanan kesiminde Batman iline ait Kozluk ilçesinin güneyinde petrol sahalarının yer aldığı bir alanda bulunmaktadır. Son zamanlardaki petrol keşifleri bu bölgeye dikkat çekmiş ve gelecekteki arama faaliyetleriyle hidrokarbon potansiyelinin ortaya konulması ve mevcut rezervlerin geliştirilmesi için ayrıntılı çalışmalar yapılmasını gerekli hale getirmiştir. Özellikle, doğrultu atımlı faylar başta olmak üzere yapısal unsurların rolü bu çalışmanın ilgi odağını oluşturmaktadır. Çalışmada arazi gözlemleri, kuyu bilgileri ve 3-D sismik verinin entegrasyonu ile (i) Geç Kretase ve sonrasında çökelen sedimanter istifin deformasyonu (fayların yayılım ve geometrileri, çatlak sistemleri ile ilişkileri) (ii) deformasyon fazlarının sayısı, zamanlaması ve mekanizması, tektonik gelişimin stratigrafı ve hidrokarbon potansiyeli üzerindeki etkisi, rolü ve kontrolü değerlendirilmiştir. Bölge Erken Kampaniyenden itibaren gelişen bir sıkışma rejiminin etkisi altındadır. Orta-Üst Kampaniyen'de organik açıdan zengin kaynak kayaların çökeldiği fay kontrollü mini havzalar gelişmiştir. Erken-Orta Miyosen bir transgresyon ile başlayarak Silvan Grubu birimlerinin çökmesi ile devam etmiş ve bu dönem NE-SW ve NW-SE yönlü faylarla kontrol edilmiştir. Üst Miyosen'de, kıta-kıta çarpışmasının son evresinde Bitlis-Zagros Sütür Zonu'nun gelişmesi ile birlikte NW-SE uzanımlı faylar ters bileşen kazanmıştır. Deformasyonun son evresinde ise fayların doğrultu atım karakteri kazandıkları gözlenmektedir. NW-SE ve NE-SW-doğrultulu faylar hidrokarbonun göçü ve birikimi üzerinde önemli rol oynamıştır.

Anahtar kelimeler: hidrokarbon, fay, 3-D sismik data, Kozluk (Batman), Güneydoğu Türkiye

To my children,
IRMAK & ARAS BEŞER
and
My husband
ŞEMSETTİN BEŞER

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CHAPTER I

INTRODUCTION

1.1 Purpose and Scope

The Arabia-Eurasia collision zone forms one of the largest Tertiary continent-continent collision zones in the world and represents a tectonically active continental collision zone, extending from the Arabian foreland in the south to the Erzurum-Kars plateau in the north. It involves plate accretion and terrane suturing, and is marked by an areally extensive deformation zone(s) of shortening, crustal thickening, and uplift. The collision zone is known as Bitlis-Zagros fold and thrust belt and extends for more than 1800 km from southeast Turkey (East Anatolian Fault) in the northwest to Makran subduction zone (east of Strait of Hormuz) in the southeast. The section of the fold and thrust belt in Turkey is termed the Bitlis-Zagros Suture Zone and is marked by an arcuate mountain belt along the northern margin of the Arabian Plate (Figure 1). Age of the initial collision across the suture zone has been the subject of long-lasting debate where claims range from Late Cretaceous (e.g., Berberian and King, 1981) to Late Eocene–Oligocene (e.g., Agart *et al.*, 2005) to Miocene (e.g., Şengör *et al.*, 1987; Dewey *et al.*, 1986; Yılmaz, 1993; Robertson *et al.*, 1996; Okay *et al.*, 2010). The complexity is originated from the progressive deformation of the area through time.

The Arabian Plate in the south of the suture zone is represented by two major rock sequences within a mosaic of horst blocks or highs, and inverted grabens or troughs: (i) crystalline basement with its Paleozoic cover and (ii) unconformably overlying (highly) variably thick (up to 10 km) Mesozoic to Tertiary strata (e.g., Ameen, 1992).

Study area, southern Kozluk, is located on the foreland section of the Bitlis-Zagros Suture Zone at its northwestern end (Figure 1). It covers an area of approximately 400 km² at 30 km northeast of Batman city and is drained by the north-south flowing Yanarsu River. TPAO's recent oil discoveries have drawn attention to this region and necessitate detailed studies in order to develop existing reserves and better understand the hydrocarbon potential for future exploration activities.

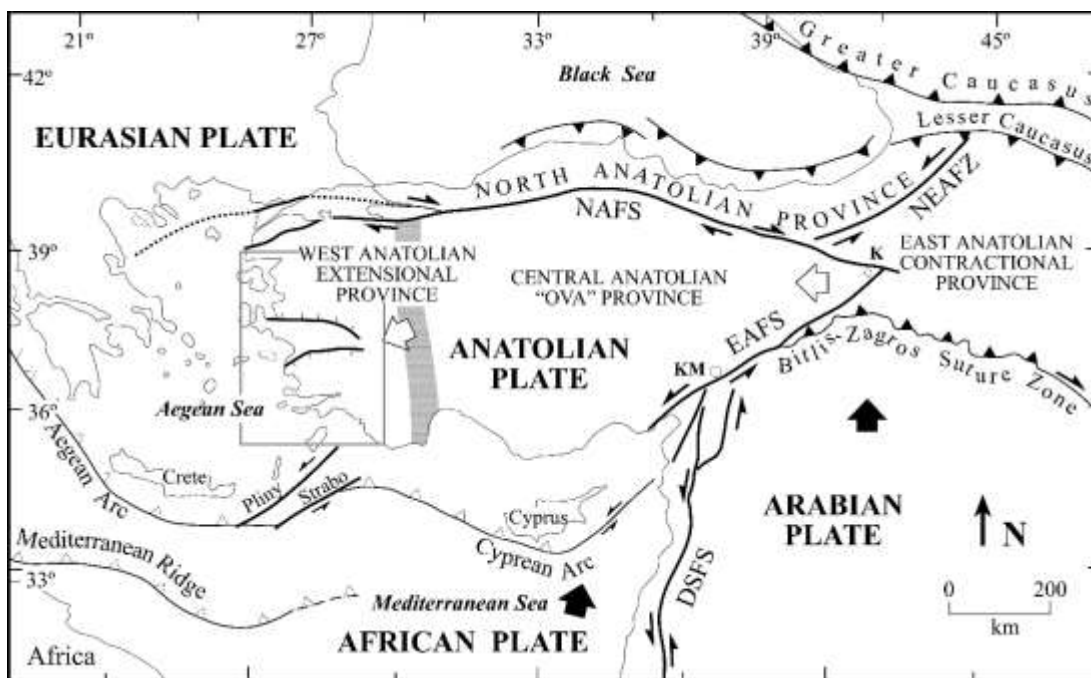


Figure 1. Simlified tectonic map of Turkey showing major neotectonic structures Dead Sea Fault System, EAFS– East Anatolian Fault System, NAFS– North Anatolian Fault System. Heavy lines with half arrows are strike-slip faults with arrows showing relative movement sense. Heavy lines with filled triangles shows major fold and thrust belt: small triangles indicate direction of vergence. Heavy lines with open triangles indicate an active subduction zone, its polarity indicated by the tip of small triangles. The heavy lines with hachures show normal faults: hachures indicate down-thrown side. Bold filled arrows indicate relative movement direction of African and Arabian plates; open arrows, relative motion of Anatolian Plate (from Barka 1992).

Most of the previous studies outline the regional tectonic trends, and discuss major tectonic elements of the foreland section of the suture zone in Southeastern Turkey (e.g., Perinçek, 1980; Perinçek and Özkaya, 1981; Perinçek *et al.*, 1987, 1992; Perinçek and Çemen, 1991). The available dataset – high quality three-dimensional (3-D) seismic data and detailed information from several wellbores – offers opportunities for improving our understanding of the structural and stratigraphic framework in the area to the south of Kozluk, Batman. The main scope of this study is therefore to execute the structural evolution of the region, by integrating seismic data with field studies and information from the drilled wells.

The existing geology map of the study area has its own question marks, and is inadequate to express existing structural elements both in the field and along the interpreted seismic sections. Thus, the field study was conducted especially to perform ground-truthing of the Miocene sequence(s) by local observations particularly along and/or near major fault zones. The surface faults and formation boundaries were checked and modified on the existing map. Once the field observations are finalized, the existing TPAO geology map is modified and structural cross-sections have been updated (Siyako *et al.* 2013). Samples from the Miocene succession outcrops have been obtained near major faults during field observations to support field definitions. Petrographic and paleontological analyses by TPAO Research Center help the determination of depositional environments, age of rock units and their distribution throughout the region. Also fault and fracture measurements are done at certain observation stations to reveal the fracture pattern and understand the structural relationship(s) and evolution from outcrop studies. After the existing wells have been analyzed and tied to seismic cubes, 3-D seismic cubes were interpreted and attribute analyses have been executed. Then, surface and subsurface data was integrated. With the help of more accurate and detailed surface data; the study would be able to explain most of the subsurface relation(s) in the frame of the tectonic evolution. In this way, the structural evolution of the Kozluk area and its role/place in the geological evolution of the Southeast Anatolia would have been propounded.

Field observations, well sections, drilling data, well logs and interpreted 3-D seismic cubes are all combined to provide insights into the timing and mechanism of deformation in the study area; the role and control of tectonic development on the stratigraphy is also evaluated. The effect of (i) Arabian Plate and Eurasian Plate collision, (ii) the final closure of the Neotethys, and (iii) subsequent strike-slip regime on the pre-existing structures and stratigraphy within the study area have also been discussed.

The results are finally analyzed to interpret the kinematic history of the study area. Because structural and stratigraphic features are visible on the new 3-D better quality seismic sections, field geology with subsurface data (such as, seismic sections and well logs) are integrated in order to (i) define the tectonic phases, (ii) analyze and discuss, the geometry and extend of faults, related fracture networks and their influence on hydrocarbon potential.

Two major objectives of this thesis are therefore to: (1) determine the deformation pattern of the sedimentary succession deposited since the Late Cretaceous and (2) investigate the effect of deformation on hydrocarbon potential in the area to the south of Kozluk (Batman) in Southeast Turkey. The 3-D seismic techniques are very useful tools to analyse in detail the structural and stratigraphical framework; this provides better understanding of geological evolution in the region. Recently, the integration of surface and subsurface data becomes a crucial task in order to develop hydrocarbon-rich Kozluk region and shed light on future exploration activities. Due to the dynamic nature of ongoing processes throughout the study, the required data from outside the defined study area was also utilized.

Southeast Turkey, which is located on the northwestern edge of the Arabian Plate, includes two main geological provinces; these are from south to north:

(1) The stable Arabian Platform, the autochthonous units, characterized by a Mesozoic–Tertiary mainly carbonate cover with clastic additions on top of

predominantly shaly-sandy Paleozoic formations (e.g., Rigo de Righi and Cortesini, 1964; Sungurlu, 1974; Perinçek, 1980).

(2) The Zagros-Tauride tectonic units, the allochthonous units, that developed during two major overthrusting events, one in the Late Cretaceous, the other, Late Miocene (e.g., Rigo de Righi, 1964; Sungurlu, 1974; Perinçek, 1980).

In general, sedimentation of the autochthonous rocks in Southeast Turkey was controlled by five major tectonic events. These are: (1) epirogenic movements causing sea-level changes and fluctuations, which have mostly influenced the depositional and paleogeographical conditions from Cambrian through Cretaceous; (2) the Late Cretaceous intense compressional tectonic regime, overthrusting, which caused various types of depositional products and is represented by clastic-dominated sedimentation in the Kastel Basin at the northern areas; (3) a widespread transgression during the Middle Eocene due to extensional regime, which formed the Maden marginal basin in the north; (4) the Miocene overthrusting producing similar features as the Late Cretaceous compressional regime (Perinçek *et al.*, 1998); (5) the Pliocene strike-slip regime through which the present framework of Southeast Turkey was established.

In general, all tectonic phases produced their characteristic structural styles. On the other hand, as the younger deformation phases mask the previous regimes significantly, the Miocene structures might be inverted structures and were caused by the direct reactivation of the pre-existing Cretaceous structures; in that regard Miocene and Cretaceous structures might share similar structural styles and trends. Perinçek (1970) summarized that each structure (either an anticline or a reverse fault) observed in Tertiary units in southeast Turkey also mark an event in Cretaceous time. Similarly, NW–SE trend of the younger Bozova Fault, Mardin and Hazro anticlines are parallel to the trend of drifted Bitlis metamorphic allochthonous units that have been emplaced over upper Miocene rock units in northern parts of Southeast Turkey (Figure 2). The main frontal thrust of Cretaceous allochthonous units emplaced during

Campanian (near Sason village) stays further north below the structural trends of Late Miocene emplacements. It is also important to note that major Diyarbakır oilfields, such as Kurkan, Beykan, Katin, Barbeş, Kayaköy, are also aligned in a direction parallel to Cretaceous allochthonous front (Figures 2 & 3).

These observations demonstrate that style and trend of Cretaceous structures are dominant structural elements in Southeast Turkey. Miocene is the time for severe tectonic activities in the region. Sungurlu (1984) and Perinçek (1980a) summarized that the tectonic movements began in Early Miocene and continued until after the Late Miocene.

Thrust faults and associated folds along the Bitlis-Zagros foothills and its foreland area have been received much of the focus as they are considered as potential of oil-bearing structures. In the Batman-Siirt area, these major anticlines and fault-related monoclines are oriented northwest–southeast in the north (such as Kentalan and Garzan-Germik anticlines) and east–west in the south (such as Raman-West Raman anticlines) (Figures 2 & 3). The Hazro Anticline, located northwest of the study area, is one of the largest high amplitude anticlines with Silurian Dadaş Formation exposed in its core. The anticlines have steeper dips on their southern flanks and more gentle dips on the northern. Most of them are bounded by north-dipping reverse faults (dips $\sim 45\text{--}60^\circ$ south), and probably having detachments in the Paleozoic sections. There are also structures characterized by northeast-dipping Miocene layers. The sedimentary section is composed of up to 3500-m-thick succession and comprises both carbonate and clastic units. Also, later strike-slip tectonic regime must have affected the final geometry of these structures; this topic has also formed the subject of the present thesis and it was studied by integration and evaluation of the new dataset with the existing information (Perinçek& Özkaya, 1992).

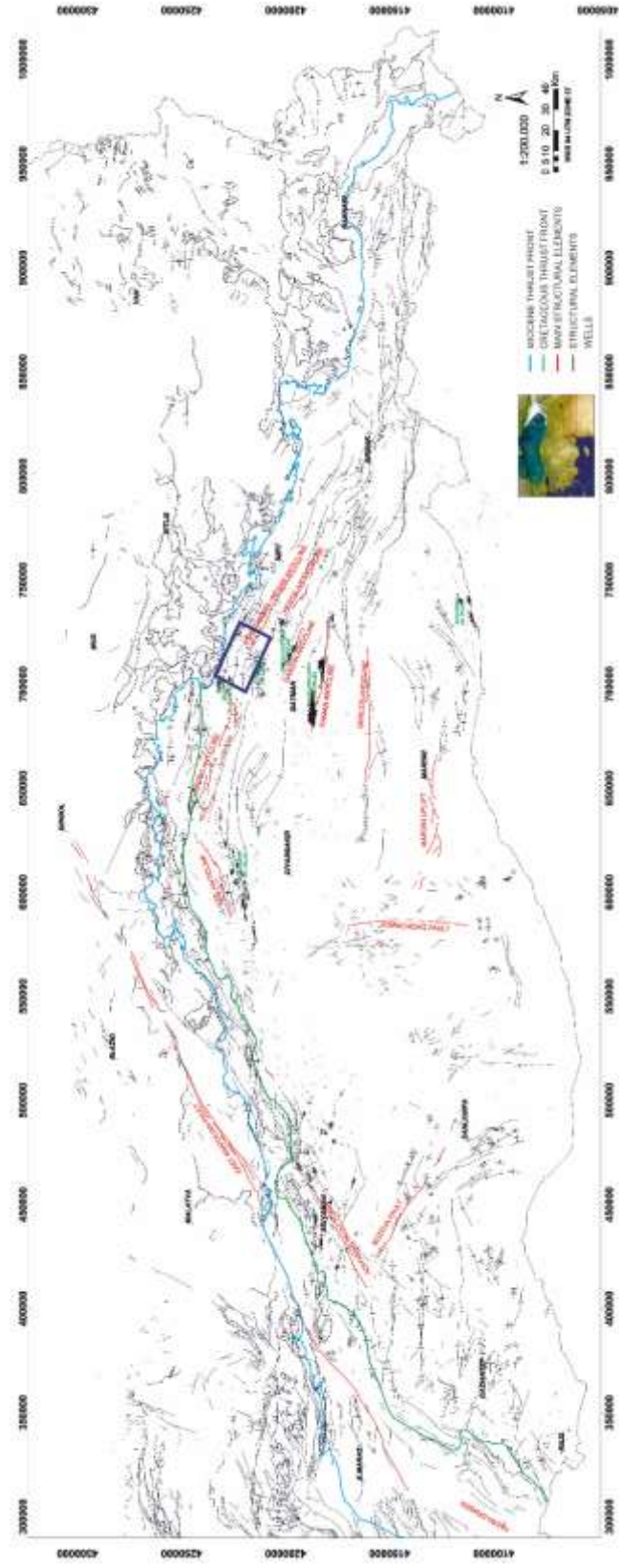


Figure 2. Tectonic elements of Southeastern Anatolia (modified from TPAO database). Box represents the location of the study area.



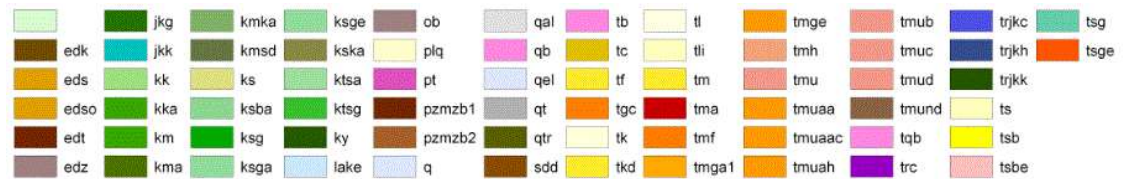
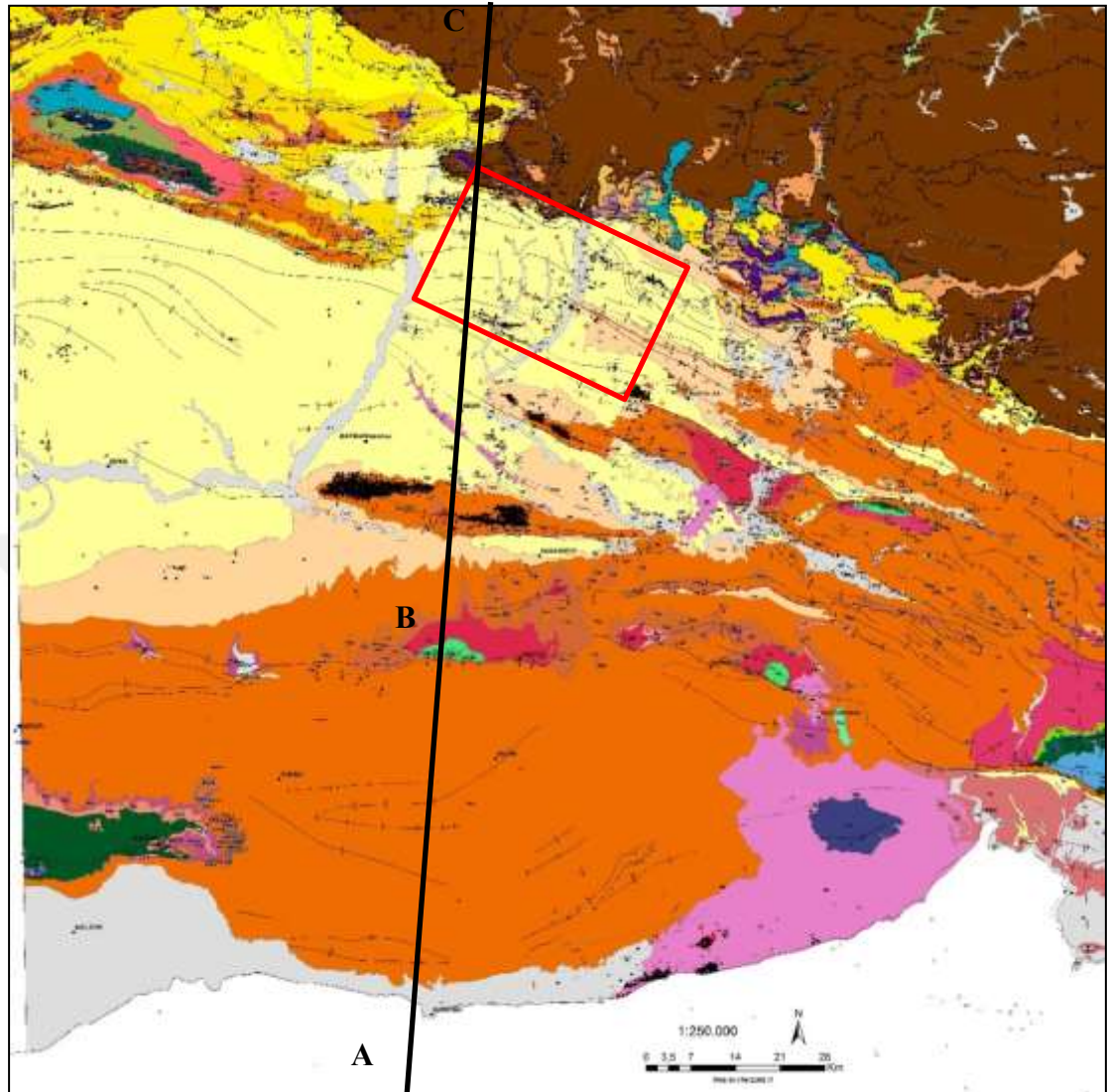


Figure 3. Geological map of the region around the cities of Batman and Siirt, showing major structures, mapped geological units and drilled wells (from TPAO database). The red box shows the study area. The N–S-trending black line represents the position of regional structural cross section in Figure 4. Please see Appendix A for the larger size of the map and the legend explanation.



1.2. Study Area

Most of the major oil fields of Southeastern Turkey are located in the area between the cities of Batman and Siirt (Figure 2). Most oil fields are structurally controlled; some of the well-known ones include Dodan, Hazro, West and East Raman, Garzan-Germik, Gercüş, Kentalan, Şelmo, and Eski Garzan-Reşan anticlines (Figures 2 & 3). Many anticlines are characterized by fold axes trending in northwest–southeast direction parallel to the Bitlis-Zagros suture zone but there are also east–west-trending anticlines (such as East Raman and West Raman anticlines). The giant Batı Raman and Raman oil fields, discovered in 1952, trend in west–east direction and occur along the Raman Anticline. The anticline with thrust fault on its southern flank is interpreted as a Cretaceous structure (Figures 2 & 3) (Salem *et al.*, 1992). Similar to Raman Anticline, Garzan Anticline is characterized by a gently-dipping northern flank and steeply-dipping southern flank. On the other hand, Kentalan and Eski Garzan-Reşan anticlines have steeper and broken northern but gently-dipping southern flanks (Figure 3). Oyuktaş-Kurtalan Fault is located on the northern flank of the Eski Garzan-Reşan Anticline.

Figure 4 shows the regional cross section from south (A) to north (C) on the foreland basin of the Bitlis-Zagros Suture Zone. The first structure on the south is the Gercüş Anticline, the size of which is about 8x2 km. The Gercüş structure forms one of the best examples of E–W-trending anticlines in SE Anatolia (Figures 2 & 3). These structures have developed during Cretaceous and acquired their final geometries during the Late Miocene–Pliocene time. The Maastrichtian Garzan Formation, major reservoir, outcrops in the crest/core of the structure. The 38-km-long Raman Anticline hosts both the Raman and West Raman oil fields, and trends east to west in the mid part of the cross section (B). The Raman structure is strongly asymmetric with a gently-dipping northern flank, and a steep to overturned southern flank. The average throw along the southern reverse fault is about 250 meters. Through north, most of the faults are covered by Plio–Quaternary Lahti Formation. Kozluk-Narlı Fault Zone,

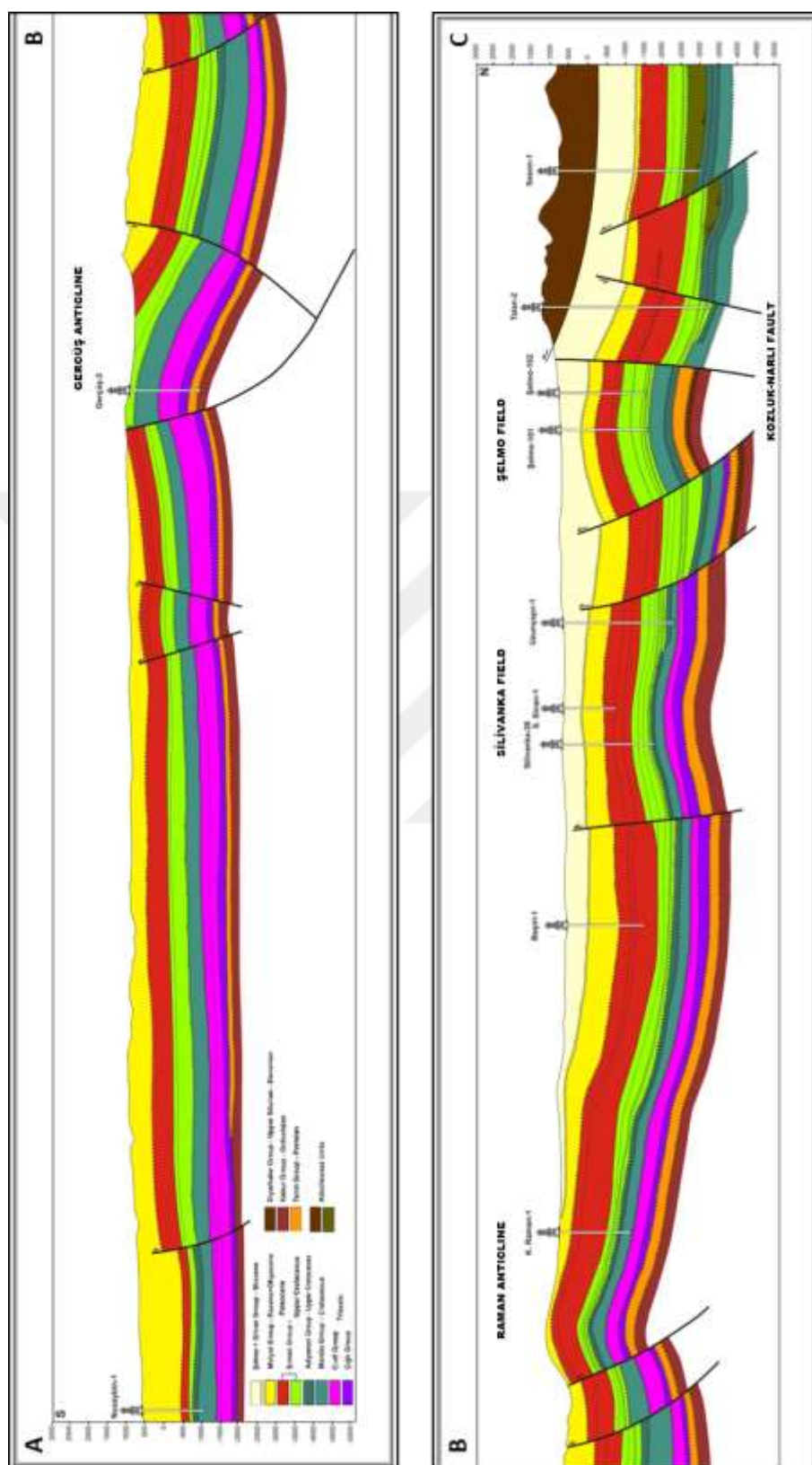
which consists of a series of NW–SE-trending right-lateral strike-slip faults, is located in front of the thrust zone to the south (Perinçek, 1990). The Kozluk-Narlı Fault Zone has pronounced morphological expression and can be traced as branching and discontinuous strands along the mountain front. Individual faults are clearly marked by sharp upturning of the Miocene units to a vertical attitude (Masson, 1986).

In the cross-section (Figure 4), the fault zone is marked by a sharp, closed anticline where the flexure appears as a compressional feature. In the later time, during strike-slip regime, the strain was localized along a strike-slip fault that follows the axis of the anticline.

Thus, most of the structures in the area should be viewed as fault-controlled asymmetric anticlines. Evaporates of the Lice Formation may be observed along the fault surfaces, and suggest that the salts are in relation with the fault zone. There are several brine springs aligned along the segments of the Kozluk-Narlı Zone and most springs have been turned in to salt factories by local people. The parallelism and proximity of the fault zone with the mountain front are too close to be coincidental. There are also some faults with the same trend (NW–SE) within the Kozluk-Narlı Fault Zone and some occur as splay faults within an imbricated zone. Also, some north–south-trending faults appear to be tear faults within the imbricated zone. The strong north–south line is also marked by Garzan and Batman rivers (Figure 4).

1.3. Previous Studies

The Bitlis-Zagros Suture Zone has developed, as part of the Alpine-Himalayan orogenic system, by the closure of the Neotethys Ocean during the Cenozoic (e.g., Dewey *et al.*, 1973; Şengör and Yılmaz, 1981; Stampfli and Borel, 2002). The NW–SE-trending orogenic belt extends almost 1800 km from the East Anatolian Fault to Makran subduction zone in south Iran (Figure 5).





The Arabia-Eurasia collision and the uplift of the Zagros region have led to (i) deformation of the Arabian Plate, (ii) slowing of northward motion of the African Plate, (iii) Mediterranean extension, (iv) rifting of the Red Sea, (v) thickening of the Eurasian Plate; the collision played an important role on the Cenozoic global cooling, and the connectivity among Indo-Pacific Ocean, the Mediterranean Sea, and the Tethys Ocean. The age of onset of the Arabia-Eurasia collision has been determined between ~65 Ma (Late Maasthrictian) (Berberian and King, 1981), based on the end of ophiolite obduction, and ~5 Ma (Late Miocene–Pliocene) based on the angular unconformity between Şelmo and Lahti formations. The debates are still ongoing about the rate and timing of the collision (e.g., Şengör and Yılmaz, 1981; Agard *et al.*, 2005, 2011; Okay *et al.*, 2010; Ballato *et al.*, 2011; Mouthereau, 2011; Mouthereau *et al.*, 2012).

In their study, Şengör and Yılmaz (1981) stated that the collision between Arabian and Eurasian continents along Bitlis-Zagros Suture Zone was developed during Middle–Late Miocene. Okay *et al.* (2010) also suggested that the collision must have occurred during Miocene time and is correlated with the final closure of the Neo-Tethyan Ocean between Arabia and Eurasia at ~20 Ma along the Bitlis-Zagros Suture Zone. The age of arc-related magmatism in the Iranian Plate suggests the beginning of the collision at 34 Ma with the final closure of the Neotethys at 20 Ma (Mouthereau *et al.*, 2012). In Iran, continental subduction and collision started at ca. Oligocene, following the last marine deposition of Asmari carbonates (Agard *et al.*, 2005, 2011). In Southeastern Turkey, the initiation of continental subduction also started in the Oligocene, but the collision could have occurred after Middle Miocene (Keskin, 2003; Şengör *et al.*, 2003). In Southeast Anatolia, last marine deposition of Silvan Group sediments dated at Aquitanian–Burdigalian (Duran *et al.*, 1988, 1989). Husing *et al.* (2009) assigned Early Tortonian age (11 Ma) for the youngest flysch deposits beneath the thrust, and matches this age with the end of underthrusting (Figure 6).

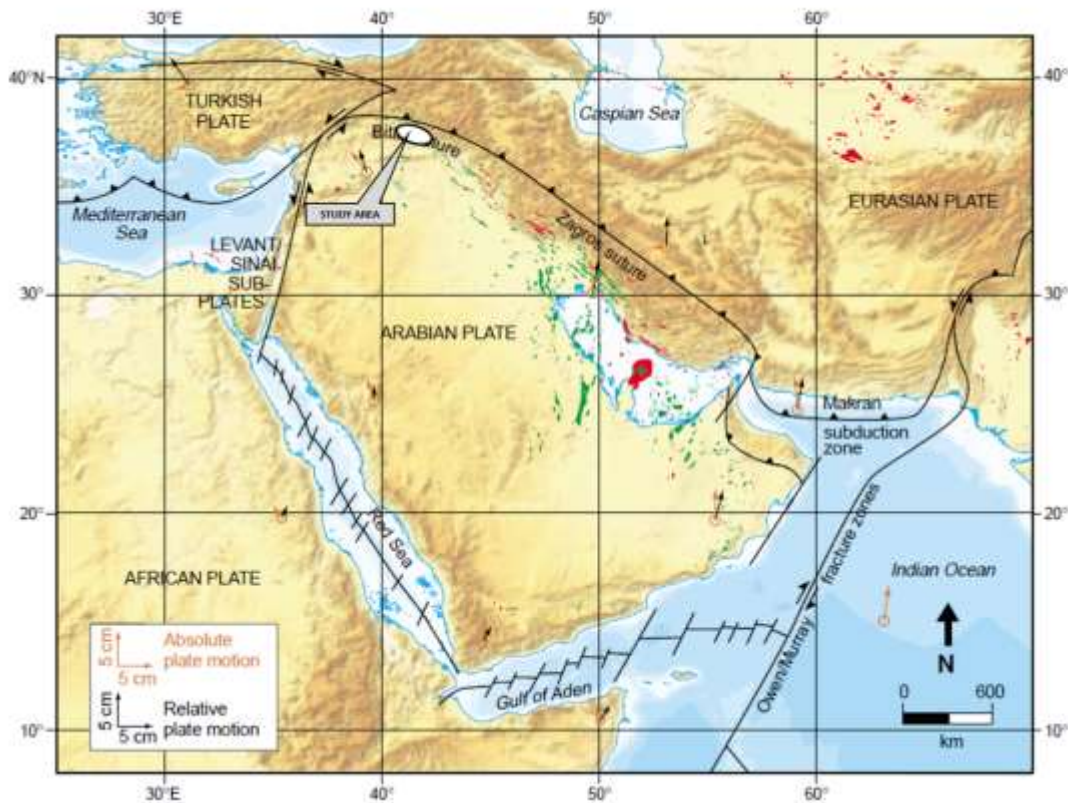


Figure 5. Simplified plate tectonic setting of the Arabian Plate. Oil (green) and gas (red) fields are shown (Al-Lazki *et al.*, 2002) (Plate motion data from <http://manbow.ori.u-tokyo.ac.jp>).

The collision affected the whole region and its geological evolution (Figure 6). The previous studies suggest that the deposition of Upper Miocene–Pliocene conglomerates marks the timing of the folding, thus Late Pliocene is assigned as age of onset of deformation (e.g., Stocklin, 1968; Falcon, 1974a, b). Saura *et al.* (2011) dated the oldest folding event as Maastrichtian age in the Amira Basin in NW of Zagros (Lorestan). The deformation initially localized near suture, then propagated through southward since 25 Ma (Mouthereau *et al.*, 2012).

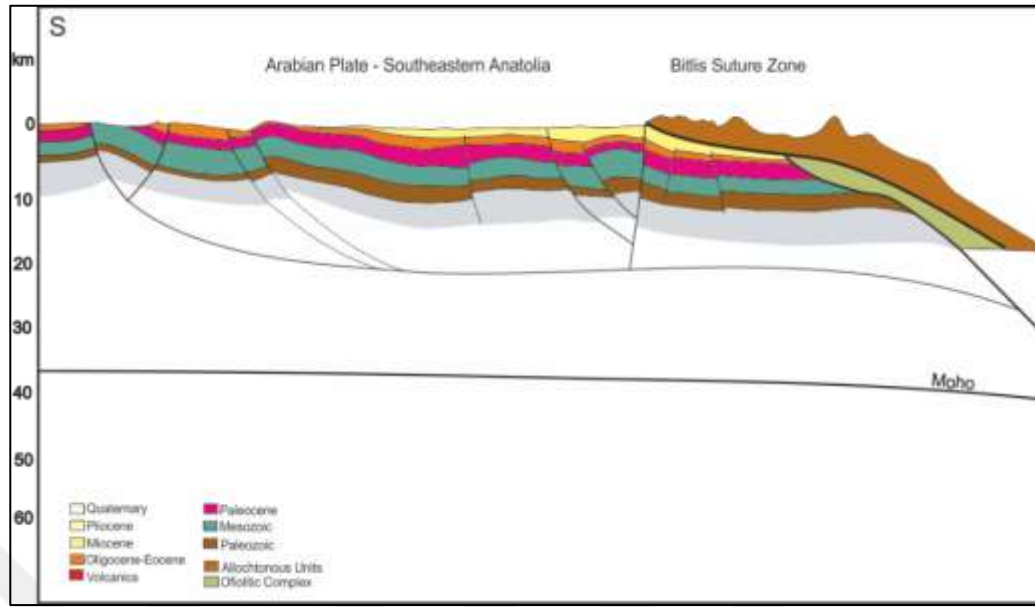


Figure 6. Simplified cross section for geodynamic setting of the Arabia-Eurasia collision (Modified from Keskin, 2007; Mouthereau *et al.*, 2012).

The timing relationship between cover and basement deformation is very crucial and it might have occurred contemporaneously, or afterwards. Recent studies however emphasize that more data and accurate stratigraphic constrains are crucial to solve the complex relationship between deposition and deformation (e.g., Mouthereau *et al.*, 2007a, b; Khadavi *et al.*, 2010). Contraction, thickening and uplifting affects the two continents for a while and then deformation with shortening replaced by lateral movements that is easier to compensate the accumulated stress. North Anatolian and East Anatolian transform faults and related structures have developed as a result of this motion and consequently the Anatolian Plate began to move/escape westward along these bounding faults since then (e.g., McKenzie, 1972; Şengör, 1979; 1980; Şengör and Yılmaz, 1981).

Bitlis-Zagros collision was developed when the Arabian Plate was underthrust the buoyant upper Eurasian Plate. Crustal shortening and thickening became dominated throughout both plates and Eastern Anatolian plateau was uplifted and elevated about 2 km. In Eastern Anatolian Plateau, the arc-related volcanic rocks are calc-alkaline in the north, transitional in the central parts and alkaline in the south of

the plateau (e.g., Keskin, 2003; Şengör *et al.*, 2008). The age of the volcanic rocks becomes younger southward (e.g., Keskin, 2003; Şengör *et al.*, 2008). Based on the tomography data, slab steepening and/or slab-breakoff has taken place along the Bitlis-Zagros Suture Zone (e.g., Keskin, 2003; 2007; Şengör *et al.*, 2003, 2008) as well as in the northwest of Zagros (e.g., Faccenna *et al.*, 2006; Mouthereau *et al.*, 2012). Mouthereau *et al.* (2012) suggests that the onset of slab-breakoff occurred at ca. 12 Ma and that this correlates well with the development of North Anatolian Fault Zone. The slab-breakoff (Keskin, 2003) might have caused westward tectonic escape of Anatolian Plate with the development of major strike-slip faults (Faccenna *et al.*, 2006). The rapid kinematic change in the region is represented by a regional unconformity between Miocene clastic rocks and Pliocene conglomerates (ca. 5 Ma).

The studies demonstrated that the crustal thickness of the Iranian plateau was initially thinner than the adjacent Zagros region and it is attributed to Eocene–Oligocene back-arc extension related with Neo-Tethyan slab rollback (e.g., Moritz *et al.*, 2006; Morley *et al.*, 2009; Ballato *et al.*, 2011); this is also the case for Eastern Anatolian plateau. Later, these inverted extensional basins started to thicken as a natural response to mantle convection and slab detachment (e.g., Keskin, 2003; Şengör *et al.*, 2003; Faccenna *et al.*, 2006; Verdel *et al.*, 2011). Kinematics of the Zagros collision indicates that the recent stress field is N–S with the components of NE–SW orogen-normal shortening and NW–SE orogen-parallel right-lateral strike-slip faulting (e.g., Talebian and Jackson 2004; Authemayou *et al.*, 2009). There are debates about the timing of stress partitioning in the Zagros collision zone. The studies claim the initiation of strike-slip movement at ca. 10–12 Ma in the Zagros (e.g., Mouthereau *et al.*, 2012) and this is correlative with the initiation of uplift of the Anatolian plateau at ca. 10–11 Ma due to slab-breakoff (e.g., Keskin, 2003; Şengör *et al.*, 2003; Faccenna *et al.*, 2006). There is evidence of flat slab subduction during Middle Cretaceous time (Verdel *et al.*, 2011) and this might have existed at the end of Late Cretaceous. Then, this was followed by slab steepening and then by slab rollback. The Cenomanian–Turonian Mardin Group carbonates have karstic features

that can be attributed to the flexure of the Arabian Plate margin due to intra-oceanic deformation (Moutherau *et al.*, 2012). The Maastrichtian Terbüzek/Kıradağ Formation clastic rocks were fed by erosion of obducted Cretaceous ophiolitic complex during mountain building period (e.g., Sungurlu 1973, 1974a; Perinçek, 1979e; Güven *et al.*, 1991) Migration of depocenters is crucial to understand the evolution during that time. While the back-arc extension and magmatism developed in the upper plate due to slab retreat, Arabian continental margin was uplifted and formed the site for deposition of red clastic rocks of Antak Formation during Paleocene/Eocene time period. There are differences in structural styles along Arabia-Eurasia collision zone from northwest to southeast. These differences can be caused due to many parameters. Moutherau *et al.* (2012) commented that while the flat subduction enhances shortening in the subducting plate as observed in Central Iran, existence of a buoyant continental block on the subducting plate can accelerate slab retreats and magmatism in the upper plate during Eocene. The subsidence in the Southeastern Turkey was occurred about ~34 Ma during Late Eocene, which was recorded by the deposition of the Midyat Group carbonates. The Midyat carbonate deposition outlines the onset of subsidence in the region during Late Eocene–Oligocene period. The subsidence might have initiated due to the decrease in subduction velocity, denser Arabian Plate, and Arabian-Eurasian Plate coupling, thus transferring the stress to upper plate. Continental evaporitic sediments in the Oligocene shows arid climate conditions persisted prior to the Miocene.

Ala and Moss (1979) documented that continued crustal shortening, triggered by the opening of the Red Sea during Middle–Late Miocene times, and resulted in thrusting and folding of the Taurus-Zagros Mountains. The debates are still ongoing about whether the mantle convection of Afar Plume pushes Arabia northward or Arabian Plate movement trigger the upwelling plume (Becker and Faccenna, 2010; Faccenna *et al.*, 2013). The initiation of rifting in Red Sea is proposed as 25–30 Ma (Late Oligocene) in McQuarrie and van Hinsbergen (2013). McQuarrie *et al.* (2003) stated that due to rifting of Red Sea and opening of Gulf of Aden, the direction of

Arabian Plate motion was changed from NE to N at 25 Ma. Mouthereau *et al.* (2012) speculated that the Arabian Plate velocity decreased by %30 at 25–30 Ma and stayed constant since then. Also they summarized the Arabian slab-breakoff and the opening of Gulf of Aden are synchronous events dated 10–11 Ma. Double-sided orogenic wedge development (north- and south-verging thrust development) was noted for Iran (Mouthereau *et al.*, 2012). The Eocene, Oligocene and Lower–Mid Miocene units have prompt lateral and vertical facies differences throughout Arabian Platform (e.g., Sungurlu, 1974; Ala and Moss 1979; Perinçek, 1979b, 1990; Beydoun, 1991; Güven *et al.*, 1991; Perinçek *et al.*, 1992; Alavi, 2004). Fırat Formation shallow-marine reefal carbonates were deposited unconformably above the Midyat Group during Aquitanian–Burdigalian (~20 Ma) (Duran *et al.*, 1988, 1989). The sedimentology and stratigraphic studies of the Asmari Formation from Iranian portion, which is the depositional equivalent of the Fırat Formation, emphasized that the section is syn-collisional and deposited in a flexural basin (van Buchem *et al.*, 2010). Mouthereau *et al.* (2012) noticed that the Asmari Formation is dated Early–Middle Miocene (18–20 Ma), and it indicates the age of the onset of the collision. They conclude that active subduction of the Arabian slab stopped in the Early Oligocene, which is synchronous with the beginning of SW slab withdrawal and the shift to collision in the Zagros region. After Zagros folding and faulting, the deposition of continental clastic rocks with the increase in the clastic sediment supply due to growing orogeny was occurred at 12–15 Ma. (Mouthereau, 2011; Khadivi *et al.*, 2012).

Understanding the detailed stratigraphy of the Oligocene–Miocene foreland basins in the Bitlis-Zagros Suture Zone is crucial to evaluate the timing of deformation and related events. Mouthereau *et al.* (2012) speculated that the decrease in plate convergence rate occurred between 12–15 Ma, once the Zagros uplifted. The slab steepening of the Arabian Plate, inferred by tomographic data (Keskin, 2003), could be the main factor for uplift and shortening of the Arabian/Eurasian plates. The approximate estimate of Arabia-Eurasia convergence rate is ~20 km/Myr since about 20 Ma (Tatar *et al.*, 2002; Hatzfeld *et al.*, 2003; Vernant *et al.*, 2004). Thus, based on

this estimate, the total convergence of Arabian-Eurasian plates could be guessed 400 km. The shortening and related deformation was performed through reactivation of basement faults and folds (Blanc *et al.*, 2003; Moutherau *et al.*, 2007; Ramsey *et al.*, 2008) and could have been accommodated by both shortening and strike-slip faulting in the cover and the basement. The style of deformation is controlled by tectonic inheritance that is in relation with sedimentation/erosion rates, mechanical stratigraphy, and geomechanical characteristics of a detachment surface (Moutherau *et al.*, 2007, 2012). Also, it should have propagated from north to south during Eocene–Miocene period. After the development of rapidly uplifted anticlines, the course of the rivers and the drainage pattern had been reorganized. Khadivi *et al.* (2012) emphasized that Miocene sedimentary rocks were primarily sourced from the obducted ophiolitic complex. This shows that there is a connection between imbricated zone and foreland through drainage pattern since Early–Middle Miocene. Çüngüş and Lice formations were served as the detachment surfaces for the obducted allochthonous units within the imbricated zone of Bitlis-Zagros suture zone. Shearing and re-opening of pre-existing fractures, and fault reactivations are the most important parameters that have affected the style of deformation in the region. The main present compressional stress has been determined as N020° for the Bitlis-Zagros region by previous studies (e.g., Lacombe *et al.*, 2006, 2011). Also these studies emphasized the change of the compression direction from NE–SW to N020° through time (e.g., Moutherau *et al.*, 2007).

Kaymakcı *et al.* (2010) have summarized five different deformation phases in SE Anatolia based on paleostress inversion and fault-slip datasets. These phases are attributed to extensional deformation due to slab rollback processes and slab detachment and compressional deformation as a result of convergence rate increase and collision. Many faults have been described in detail by using earthquake focal mechanisms in the Iranian portion of Zagros orogenic zone (e.g., Moutherau *et al.*, 2012). It is suggested that these thrust faults dip 30–60° NE (Talebian and Jackson, 2004) and they are inverted normal faults, which originally developed during rifting

of the Arabian continent (e.g., Jackson, 1980; Berberian, 1995; Talebian and Jackson, 2004). Nissen *et al.* (2011) indicated that some earthquakes have been ruptured the basement, and that the basement involved deformation can be noticed from the abrupt changes in topography. The decollement zone have been identified along Precambrian–Cambrian Hormuz Salt horizon (Arian and Noroozpour, 2015) but it also cut occasionally the basement rocks in the Iranian section (Mouthereau *et al.*, 2007b, 2012).

1.4. Regional Geology

The depth to the top of the crystalline basement is almost 14 km along the Arabian Plate and 2–8 km in southeast Turkey. From the Late Proterozoic to Middle Carboniferous, the present Arabian Plate formed part of the northern passive margin of Gondwana on the southern side of the Paleotethys Ocean (Figure 7). The Paleozoic section in Arabia was deposited along the continental margin of Gondwana in predominantly clastic environments that ranged from continental near the Arabian shield to outer shelf in Iran, Turkey and Syria. Carbonate deposition became dominant during the Permian opening of the Neotethys.

The paleo-environments ranged from arid to glacial, reflecting the drift and rotation of the region during the Paleozoic from equatorial to high southern latitudes and back (Şengör *et al.*, 1984). Combined with the edge effects of the distant Hercynian Orogeny, tectonic instability led to both extensional and compressional pulses with little sediment preservation. During Late Triassic spreading was successful, the Cimmeride separated from Gondwana, and the Southern Tethys Ocean was formed (Şengör 1984; Stoneley, 1990). A new, very extensive, stable passive margin was created along the full length of the northeast Arabian Plate. Permian sediments are thin in SE Turkey, but widespread Triassic reservoir carbonates and

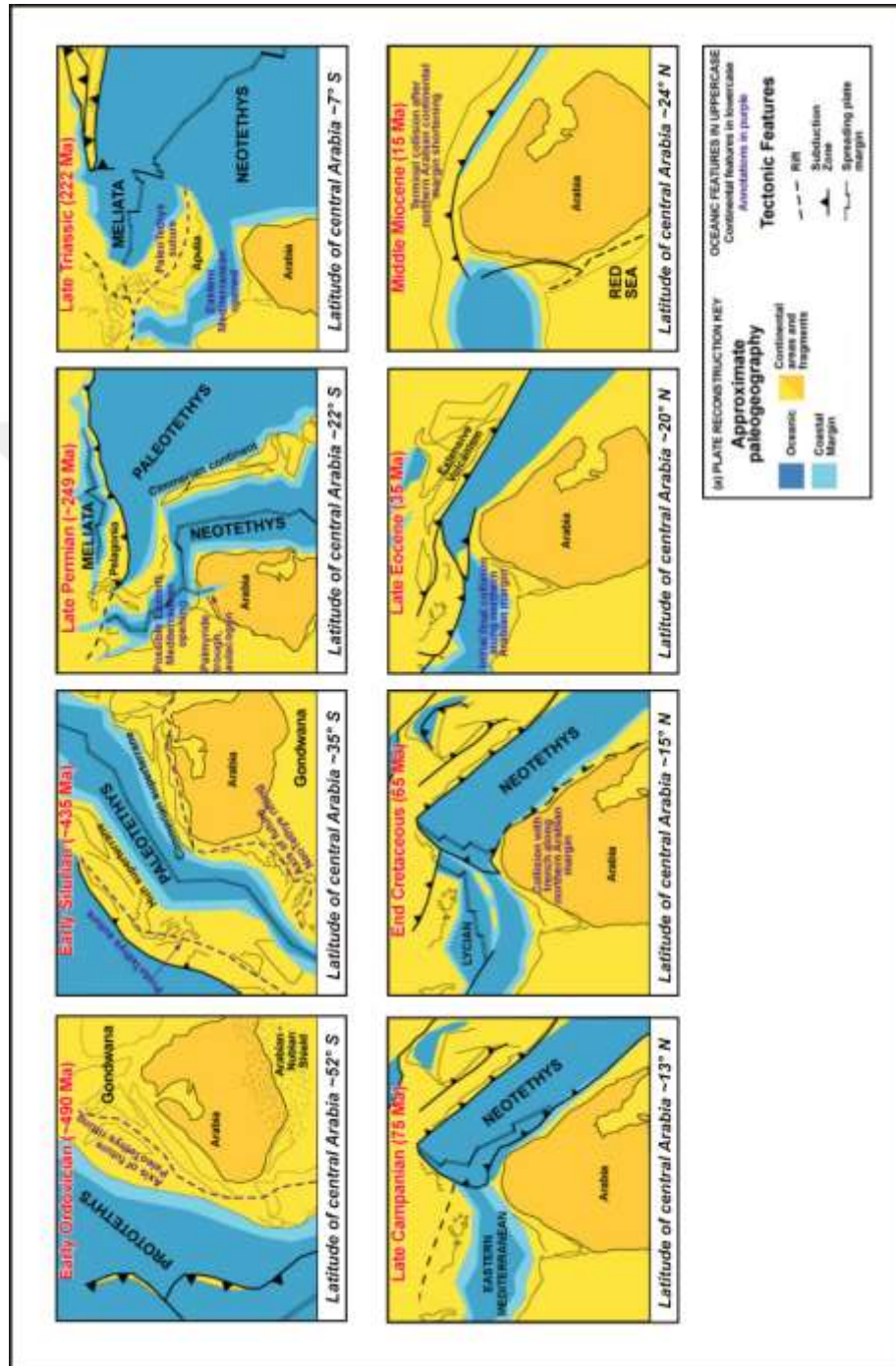


Figure 7. Tectonic Evolution of Arabian Plate through time (from Syrian Tectonic Reconstruction, GEO2008).

interbedded evaporates are preserved. Similar restricted carbonate shelf environments continued into the Jurassic.

Tectonic instability developed during the Late Jurassic over the northern edge of the Arabian Plate as a result of major strike-slip movements along the North African Tethyan margin related to Atlantic opening even further west. Jurassic sediments were deeply eroded by a base Cretaceous unconformity and while the Mardin High remained positive, thick Cretaceous sediments were restricted into the Diyarbakır Basin.

A shallow-marine carbonate shelf had transgressed all the uplifted areas by end-Aptian and deposited the reservoir carbonates and source rocks of the Mardin Group. The NE Arabian Plate was remained as the compressive margin from the Turonian time. This began with SW-directed ophiolite obduction onto the previously passive NE plate margin that created a narrow mountain belt along the Taurus suture zone. Just to the south, a NW-trending foredeep developed that filled with locally generated flysch sediments and slumped blocks (Kastel Formation). Syn-depositional block faulting further south resulted in wide variations in sediment thickness. Basinal conditions prevailed in the graben, while reef complexes (Beloka Formation) developed in the ramp area. The foredeep expanded southward over SE Turkey through the Maastrichtian, depositing shales of the Germav Formation, but carbonate banks built up locally to form the Garzan Formation reservoir (Güven *et al.*, 1992; Perinçek *et al.*, 1992).

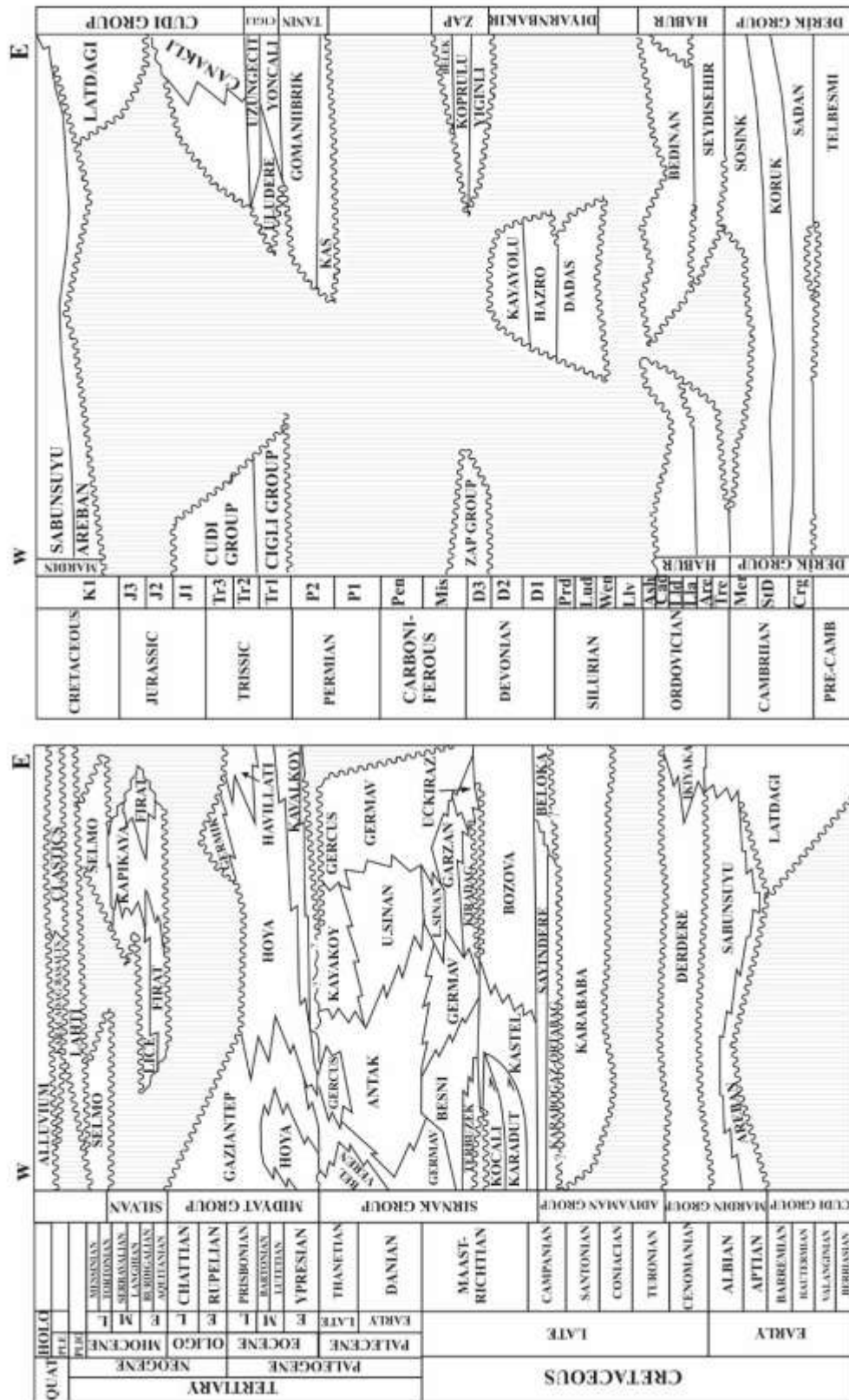
Finally, regional uplift produced an extensive unconformity in latest Cretaceous times (Dunnington, 1958), but in SE Turkey, shale deposition rapidly resumed in deepening water. The late Eocene saw the onset of closure of the Southern Tethys Ocean and collision between the Arabian and Eurasian plates, first to the NW in the Turkey section, then moving progressively SE during the Eocene and Oligocene. Crustal shortening to the NE and thermal doming of the incipient Red Sea rift in the SW resulted in uplift and erosion of these two margins of the Arabian Plate

and an increasing supply of clastic sediment (Gercüş Formation) into the intervening foreland basin. A NW-trending interior seaway developed in the Late Eocene foreland basin that filled with shallow-marine embayment carbonates of the Midyat Formation and ultimately in the Oligocene with evaporites of the Germik Formation. Continental to marginal marine conditions has dominated SE Turkey since Miocene times.

The tectonic zones have experienced the vast majority of tectonic deformation in SE Turkey, while the stable zones remained structurally high and relatively undeformed. The pre-existing weakness in the crust will be the focus of future strain accommodation. It has been proved that the style of reactivation is dependent on the orientation of the tectonic zone to the prevailing stress direction (Brew *et al.*, 2001).

1.4.1. Stratigraphy

The known oldest stratigraphic unit in the SE Turkey is the Precambrian Telbesmi Formation, and it consists of volcanic and volcanoclastic rocks, shales, and sandstones (Figure 8). The formation is deposited under marine conditions with slow transgression from north to south (Perinçek *et al.*, 1992). There is no diagnostic fossil evidence for the age of the Telbesmi Formation, and it is dated with respect to its stratigraphic position. Thick and widespread Cambrian Derik Group unconformably overlies the Telbesmi Formation. Derik Group is composed of marine clastic rocks at the bottom (Sadan Formation); shelf carbonates in the middle (Koruk Formation), and shallow-marine shale and sandstone alternations (Sosink Formation) at the top. Thickness of the Koruk Formation ranges between 50–200 metres and it is a seismically definable key unit in southeast Turkey due to its homogeneously widespread tidal flat carbonate lithology. Stable platform-style depositional environment was dominated during the Cambrian time and the deposition become younger to east indicating also the direction of the transgression (Perinçek *et al.*, 1992).



Derik Group passes gradually into coastal plain to shallow-marine deposits of Ordovician Habur Group. Habur Group is composed of two formations. These are the Lower Ordovician shallow-marine clastic rocks of the Seydişehir Formation, and Middle–Upper Ordovician marine and shallow-marine shale and sandstone alternations of the Bedinan Formation. Then, a depositional break occurred in the rest of the area. During the Early Silurian, widespread unconformity was developed. The Ordovician Habur Group is covered by Upper Silurian–Middle Devonian shallow-marine rocks of the Diyarbakır Group in the central Southeast Turkey.

Diyarbakır Group is represented by three formations: (1) Silurian–Lower Devonian Dadaş Formation is composed of organic-rich dark gray-black shales layered with limestone and sandstone intervals, deposited in deltaic to shallow-marine environments. Dadaş Formation comprises three members where Dadaş-1 member is the main source rock of the many oil fields in the Arabian Plate. (2) Dadaş Formation is covered by 100–250-m-thick Lower–Middle Devonian Hazro Formation. It is characterized by clastic rocks interlayered with a dolomite section (Hazro-F4 member, key unit) in the middle. This unit is deposited in shallow-marine and tide-dominated clastic environments. (3) Middle–Upper Devonian Kayayolu Formation consists of carbonates with shale and sandstone interbeds in the lower part; and sandstones and shales with thin bedded dolomites and evaporate interbeds in the upper part. The final deposition of the Diyarbakır Group was took place in lagoonal to supratidal and fluvial environments (Perincek *et al.*, 1991; Karabulut *et al.*, 1993).

Diyarbakır Group is overlain by coastal plain to shallow-marine sediments of the Zap Group of Late Devonian–Early Carboniferous age. This group consists of Yığınlı, Köprülü and Belek formations. Zap Group is overlain by either Tanin Group or Çıgılı Group (Figure 8). Yığınlı Formation is represented by gravely sandstones and intercalation of limestones and shales. The middle unit Köprülü Formation is composed of limestone at the bottom and grades into black shales with siltstone-sandstone interlayers upward. The youngest unit Belek Formation is composed of

dark gray-black biostromal and biohermal carbonates. Early Carboniferous age is assigned for this unit (Cebecioğlu and Köylüoğlu, 1986). The Late Devonian–Early Carboniferous transgressive marine conditions have prograded towards the Mardin high from east to west.

Another regional unconformity is observed between the Diyarbakır or Zap groups and the Tanin Group due to the uplift and following sedimentological break developed during Middle Carboniferous–Early Permian. The Permian Tanin Group was deposited in a transgressive environment and its deposition was controlled by Mardin-Kahta high becoming thicker to the east. The 40–50-m-thick basal unit, Kaş Formation (the transgressive surface) grades into the upper unit, Gomanibrik Formation. Kaş Formation is composed of shales and sandstones with coal layers, and alternation of limestone and marl. Similarly, the Gomanibrik Formation is represented by bioclastic limestone at the base, shale and sandstone with coal lenses in the middle, and dolomite and bioclastic limestone becoming sandy and argillaceous upwards.

There is a continuous transition between the Paleozoic units to the Mesozoic units in Southeast Turkey. The Lower Triassic is represented by Çığlı Group in this area. The Çığlı Group is divided into three formations. The lower Yoncalı Formation is composed of limestones that grade upwards into shales. The widespread middle unit Uludere Formation consists of shales, siltstones and sandstones. The upper Uzungeçit Formation comprises limestone and dolomite with shale and sandstone intercalations. Lower Triassic sediments of the Çığlı Group represent shallowing marine depositional environment, afterwards the sea level rises up during the deposition of the Cudi Group. The sequence is generally composed of dolomites and anhydrites, with minor amounts of shales, sandstones and micritic limestones, deposited during the rifting phase of the southern Neotethys on the northern edge of the Arabian Plate. The volcanic units at the lower parts of the section and also dykes indicate the rifting during the deposition of this unit. The Cudi Group is represented by Çanaklı and

Latdağı formations on the eastern part of the area. The Çanaklı Formation is composed of dolomite and limestone with minor evaporates shale and chert. It is about 2000 m thick in the east, 800 m thick in the west and, gets thinner and absent in the central part of the southeastern Turkey. Köylüoğlu (1984, 1986) proposed Middle Triassic–Early Cretaceous age for the Cudi Group.

In the Middle Jurassic, a sedimentological break in the central part of Southeast Turkey occurred probably due to uplifting (Figure 3). Afterwards, Aptian–Turonian Mardin Group was deposited with basal clastics and then shallow-marine carbonates with a regional unconformity all over Southeastern Turkey. The Mardin Group is represented, from bottom to top, by Areban, Sabunsuyu and Derdere formations. The basal transgressive Areban Formation is composed of sandstones, sandy limestone, and dolomites with shale interbeds. The maximum 50-meter-thick unit overlies unconformably either the Lower Mesozoic or Paleozoic rocks, or grades gradually into the Sabunsuyu Formation. Sabunsuyu Formation consists of restricted lagoonal, tidal flat to shallow subtidal carbonates. Derdere Formation, the youngest unit of the Mardin Group, is composed of organic-rich fossil-bearing carbonates deposited under restricted, semi-restricted unoxic conditions, and lagoonal to tidal flat (Çelikdemir and Dülger, 1990). Basinal sediments started accumulating on the northern margin of the Arabian Plate, and first stage of obduction might have initiated during Turonian time (Perinçek and Özkaya, 1981). Then, the ophiolitic nappes were overthrust onto continental crust during the Senonian. The tectonic slices of allochthonous Karadut Complex was overthrust the ophiolites.

Coniacian–Upper Campanian Adıyaman Group overlies the Aptian–Turonian Mardin Group. Karababa, Karaboğaz, Sayındere, Ortabağ and Beloka formations belong to this group as they have similar biostratigraphy. The Karababa Formation is represented by dark gray planktonic foraminiferal organic-rich limestones in the lower part and thick-bedded bioclastic limestones and dolomites in the upper part. There is a disconformity identified between the Karababa and overlying the Karaboğaz

formations. Phosphate- and chert-bearing, planktonic foraminiferal organic-rich limestones of the Karaboğaz Formation is dated Early Campanian. The Karaboğaz Formation grades into the Sayındere Formation and it can be considered as partially time equivalent of the Beloka, Ortabağ, and Sayındere formations in the central and eastern areas (Güven *et al.*, 1991). It consists of dark-colored shale, siltstone, sandstone and bioclastic limestones. Also, in the central parts, plankton-bearing argillaceous creamy limestones and calciturbiditic limestones of the Sayındere Formation were deposited. The Beloka Formation is the platform shallower deposited equivalent of Sayındere Formation. Upper Campanian Beloka Formation is composed of bioclastic limestones and dolomites. The Kıradağ, Garzan and Bozova formations overlie the Beloka Formation with an unconformity.

The majority of Southeast Turkey was under the influence of deep-marine conditions during Late Campanian when Coniacian–Upper Campanian Adıyaman Group was deposited. Karaboğaz and Ortabağ formations were deposited under unoxic deep-marine conditions. Şırnak Group overlies the Adıyaman Group and starts with basal Kastel Formation, which is composed of planktonic foraminiferal shale and marls alternated with sandstones and conglomerates. In southern part of the area, the Kastel Formation grades into gray marls, calcareous shales and carbonates of the Bozova Formation. Upper Campanian–Lower Maestrichtian Bozova Formation is overlain conformably by Germav and Üçkiraz formations. The Terbüzek and Kıradağ formations occur as clastic units at high areas to the north. Above the Garzan (east) and Besni formations (west) are represented by rudist and large foraminiferal reefal bank-type carbonates. While Besni has both conformable and unconformable contacts with the Germav Formation, there is a transitional contact among Garzan, Germav, and Sinan formations (Figure 9-a). The Germav Formation is composed of shale and marl alternations with siltstone and sandstone layers, and it is divided as upper and lower units. The Sinan Formation consists of rudist-foraminifera bearing carbonates and is divided into upper and lower units. The Upper Sinan grades into the Upper Germav to the south and Kayaköy and Antak clastic rocks to the north. The Antak Formation is composed of polygenic conglomerates and sandstones, derived from

allochthonous rocks, and alternations of mudstone, siltstone and gravelly sandstones. The Kayaköy Formation is interpreted as a part of the Antak Formation (Güven *et al.*, 1991).

Age of the Terbüzek, Kıradağ, Besni, Garzan, Lower Sinan, Lower Germav, Haydarlı and Üçkiraz formations are accepted as Late Maastrichtian (Figure 9a). Paleocene age is assigned to the Upper Sinan, the Upper Germav, the Becirman, and the Kayaköy sequences (Figure 9b). Upper Maastrichtian to Paleocene age is however proposed for the Antak Formation (Perinçek *et al.*, 1992). Kastel Basin was developed during Late Campanian–Early Maastrichtian time and sandstones, shales with olistostromal blocks were deposited. Later allochthonous units were placed tectonically over the Kastel Basin. The Paleocene carbonates (Upper Sinan, Becirman and Belveren) were deposited over platform shoals. Alternated evaporates, red continental clastics, and marine carbonates (Kayaköy, Antak, and Becirman formations) were deposited in restricted to semi-restricted and transitional to continental depositional environments. The deposition of the Germav Formation continued in deeper parts of the basin.

The Midyat Group unconformably overlies the Şırnak Group. Lower Eocene–Upper Oligocene Midyat Group is represented by Gercüş, Kavalköy, Hoya, Germik, Havillati and Gaziantep formations. The Gercüş Formation is composed of red-wine colored conglomerates, sandstones, siltstones, and mudstones with some evaporate-carbonate intervals. The Gercüş Formation is deposited in fluvial to alluvial, playa and tidal flat environments and made up of intercalations of sandstone, shale and siltstone. The lower Eocene Kavalköy Formation occurs in the Hakkari region and consists generally of thin- to medium-bedded limestones; it is overlain conformably by the Hoya Formation. Widespread Hoya Formation is represented by thick-bedded to massive limestones and dolomites. The Hoya and Kavalköy formations were developed over platform areas in restricted, semi-restricted to shallow-open-marine conditions (Figure 9c). The Hoya Formation grades to the Gaziantep Formation in the Adıyaman and Gaziantep areas. The Gaziantep and

Havillati formations were deposited in relatively deep-marine conditions. The Germik Formation is defined in a limited area around Siirt region and is represented by chert-bearing planktonic foraminiferal chalky limestones and marls with channel-type carbonate sand bodies deposited in restricted, evaporate-bearing conditions, which indicates the last stage of regression.

With an unconformity, Lower to Middle Miocene Silvan Group overlies the Midyat Group. The last transgresional phase is represented by the Silvan Group and it comprises Kapıkaya, Fırat, and Lice formations (Figure 9d). The Lower–Middle Miocene Kapıkaya Formation is composed of brown to gray conglomerates, sandstones, siltstones, and mudstones. Evaporate and carbonate lenses can be observed. The Kapıkaya grades laterally and vertically to reefal-bank type carbonates of the Fırat Formation. The Lice Formation covers the Fırat Formation in the northern areas. Lower Miocene Lice Formation is made up of generally by marl, shale, siltstone and sandstone alternations. Its lower contact was conformable, but the upper one is always tectonic with overthrust rocks. Upper Miocene Şelmo Formation is composed of mudstone, siltstone, sandstone and conglomerates. Şelmo Formation is overlain unconformably by the Pliocene deposits and Upper Neogene Karacadağ Basalts. The volcanic activity in the region is divided in to three stages: the Mid-Upper Miocene Siverek, the Pliocene Karacadağ, and Pleistocene to Recent Ovabağ Groups. The Karacadağ volcanic products are sourced predominantly from mantle-derived melts associated with post-collisional rifting within the Arabian Plate (Lustriono *et al.*, 2012; Koçbulut *et al.*, 2013). Late Miocene is also the time for the intense compressional movement that triggered the allochthonous imbricated thrust sheets.

(a)

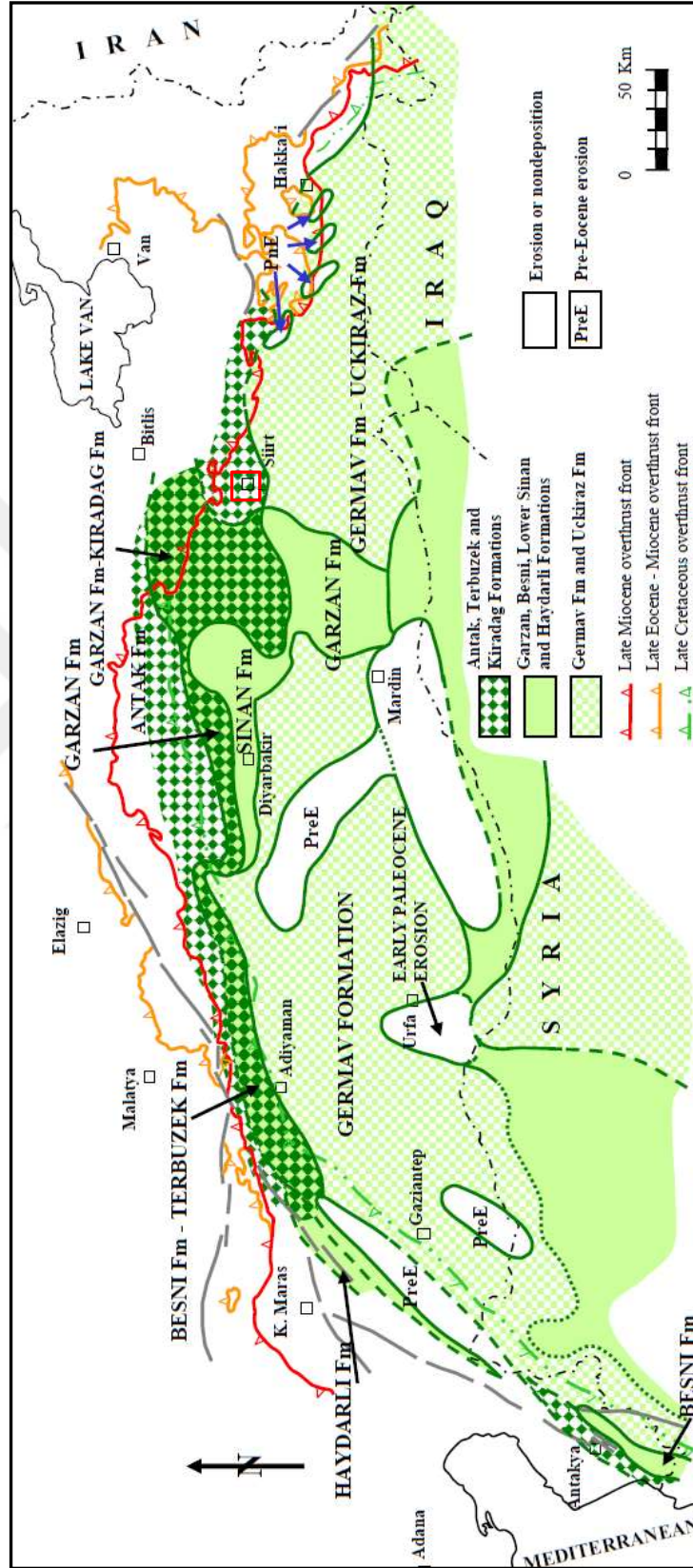


Figure 9. Paleogeographic maps of the Northern Arabian Plate (SE Turkey). **(a)** Late Maastrichtian, **(b)** Paleocene, **(c)** Late Eocene–Oligocene, **(d)** Early–Middle Miocene (Perinçek *et al.*, 1990). Red boxes show the location of study area.

(b)

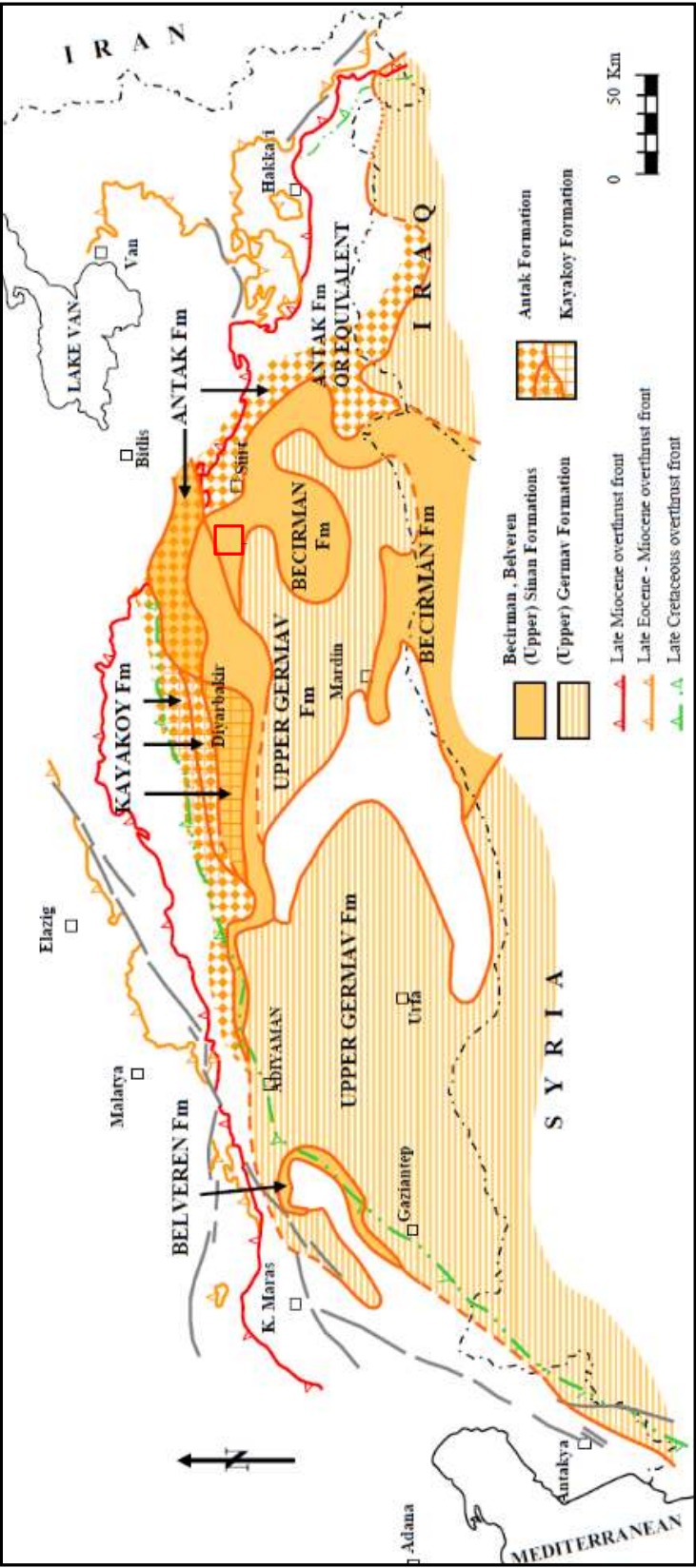


Figure 9 continued...

(c)

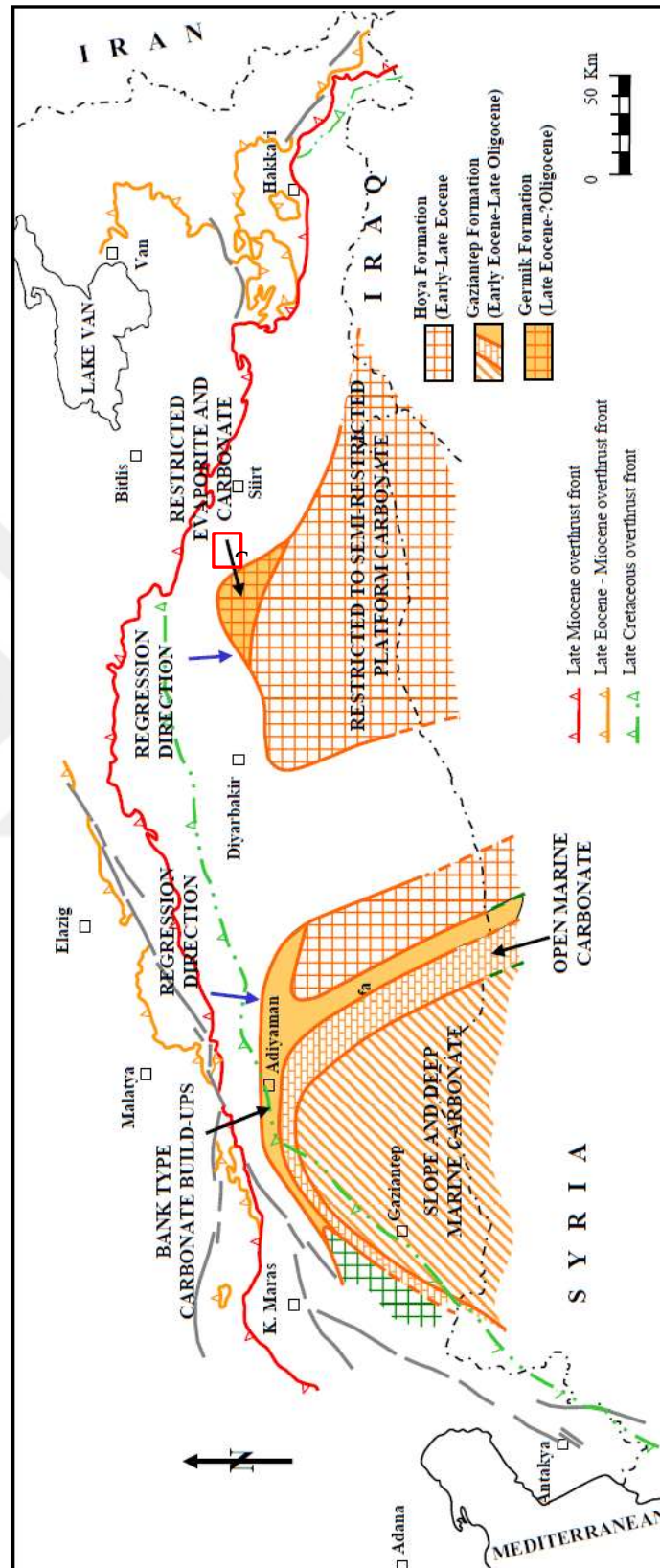


Figure 9 continued...

(d)

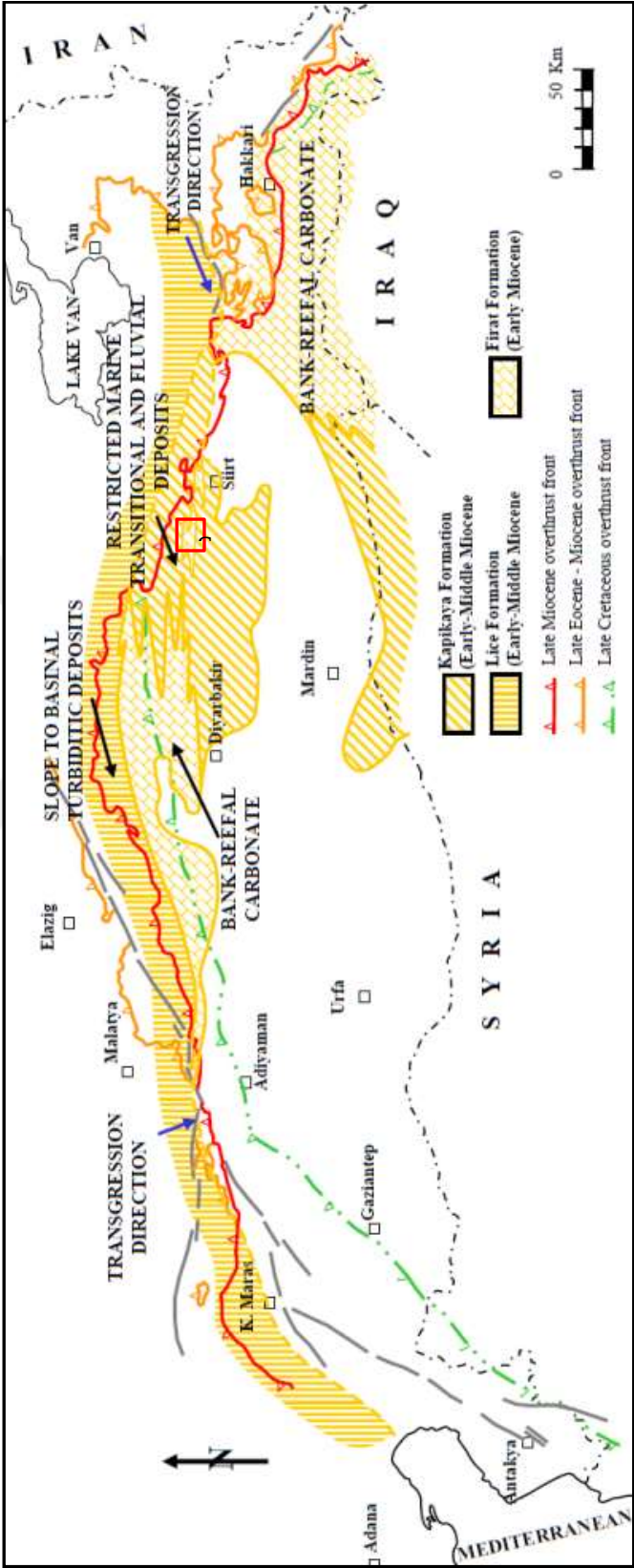


Figure 9 continued...

1.4.2. Tectonic Setting

Southeastern Anatolia contains four well-developed structural highs, which trend northwest–southeast and make acute angle with the fold and thrust belt. From west to east, these structural highs are the Bozova, Mardin, Hazro, and Körkandil highs (Figure 10). Perinçek and Çemen (1992) suggested that although the structural highs have earlier deformation patterns, they obtained their final geometries sometime prior to Eocene, possibly during Paleocene. Most compressional structures in the Southeast Anatolia were produced by Cretaceous and Miocene major compressional tectonic events. The Late Cretaceous structures generally trend northeast–southwest whereas the Miocene structures trend northwest–southeast on the eastern section and northeast–southwest on the western section of the region. From Pliocene to the present, the region has been affected by strike-slip tectonics, which resulted from stress inversion after the collision of the Afro-Arabian Plate with Eurasian Plate. This collision caused the escape of the Turkish Plate to the west and initiated the neo-tectonic period in Anatolia (e.g., Şengör and Yılmaz, 1981; Şengör *et al.*, 1985; Perinçek and Çemen, 1990, 1992; Bozkurt, 2001; Koçyiğit *et al.*, 2001).

The tectonic events affected Southeast Anatolia are Precambrian ice age (Beydoun, 1991), Early Cambrian extension (super continent Pannotia split into Gondwanaland, Laurentia, Baltica, Siberia, China, Kazakia; Stampfli, 2000), Late Ordovician Taconian orogeny and following ice age (Beydoun, 1991), Late Ordovician–Early Silurian opening of the Paleotethys (Beydoun, 1991; Stampfli, 2000), Late Silurian–Early Devonian Caledonian Orogenesis, and erosion of Silurian and early deposits, Mid–Late Carboniferous Hercynian orogeny, Late Carboniferous Early Permian ice age, Mid Carboniferous–Early Permian closure of Paleotethys, Late Permian–Triassic opening of Neotethys (separation of Iran, Turkey from Arabian Plate), opening of all Tethys oceans and closure of Paleotethys during Triassic, closure of Paleotethys during Jurassic, Late Jurassic opening of block fault-bounded

basins, closure of Neotethys and deepening of Kastel trough in Late Cretaceous (Perinçek and Özkaya, 1981),

Late Cretaceous compressional tectonics, Late Paleocene–Early Eocene compressional tectonic, Middle Eocene opening of Maden and Çüngüş basins, Middle Eocene compression, Miocene compression (Açıkbaş *et al.*, 1981; Perinçek and Özkaya, 1981), and Neotectonic period.

After the Late Ordovician glaciation, Early Silurian organic matter-rich Dadaş Formation ‘hot shale’ member was deposited in the Arabian Plate by the opening of Paleotethys Ocean in the northern part of Gondwana (Beydoun, 1991) (Figure 11). Most of the pre-Silurian and Silurian sediments were eroded. The Arabian Plate was rotated through 90° in an anticlockwise direction due to the collision between Africa and North American-North European continents (Konert *et al.*, 2001). The Hercynian (Variscan) Orogeny caused a period of non-deposition and erosion during Mid–Late Carboniferous on the northern edge of Arabian Platform. During Late Carboniferous–Early Permian time, Arabian Plate has moved 30–50° towards south, which caused ice period in Gondwana and yielded carbonate starvation (Beydoun, 1991; Ghiennie *et al.*, 2010). Paleotethys started to close during Middle Carboniferous–Early Permian time, then the northern edge of Gondwana (Southeast Anatolia) become an active margin. During Late Permian–Triassic, from north to south, Paleotethys oceanic crust units subducted beneath Anatolian-Iranian plate that has yielded separation between Arabian and Anatolian-Iranian plates (Beydoun, 1991).

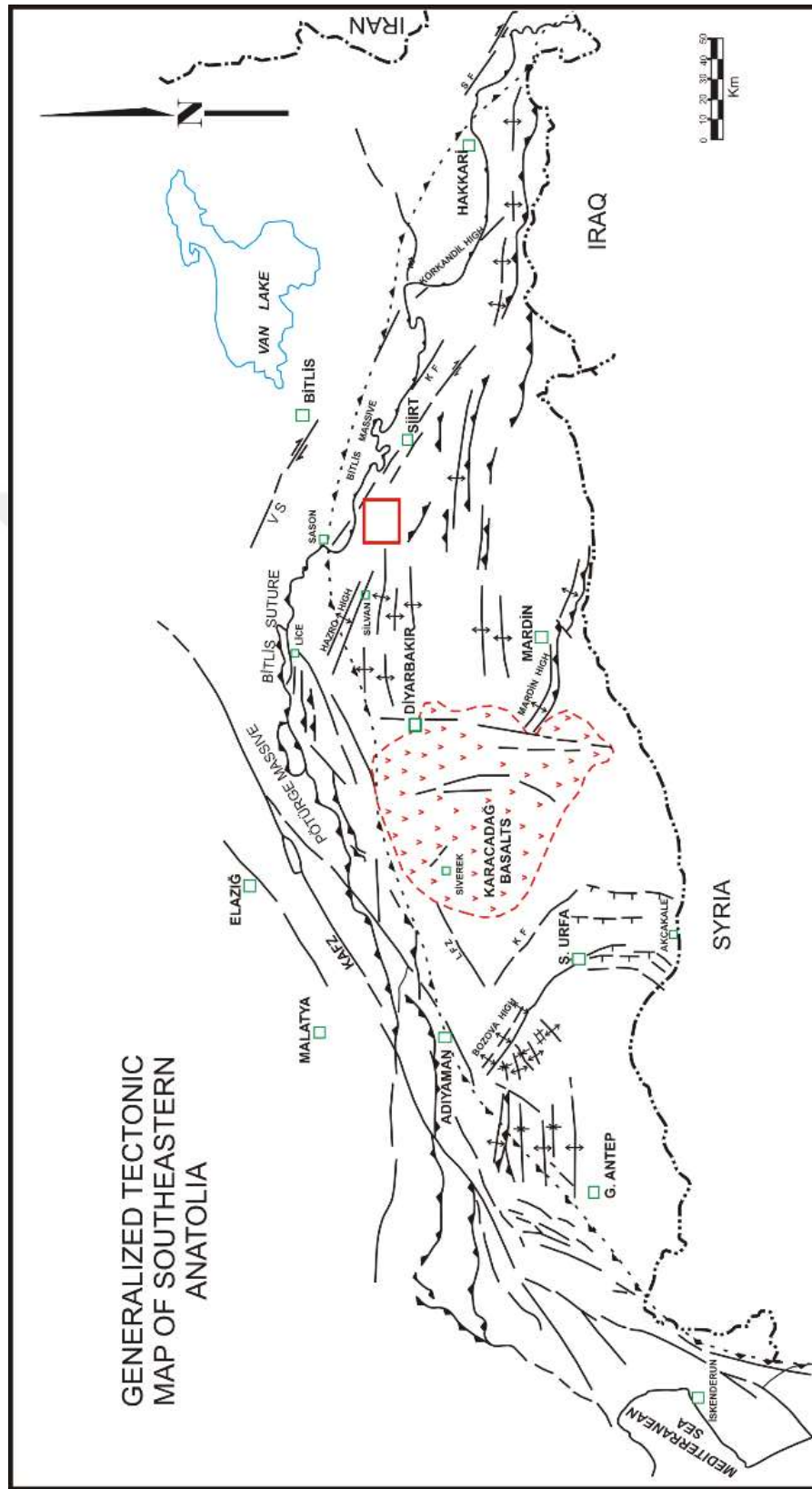


Figure 10. Generalized tectonic map of Southeastern Anatolia. Compiled from various sources including Perinçek *et al.* (1987), Çemen (1990), Perinçek and Çemen (1990). The through-going dotted line marks the northern boundary of the leading edge of the Cretaceous thrusts (Perinçek and Çemen, 1991).

Neotethys Ocean was started to open between Anatolian and Arabian plates during Late Permian and Triassic (Şengör and Yılmaz, 1981). Paleotethys was closed during Triassic–Jurassic interval and thus, ophiolitic suture zone was developed in Jurassic. During Late Jurassic, block faulting and mid-ocean spreading of the Neotethyan Ocean have continued. South East Anatolia became a carbonate platform and the Cudi Group carbonates were deposited in Late Jurassic–Early Cretaceous time during opening of Neotethys Ocean (Figure 11). Mardin-Kahta high was subjected to erosion and/or non-deposition during Late Jurassic–Early Cretaceous time (Çelikdemir *et al.*, 1991). The Cenomanian–Turonian Mardin Group covers the succession from Precambrian to Jurassic with a regional unconformity and transgression in Early Cretaceous. While the Cenomanian–Turonian Mardin Group carbonates were deposited in the platform areas, the Karadut complex were deposited in deeper northern parts near the edge (Perinçek and Özkaya, 1981). During Late Campanian, almost deep-sea environment was established and clay-rich carbonates were deposited, then the Kastel Basin was opened. Flysch-type sediments were deposited during early Campanian. While the deepening continuing, allochthonous units transported tectonically from northern parts into the Kastel Basin (Karadut and Koçali complexes); due to that northern edge of the Arabian Plate was compressed and thickened.

During Middle Campanian, deep-sea environment continued and finally environment became deeper during Late Campanian. The Kastel Basin was opened and flysch-type sediments were deposited in the area. The allochthonous units transformed into the Kastel Basin from northern parts through Arabian Plate (Karadut and Koçali complexes). Tectonic aggregation and thickening have developed on the northern edge of Arabian Plate due to subduction of Neotethyan oceanic crust. At the end of Late Maasthrictian, transgression has started and marine environment dominated the region. At the end of Paleocene, compressional regime dominated with the evidence of lateral transition between terrestrial and marine sediments. Then, transgression had started with carbonate deposition in the Early Eocene. During

Middle Eocene time the region partly uplifted under the influence of north-south compressional regime (Perinçek *et al.*, 1992; Duran *et al.*, 1998).

The compressional regime continued through Miocene and triggered the southward movement of nappes. Due to that progress, a basin opened right in front of advancing nappes and sediments were deposited in both terrestrial and marine environments (Lice Basin). At the end of Middle Miocene, these allocthonous units transported further south and thrust on the Lice Basin deposits. Late Miocene is a time of intensive compressional tectonic in the area, thus imbricated thrust sheets formed as a result of this regime. After the final collision of Arabian and Eurasian plates, strike-slip regime becomes the dominant tectonic regime throughout the area since Pliocene.

Figure 12 represents the present-day stress map of the Arabian Plate and shows the maximum horizontal in-situ stress direction (red lines) and the interpreted stress environments (color codes) (GeoTech webpage, 2010). The regional stress field (maximum horizontal stress, σ_{Hmax}) is oriented approximately north–south in the south of Kozluk (Batman) (black circle). σ_1 and σ_2 are anticipated to be horizontal at a depth of over 1000 m, indicating a thrust environment. This stress state may, however, be changed with depth below 2500 meters as the σ_3 increases and becomes σ_2 .

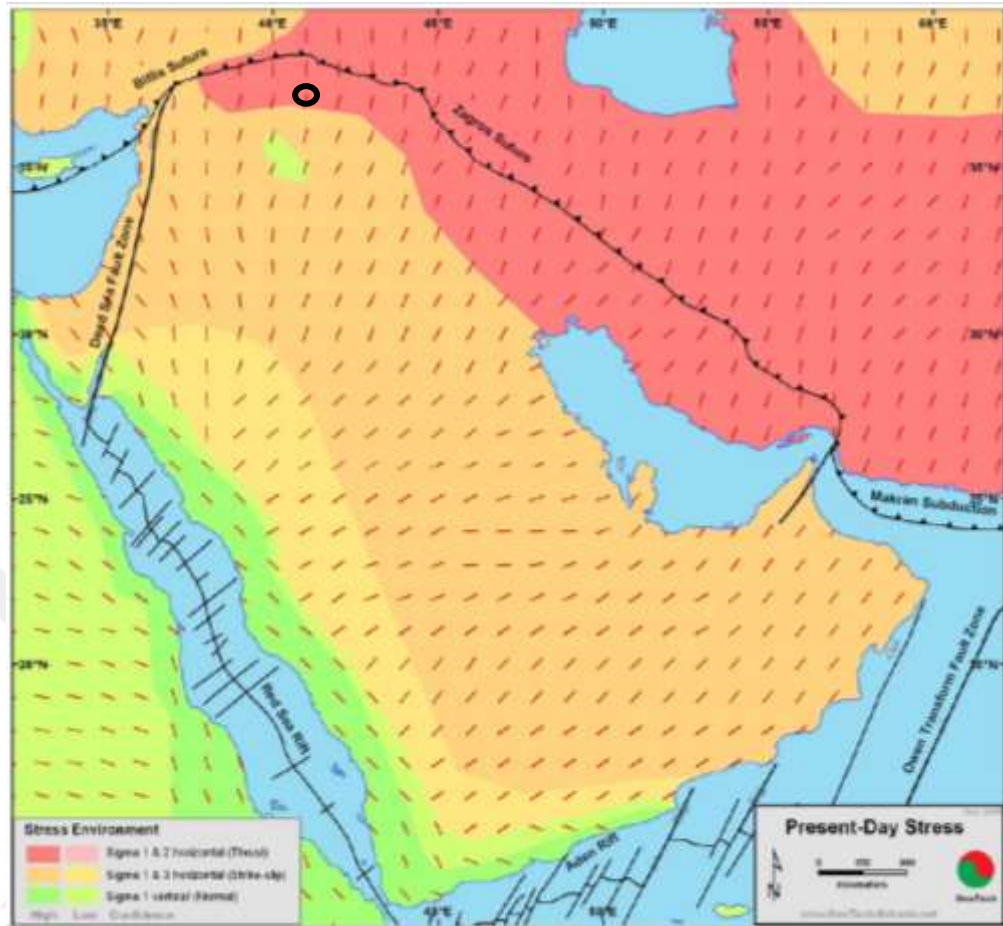


Figure 12. Arabian Plate present-day stress field map (at ~1 km depth). (GeoTech, 2010). Black circle shows the location of study area.

1.5. Data

The 3-D seismic cube is the major dataset evaluated during this study. There is also 72 wells data, drilled across the 400 km² study area, available to the present research (Figure 13). By integrating topographic and updated geologic maps with the high quality seismic data and information from drilled wells, the geological evolution of the study area is discussed. Well data covers stratigraphic information from penetrated formations, well log, leak-off tests and check-shot data. Conventional logs are also very helpful for obtaining information about lithology boundaries, porosity, permeability, formation fluids, and also seismic tie. On the other hand, leak-off tests

and micro-resistivity logs (FMI, XRMI) give information to illuminate the structural features, such as orientation of bedding, existing fractures, faults, and present day stress field. The data has been loaded in Petrel Software version of 2016. All the well tops match, well-log correlation, 3D seismic interpretation, seismic attributes and structural modeling have been completed using Petrel 2016 which is a Schlumberger product.

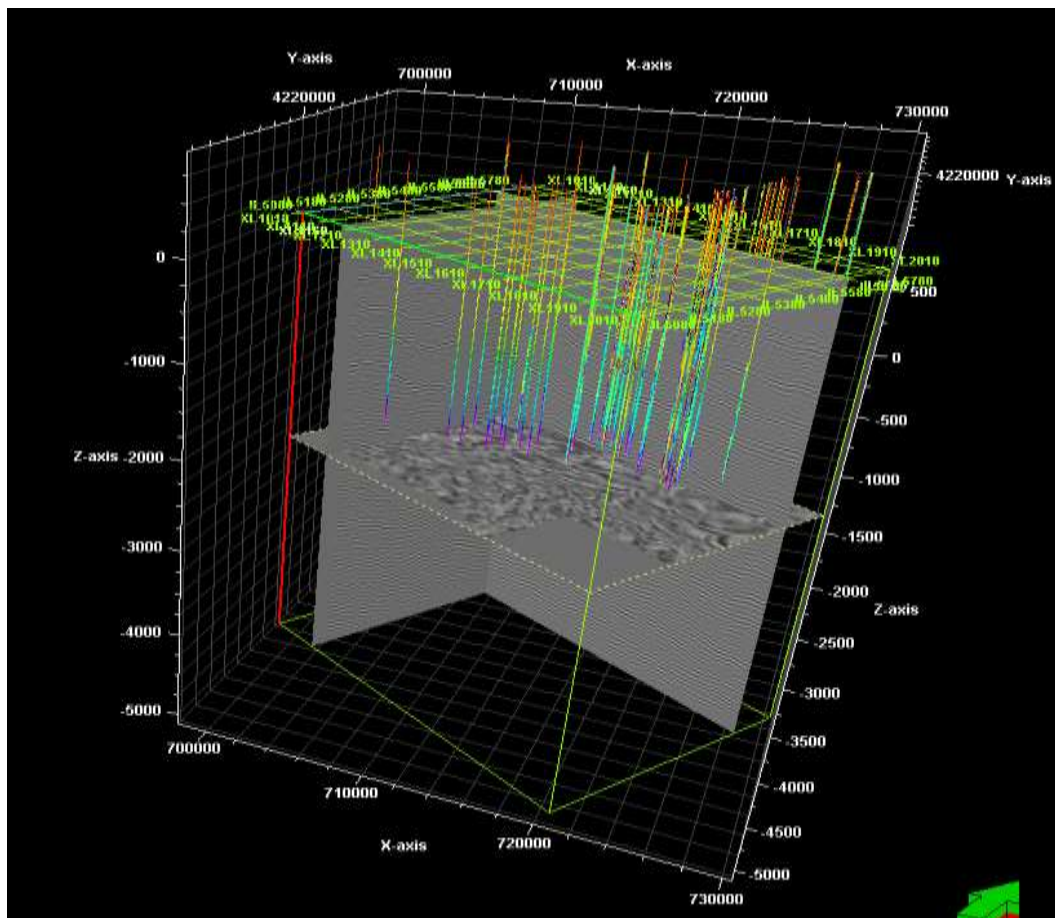


Figure 13. Study area available seismic cube (Kozardere 3D) and wellbore data (72 wells) visualized by Petrel 2016.

1.6. Methodology

First, the field observations have been completed in and around the study area that is covered by 1/25000 scale topographic map sheets of L46c1, L46c2, L46c3, L46c4, L47d4, L47d3, M47a1, M47a2 and M47b1. The field study is mainly focused on the ground-truthing the Eocene–Miocene units, exposed in the area between Oyuktaş through Kurtalan. Then, the existing wells drilled in the study area have been evaluated by using well logs (GR, DT, XRMI, FMI, and FED) and extended leak-off tests (DFIT) that have been obtained during drilling operations. These analyses have been used to understand lithology, mechanical properties, fracture distribution, depositional environments, faults, bed-boundaries, sedimentological features, and stress fields. The main data is the 3D seismic cube which is loaded and interpreted with Schlumberger's Petrel version 2016. The Petrel Software enables to interpret horizons and faults in the seismic cube (Kozaredere 3D) with allowing creation of various attributes, then finally helps to generate the most accurate geological model of the study area. The detailed information about the different methods employed will be provided in the following subsections.

1.6.1. Field Ground-truthing

The Eocene–Miocene units and dissecting faults formed the focus of the field studies. Sampling of different lithologies along Oyuktaş-Kurtalan Fault for paleontologic and petrographic analyses, and fault-plane measurements both in the study area and also in the nearby region were completed. The samples have been analysed in TPAO Research Center Department and the results are summarized in Chapter II. The fault measurements are obtained from observation points. The data from the striated slip surfaces are analysed in order to determine the kinematics of the faulting. Analysis are performed by using the stress inversion method of Angelier

(Angelier, 1984, 1991, 1994), and computed using the software T-Tecto 3.0 developed by Zallohar and Vrabec (2007).

1.6.2. Well Data Evaluation

There are 72 wells drilled in the study area. Most provides valuable subsurface information in order to understand lithology, mechanical properties, and fracture distribution, and depositional environments by evaluating well log data, cutting samples, and cores. The GR and sonic logs were used to tie formations and well correlation. The image logs (XRMI, FMI...) were used to characterize fractures, faults, bed boundaries, sedimentological features, and stress fields.

1.6.2.1. Gamma-ray Logging

Gamma-ray logging measures the natural radioactivity of the formation. The uranium, thorium, and potassium are the three radioactive minerals in the rocks. These elements regularly emit the alpha, beta and gamma rays. The gamma rays have been counted with a special detector, and the number of rays that reaches to counter changes with time. Gamma-ray logging tool cannot be easily affected by borehole diameter changes and it is able to read both open and cased hole.

The readings can however be affected by heavy mud and KCl polymer-based mud. The most common usage is depth correlation, determination of formation contacts, clay-rich zones, and shale volumes (Figure 14).

1.6.2.2. Sonic Logging

Sonic logging is a well-logging tool that allows a formation interval transit time, which is a measure of a formation's capacity to transmit seismic waves. The tool mainly consists of upper transmitter, lower transmitter and two pairs of receiver. The main usage of sonic log is to determine porosity, cement evaluation, mechanical properties, and formation velocities for seismic studies (Figure 14). The porosity can be determined by using the empirical relation called Wyllie equation.

1.6.2.3. Image Logs: XRMI, FMI & FED Logs

Borehole resistivity imaging logs were studied to characterize fractures, bed boundaries, breakouts and sedimentological features. The advantage of the borehole imaging techniques compared to conventional logging is the higher vertical resolution of the logging technique, which helps better identification of sedimentological and structural features.

In resistivity imaging techniques, rock resistivity is measured with a number of microelectrodes. Resistivity contrast maps of the borehole wall are generated by plotting the resistivity traces side by side as a function of depth. The observation, description and interpretation of these maps provide detailed information about rock composition, texture and structure. Schlumberger FMI (Formation Micro Imaging) and Halliburton XRMI (X-tended Range Micro Imager) borehole imaging tools are used in this study. The XRMI electrical wireline borehole imaging tool is designed to obtain high quality images in high resistivity environments. Pads of the XRMI tool are mounted on six independently articulated arms help maintain pad contact in rugose, washed-out, elliptical, or highly deviated boreholes. It has a good sampling rate (120 samples per foot) and borehole coverage (67% in 8.5" holes).

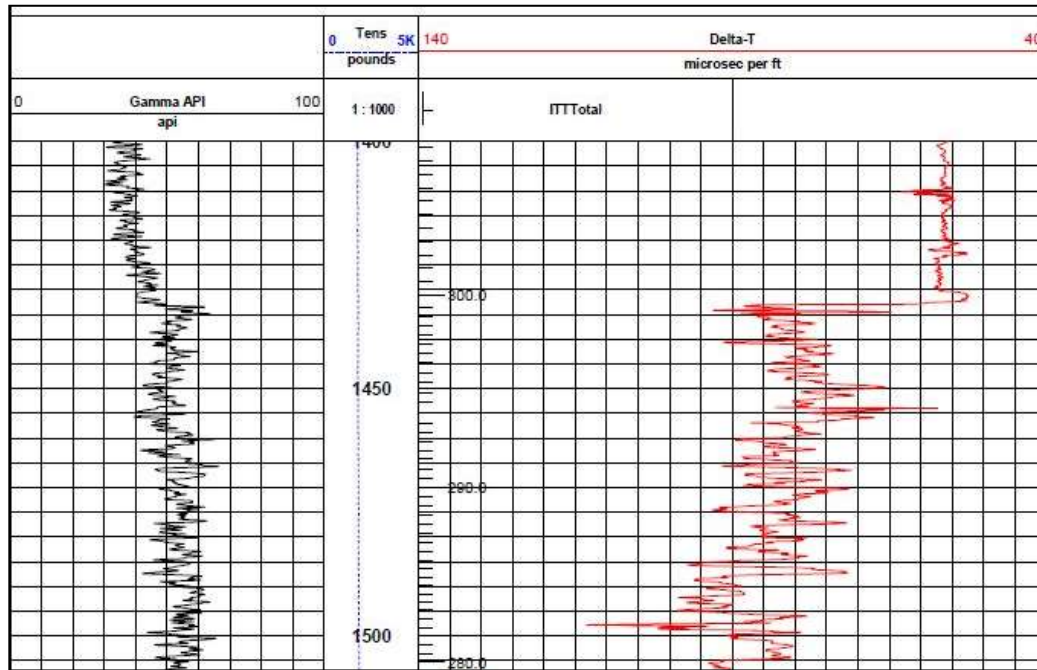


Figure 14. Example of Gamma-ray and sonic log recorded in a well in the study area (from TPAO database).

Borehole images are presented in a variety of 2D and 3D visualizations. Both image results are displayed as unrolled 360° views of the surface of the borehole wall versus depth. The resistivity images are represented as unrolled conductivity maps of the borehole wall by using two modes; static and dynamic. In the static display, the color scale is normalized for the entire recorded depth interval. In the dynamic display, the color scale is normalized over a short moving window to get the maximum dynamic range. In both modes, higher conductivity values are indicated as darker colors and lower conductivity values are indicated as lighter colors. Dynamic image displays are used to detect small resistivity variations and static image displays are used to detect large resistivity variations around the borehole.

The rock non-planar features (such as grain size, lithological composition) and also the planar features (such as bed boundaries, fractures and faults) are all possibly determined by the interpretation of borehole image data.

Any planar feature that intersects the borehole with an angle to the borehole axis is represented by a sine wave on the unrolled borehole wall picture. The sine wave represents the depth, dip angle and dip azimuth of the planar feature. If any planar feature is parallel to the borehole axis, it is represented by a vertical straight line. If any planar feature is perpendicular to the borehole, it is represented by a horizontal straight line (Figure 15).

As the faults show loss of continuity between two sides of the event, there should be depth shifts between each side of an oblique event. The identification of a fault plane includes the dip, strike data and the offset nature. Two types of fractures can be identified in the image data. They could be either induced or natural fractures. While the induced fractures are always open, natural ones are either open or closed. Drilling conditions force borehole fluid into the fractures and the fluid in the fractures creates both resistivity and acoustic impedance contrasts with the adjacent rocks. If the fracture is healed, the infill mineralization controls the resolution of the fracture. They generally appear as light color sine waves in resistivity images. Open natural fractures are seen in darker colors. Unlike drilling induced fractures, natural fracture orientation is different in different depth intervals.

The drilling of the borehole causes elongation due to in-situ stress distribution of the area. The elongations or borehole breakouts develop perpendicular to the maximum horizontal stress (S_{Hmax}). Borehole breakout develops when the stress around the borehole exceed that required to cause compressive failure of the borehole wall (Zoback *et al.*, 1985). Borehole breakouts can be visible in acoustic and electrical image logs. Especially, resistivity imaging logs can provide high-resolution images of wellbore wall with contrasts that help direct observation of breakouts. Borehole breakouts are appeared to be broad and parallel conductive zones separated by 180° with accompanying caliper log enlargement (Figure 16).

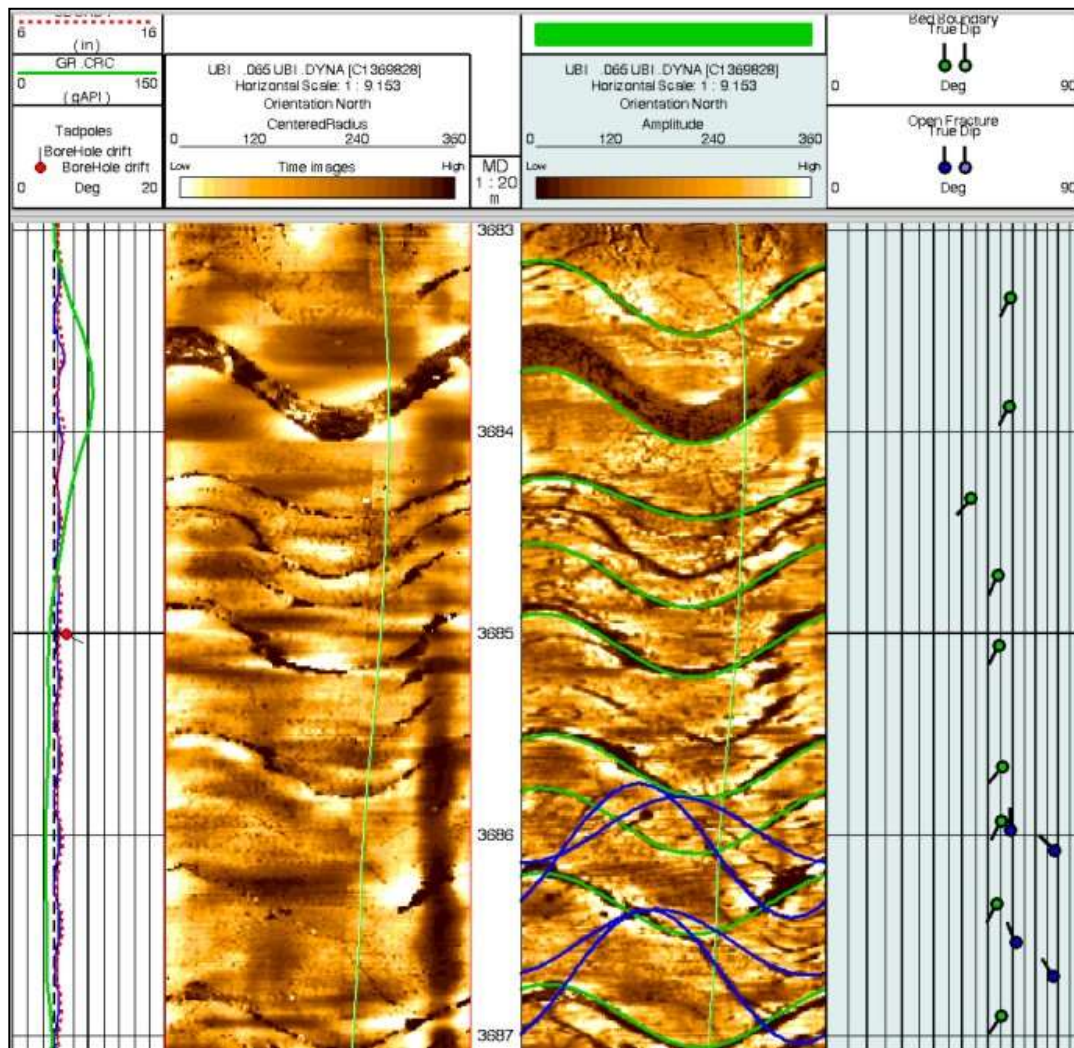


Figure 15. Ultrasonic (acoustic) image log; travel time image (left) indicates borehole diameter, amplitude image (right) shows acoustic impedance, dips calculated from image show both bedding (green) and fracture (blue) dips. The dark areas on the travel time image show borehole elongation in the NW–SE direction, with maximum stress direction at right angles to this axis (from <https://www.spec2000.net/07-acousticimagelog.htm>).

S_{Hmax} is the most difficult component of the stress tensor to accurately estimate as it cannot be measured directly. The drilling induced tensile fractures and/or the width of wellbore breakouts can also be used to approach the value of maximum principal stress (S_{Hmax}). It can be better estimated with the help of rapid development of wellbore imaging techniques. The method is based on modeling breakout rotations to estimate the magnitude of S_{Hmax} . If S_{Hmax} had been lower, the

breakout widths would have been smaller. As the breakouts are common in many wells and it is simple to measure their widths, by knowing pore pressure, vertical stress, the least principal stress, the rock strength we can determine maximum principal stress (S_{Hmax}) by using formula suggested by Zoback (2007). The uniaxial compressive strength, C_o , is determined from theoretical acceptance for Middle Eastern carbonate rocks in Chang *et al.* (2006) and Zoback (2007) (Table 1, equation 1).

$$S_{Hmax} = \frac{(C_o + 2P_p + \Delta P + \sigma^{\Delta T}) - S_{hmin}(1 + 2\cos 2\theta_b)}{1 - 2\cos 2\theta_b}$$

Equation 1

where $2\theta_b = \pi - W_{bo}$

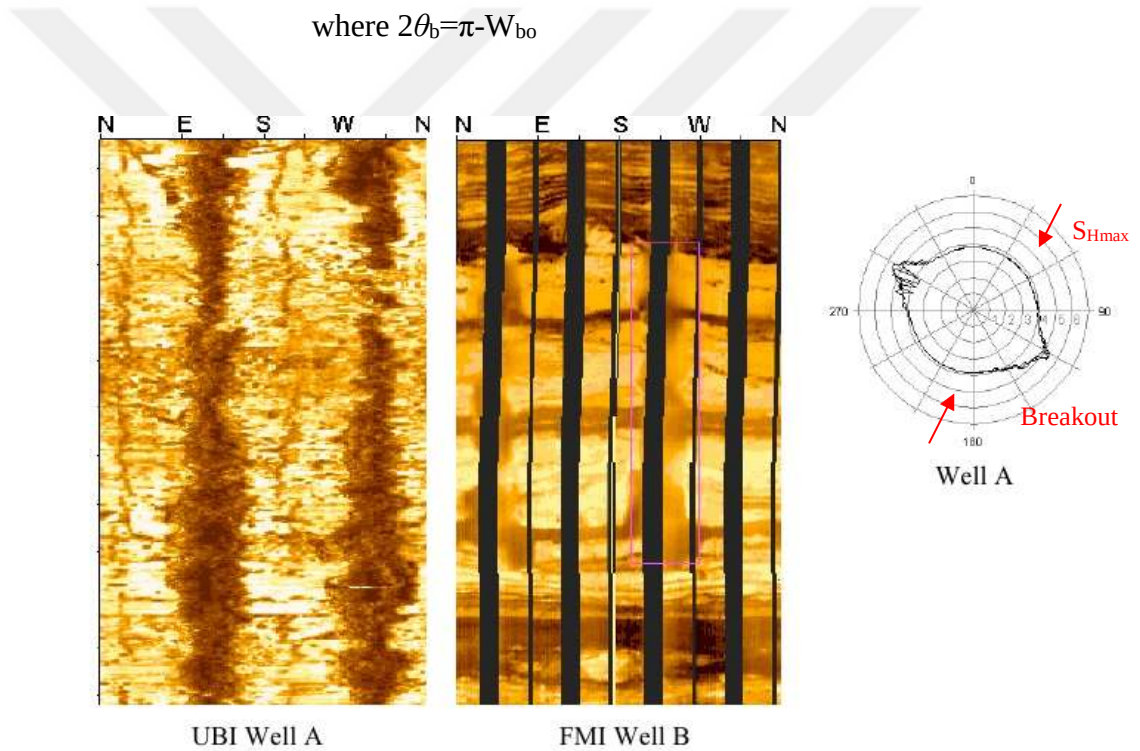


Figure 16. Example of borehole breakout interpreted on borehole televiewer image as dark bands on borehole walls (UBI Well A) and electrical image data visible with the poor contact of pads of the FMI tool (Formation Micro Imager- FMI Well B). Also note the drilling induced fractures are directed 90° apart from the azimuth of breakouts in UBI Well A image. Breakouts and drilling induced fractures indicate maximum horizontal stress direction is almost Northeast-Southwest (from Zoback, 2007).

1.6.2.4. Leak-off Tests

The knowledge of the wellbore failure helps us to estimate the magnitude and orientation of in-situ stress at depth. Drilling induced tensile fractures are developed due to change of stress distribution around wellbore. In some cases, these fractures can effect wellbore stabilities and cause drilling problems. High mud weight usually leads to the development of these tensile fractures. The least principal stress, σ_3 , can be determined from extended leak-off tests at casing set points in normal and strike-slip faulting areas (Zoback, 2007).

Table 1. Empirical relationships between UCS and other physical properties in limestone and dolomite (Chang *et al.*, 2006; Zoback *et al.*, 2007).

	UCS, MPa	Region where developed	General comments	Reference
20	$(7682/\Delta t)^{1.82} / 145$	–	–	(Militzer 1973)
21	$10^{(2.44 + 109.14/(t))} / 145$	–	–	(Golubev and Rabinovich 1976)
22	$0.4067 E^{0.51}$	–	Limestone with $10 < \text{UCS} < 300$ MPa	Unpublished
23	$2.4 E^{0.34}$	–	Dolomite with $60 < \text{UCS} < 100$ MPa	Unpublished
24	$C(1-D\phi)^2$	Korobcheyev deposit, Russia	C is reference strength for zero porosity ($250 < C < 300$ MPa). D ranges between 2 and 5 depending on pore shape	(Rzhevsky and Novick 1971)
25	$143.8 \exp(-6.95\phi)$	Middle East	Low to moderate porosity ($0.05 < \phi < 0.2$) and high UCS ($30 < \text{UCS} < 150$ MPa)	Unpublished
26	$135.9 \exp(-4.8\phi)$	–	Representing low to moderate porosity ($0 < \phi < 0.2$) and high UCS ($10 < \text{UCS} < 300$ MPa)	Unpublished

The assigned pore pressure value (Pp) is used 10 MPa/km (~0.44 psi/ft) (Zoback *et al.*, 2007). The value of σ_{hmin} in the formula is determined by evaluating leak off test data gathered from wells in and around study area.

Principal stress trajectories around a cylindrical opening in a bi-axial stress field are based on the Kirsch equations (from Zoback, 2007). In this situation, the wellbore wall is the free surface which cannot maintain shear traction. While the stress trajectories are perpendicular to the wellbore in the direction of S_{Hmax} , the trajectories are parallel to the wellbore in the way of σ_{hmin} , when the well is vertical (Figure 17).

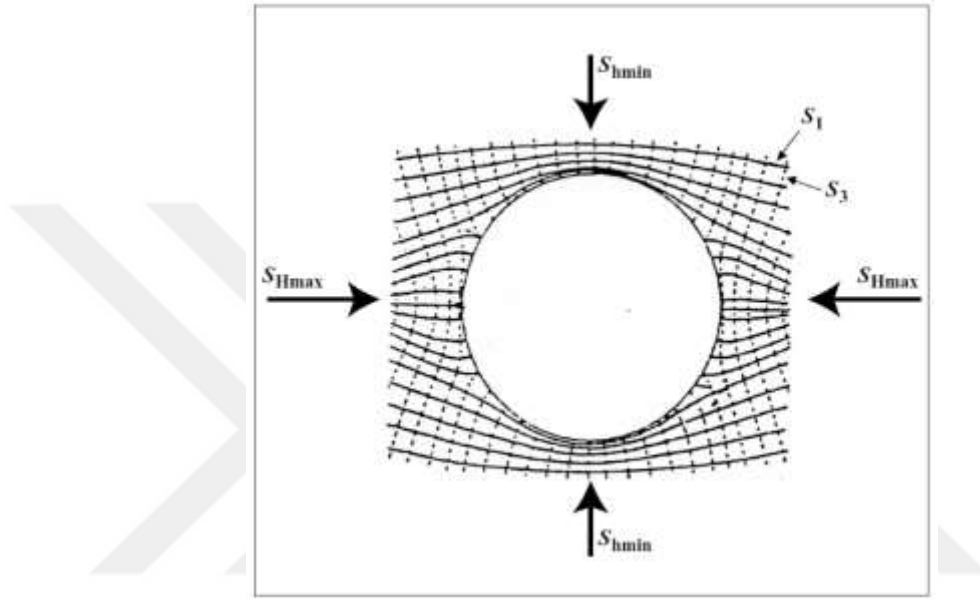


Figure 17. Principal stress trajectories around a cylindrical opening in a bi-axial stress field based on the Kirsch equations (from Zoback, 2007) (Wellbore wall: Free surface; σ_{Hmax} : Stress trajectories are perpendicular to the wellbore; σ_{hmin} : Stress trajectories are parallel to the wellbore, in the case of a vertical well).

One of the most reliable methods to determine the least principal stress is the direct measurements of σ_{hmin} from hydraulic fracturing operations in the wells and wellbores at any depth. Also the least principle stresses can be determined from extended leak-off tests, which can be done after the assigned casing has been placed and cemented at certain depth and the well drilled in short distance ($\sim 3\text{--}6$ meters). At this point, the open section of the well is pressurized to the point that a hydraulic fracture is developed and thus, the magnitude of the least principle stress can be evaluated. If there is a considerable mud losses developed during drilling, this means

an unintended development of hydraulic fracture in a well, in a condition where mud weight decreased from least principal stress or frac-gradient. The leak-off point (LOP) should be a distinct break in slope, and then it would be equal to the least principal stress (Figure 18). If the leak off point (LOP) hasn't been reached then the test is called *Formation Integrity Test (FIT)*. Then, in this situation, the maximum pressure cannot be used to estimate the least principle stress.

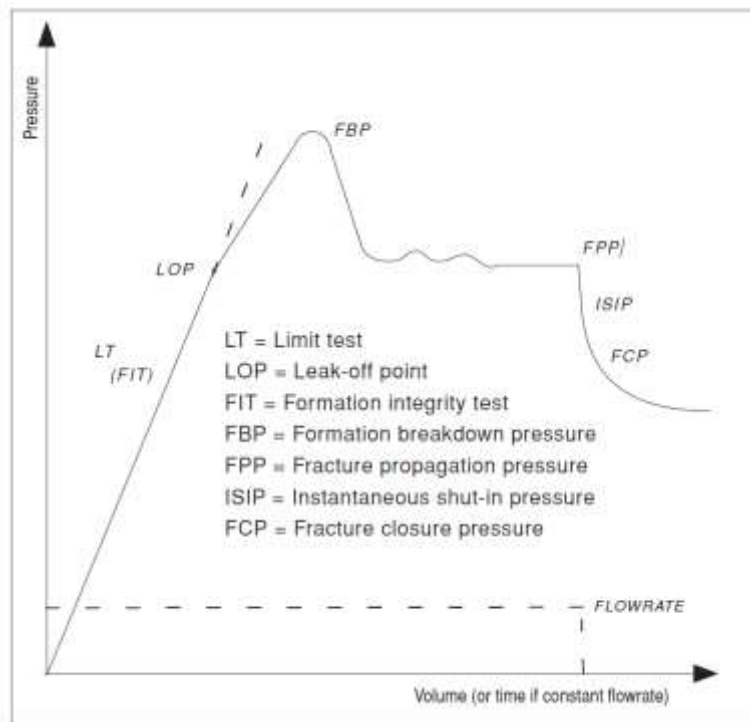


Figure 18. Diagram shows extended leak-off test showing pressure as a function of volume or time (Zoback, 2007).

The peak pressure reached during a leak off test is called formation breakdown pressure (FBP). It represents the pressure at which unstable fracture propagation away from a wellbore occurs, then, loss circulation or fluid flow occurs into the fracture and the pressure drops. If pumping continues at a constant rate, the pumping pressure will drop after the FBP to relatively constant value, named fracture propagation pressure (FPP). This pressure is related with propagation of the fracture away from wellbore. To calculate the magnitude of the least principle stress at the depth of the test, it is important to include the pressure in the wellbore due to the column of wellbore fluid.

1.6.2.5. Frictional Strength of Faults and Stress Profiles

There are three principal stress magnitudes, σ_{Hmax} , the maximum principal horizontal stress; σ_{hmin} , the minimum principal horizontal stress, and σ_v , the vertical stress, the weight of the overburden, that help the determination of stress regimes in earth crust (σ_1 , σ_2 , and σ_3 referred to σ_v , σ_{Hmax} , σ_{hmin}) (Anderson, 1969) (Figure 19). The vertical stress, σ_v , is the maximum principal stress (σ_1) in normal faulting regime, the intermediate principal stress (σ_2) in strike-slip regimes and the least principal stress (σ_3) in reverse faulting regimes (Table 2).

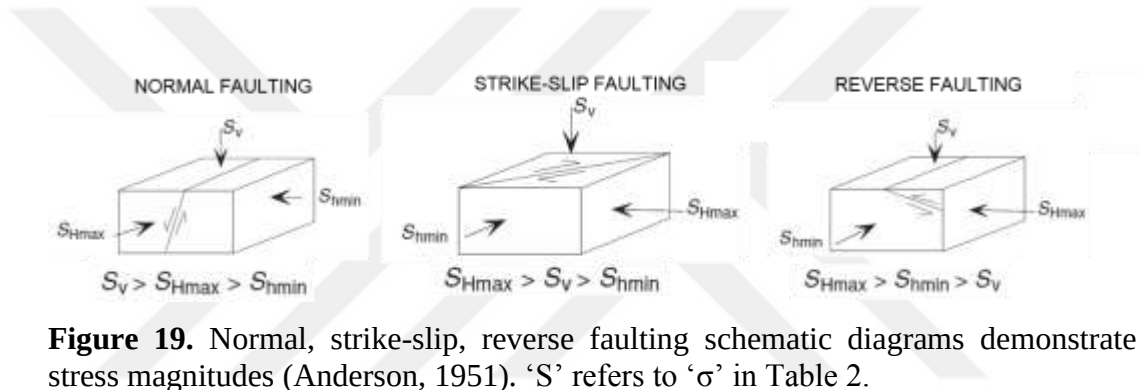


Figure 19. Normal, strike-slip, reverse faulting schematic diagrams demonstrate stress magnitudes (Anderson, 1951). ‘S’ refers to ‘ σ ’ in Table 2.

Table 2. Relative stress magnitudes and faulting regimes.

Regime	Stress		
	σ_1	σ_2	σ_3
Normal	σ_v	σ_{Hmax}	σ_{hmin}
Strike-Slip	σ_{Hmax}	σ_v	σ_{hmin}
Reverse	σ_{Hmax}	σ_{hmin}	σ_v

The shear and the normal stresses acting on the fault depend on the magnitudes of the principal stresses, pore pressure and the orientation of the fault with respect to the principal stresses. Normal faults are expected to form in conjugate pairs that dip $\sim 60^\circ$ and strike parallel to the direction of σ_{Hmax} . Strike-slip faults are expected to be vertical/near vertical and form in conjugate pairs that strike $\sim 30^\circ$ from the direction of σ_{Hmax} . Reverse faults are expected to dip $\sim 30^\circ$ and form in conjugate pairs that strike normal to the direction of σ_{Hmax} . Faults that are oriented almost orthogonally to

σ_{Hmax} have too much normal stress and not enough shear stress to slip. The maximum and minimum principal effective stresses for strike-slip faulting are limited by the frictional strength of pre-existing faults. The relationship between pore pressure and effective principal stresses are shown in Mohr circles demonstrated in Figure 20. The figure illustrates how the Mohr circle gets smaller with increasing pore pressure. This means when pore pressure gets higher, faulting develops with smaller differences between the maximum and minimum effective principal stress. The existence of overpressured formations at depth, there will be minor differences between three principal stresses. When pressure approaches the vertical stress, both horizontal stresses must also be close to the vertical stress, regardless of faulting style. Figure 21 represents possible stress magnitudes for normal, strike-slip, and reverse faulting environments when pore pressure is hydrostatic and when pore pressure is lithostatic (overburden) values at depth. The area should be evaluated with concerning vertical stress and pore pressure in order to understand the tectonic regime in an environment. The lower bound for σ_{hmin} is approximately $0.6\sigma_v$. In the extensional regimes (normal faulting-hydrostatic) the least principal stress (σ_{hmin}) can be dramatically below the vertical stress. This is represented by maximum horizontal stress (σ_{Hmax}) must be between σ_{hmin} and σ_v (Figure 21a). Strike-slip faulting regime is defined when σ_{Hmax} exceeds σ_v in a more compressional situation (Figure 21b). Finally, if the least principal stress is equal to overburden, then the reverse faulting regime is represented by both horizontal stresses might be greater than the vertical stress (Figure 21c).

1.6.3. Seismic Data Interpretation

The seismic data set available for this study consists of a three different merged 3D seismic reflection data called Kozardere 3D (Table 3). Based on interpretation of horizons and faults, a 3D geological model of the horizons and faults were constructed using Schlumberger's Petrel version 2016. Picking of horizons and faults was performed manually on 3D sections. Horizon models were obtained by interpolating

picked horizons on the 3D volume. The 3D area covers almost 350 km², with 50 m group shot interval, and 300 m receiver interval (Datum: 600 m.).

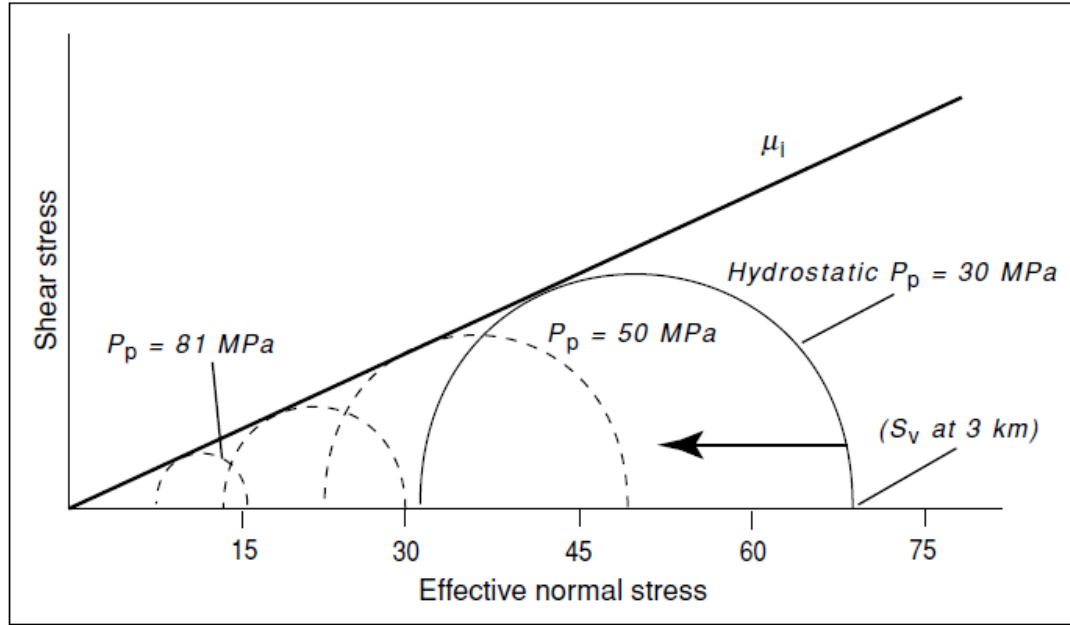


Figure 20. The difference between maximum and minimum effective principal stress (controls the size of Mohr circle) decreases with increasing pore pressure at the same depth.

Time slices and seismic attributes have been a common tool in seismic data analysis. Seismic attributes may highlight geological or geophysical effects, thus help making a quicker analysis of the data. Seismic data allows us to create certain reflection pattern attributes from the cube. Attributes used in this study are amplitude variance-edge method, ant track, reflection spacing, dip, and azimuth.

Table 3. The components of the 3D Seismic data.

KOZARDERE 3D	Inline	Crossline
Number of lines	751	1021
Length (m)	25502	18750
Interval (m)	25	25
Inline rotation from north (°)	120.80	

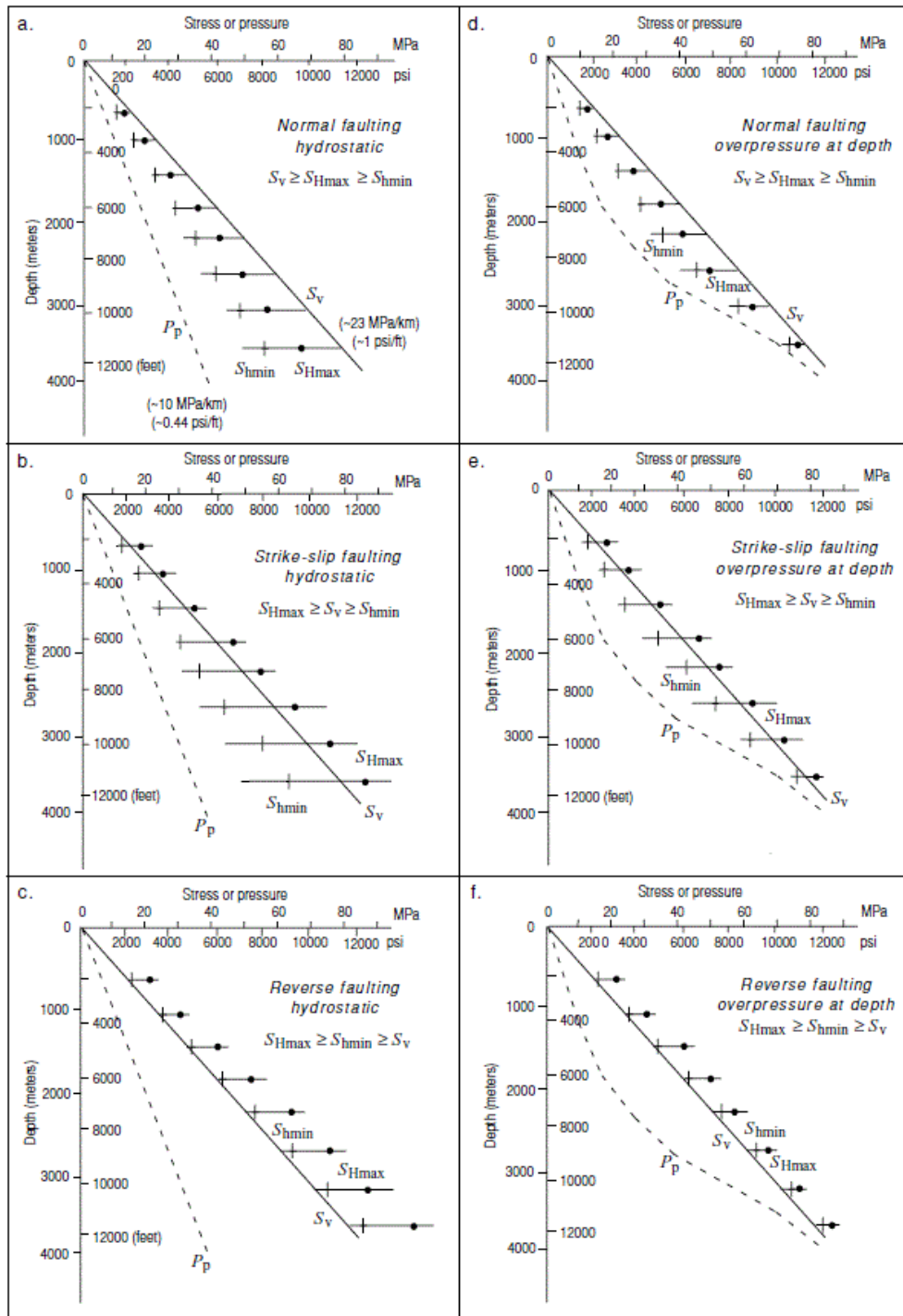


Figure 21. Variation of stress magnitudes with depth in normal, strike-slip and reverse faulting stress regimes for hydrostatic conditions. The difference between principal stresses increases with depth due to the increase of frictional crustal strength of the crust with depth (a–c), however, it decreases with sudden overpressure develops due to the decrease of frictional strength with elevated pore pressure (d–f) (Zoback, 2007).

CHAPTER II

STRATIGRAPHIC FRAMEWORK AND DEPOSITIONAL SYSTEM

2.1. Field Ground-truthing

The field groundtruthing was concentrated on the area covered by 1/25000 scale topographic map sheets of L46c1, L46c2, L46c3, L46c4, L47d4, L47d3, M47a1, M47a2, and M47b1. Major settlements in and around the study area are Baykan, Bekirhan, Kozluk, Kurtalan and Yanarsu towns (Figure 22). The field study is mainly concentrated on the stratigraphy and deformation of the specifically Eocene–Miocene units, exposed in the area between Oyuktaş through Kurtalan because better understanding of the style and timing of the structural elements formed the main subject of the present study. Although the stratigraphy of the area has been studied by different groups in TPAO during the last decades, there are still controversies exist. More importantly, the data from the most recent wellbores necessitates an urgent revision in the Miocene stratigraphy. This stems mainly from the similarities in the lithology, particularly presence of evaporates, in several Miocene formations and this creates confusion (Figure 23). The field study is mainly concentrated in the area to the north of the Reşan anticline, which is bounded by the segments of the Oyuktaş-Kurtalan Fault in the north and south (Figure 24).

The study area is located between the cities of Batman and Siirt. The modelled area covers an area of about 400 km²; it mainly lies within the limits of Batman city but a small portion is located in Siirt. Kozluk town is located 2.5 km north of the study area (Figure 22). The geology map of the study area in Figure 22 was compiled by Günay (1999). Because there are problems in description and boundary relationships of the Miocene units, this map was revised during 2009 field campaign. Also, Siyako *et al.* (2013) has re-mapped some parts near the study area. The map used in this study

has therefore been updated both by using personal field observations and Siyako *et al.* (2013) field work (Figure 24).

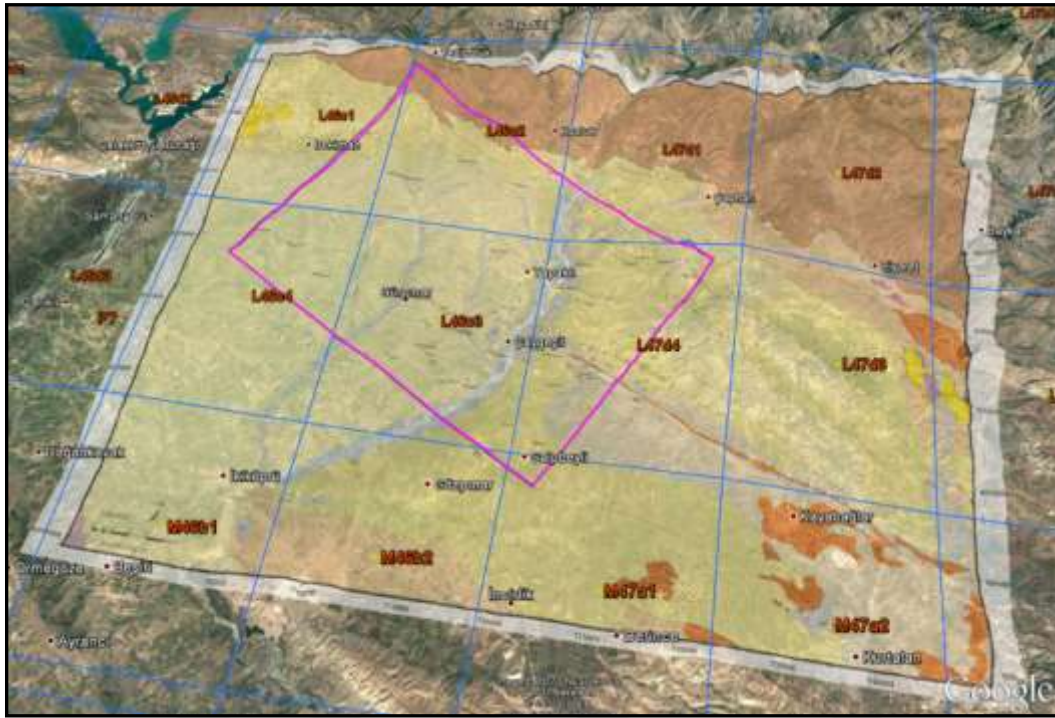


Figure 22. Map showing the studied 1/25000 scale topographic sheets of the study area. The pink square represents the coverage of 3D seismic data.

The Eocene–Miocene units and dissecting faults formed the focus of the field observations; sampling of different lithologies from fault zones for paleontologic and petrographic analyses, and fault-plane measurements both in the study area and also in the nearby region (such as Kurtalan and Malabadi area) were carried out during fieldwork. The oldest unit outcropped near the study area is the Eocene–Oligocene Germik Formation. It is unconformably overlain by a Miocene sequence (Figure 24). The Miocene succession is represented by several formations including, from the oldest to the youngest, the Kapıkaya, Fırat, Lice and Şelmo formations; the first three are named as Silvan Group. The Pliocene Lahti Formation overlies, with an angular unconformity, the deformed and tilted Miocene succession. Alluvium is the youngest lithological association (Figures 24 & 25).

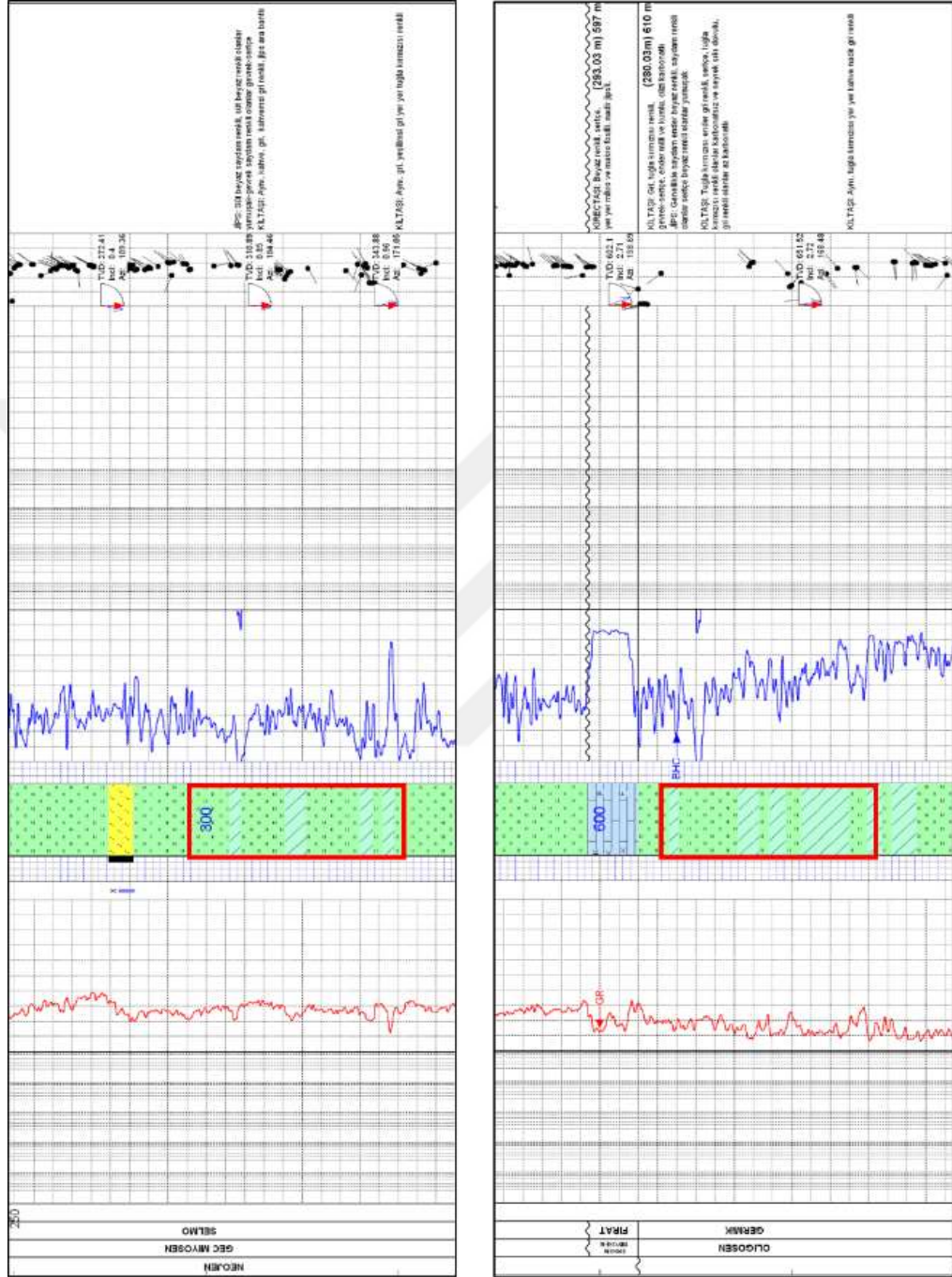


Figure 23. B-1 well composite log (TPAO database) showing Lower Miocene Firat Formation above and below evaporitic units (red boxes).



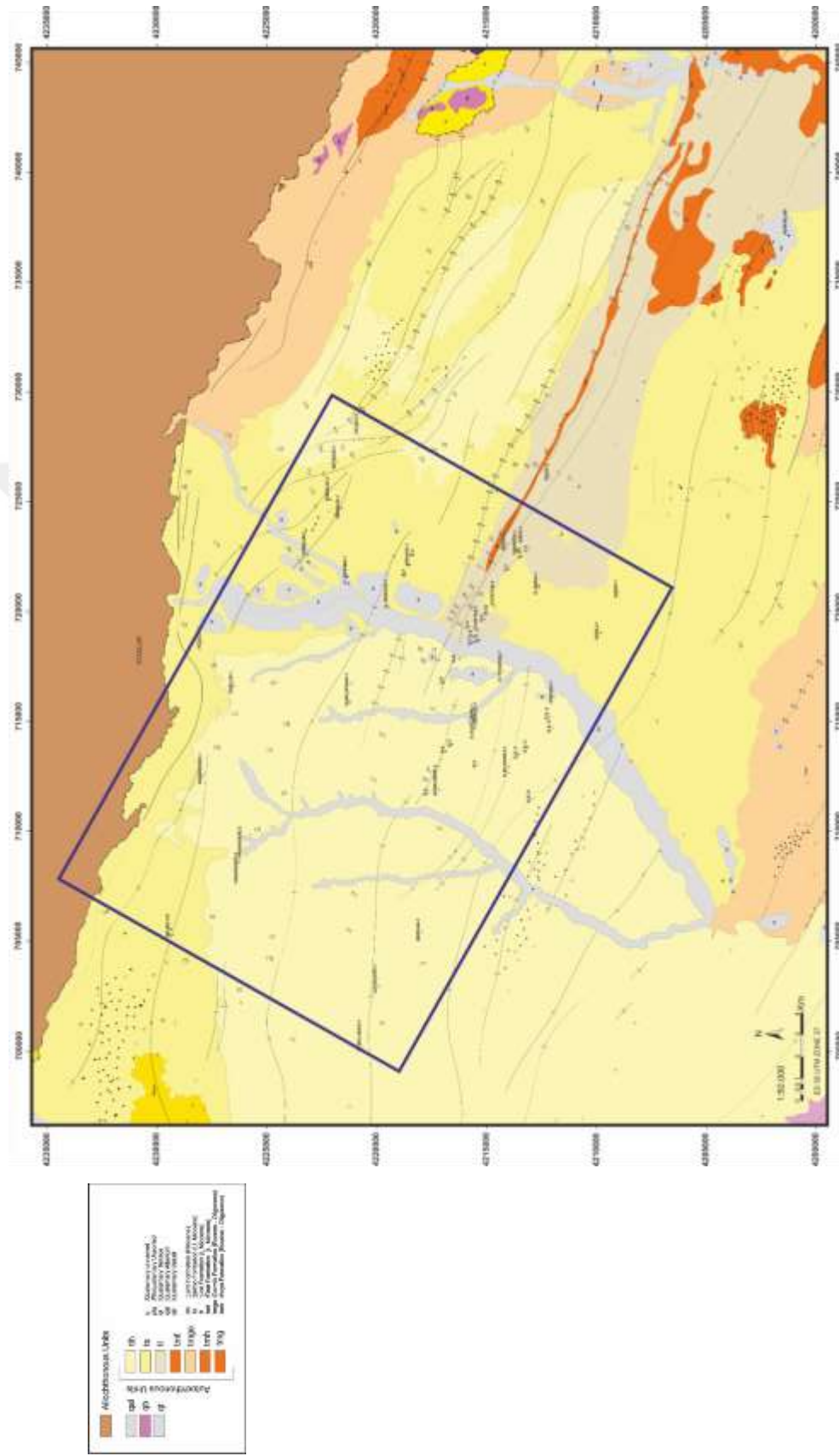


Figure 24. Geology map of the study area and surroundings. The map is compiled from the existing TPAO maps and then modified, based on the personal field observations and work of Siyako *et al.* (2013).



The Paleozoic–Miocene succession (allocthonous units), deposited in the area between Eurasian and Arabian plates, thrust on the Arabian Plate during the Early Miocene (Yılmaz, 1993; Robertson, 2000). During the emplacement of the nappes, the Lower Miocene Lice Formation was deposited in a shallow-marine foreland basin developed in front of the advancing nappes. While the compressional regime continued during the Miocene, the allocthonous units advanced further south and thrust over the Lice and Şelmo formations (Sungurlu, 1974). As the Lahti Formation was deposited subsequent to the Miocene tectonism, it occurs as undeformed horizontal units.

First observations were made on the western flank of Eski Garzan-Reşan Anticline (Figure 22) in Kayabağlar (Zokayıt) village in northwest of Kurtalan town. In the existing TPAO geology maps, the Oyuktaş-Kurtalan Fault zone is also located in the area. It is also important to note that there is still confusion and controversies among existing maps and stratigraphic scheme. Here, the present work chooses to use the modified map based on personal observations and work of Siyako *et al.* (2013).

There are evaporitic units within the Eocene–Oligocene–Miocene succession, exposed in area between the Oyuktaş Oil Field in the west and Siirt in the east and this makes confusion between formations. Perinçek (1980) first named the unit of limestone and evaporates as the Kapıkaya Formation (named after village Kapıkaya) and defined it as the lateral equivalent of the Fırat Formation (Figure 25). Açıkbay *et al.* (1981) also adopted the same nomenclature. In the previous TPAO geology maps, the shallow-marine reefal limestone unit is mapped as the Fırat Formation and the evaporitic units, as the Germik Formation. The new wells drilled in 2007 and 2013 have however penetrated two different evaporitic horizons above and below the reefal limestones of the Lower Miocene Fırat Formation (Figure 23). Observations are made in the area covered by topographic sheet M47-a2, as shown in Figure 22, to observe these two evaporitic horizons in the field in order to verify and understand their age and lithostratigraphic positions. Samples are taken for palynology and analysed in

TPAO Research Center Department of Stratigraphy and the results of the study will be represented below (Figure 25).

The Eocene–Oligocene Germik Formation outcrops near the study area in the north of Çelikli oilfield and in the south near Garzan-Germik oilfields (Figures 24, 25 & 26). The unit is named by Bolgi (1961) and it is composed of carbonates (dolomite and micritic limestone)-evaporate (gypsum and anhydrite) alternation with some mudstone and marl intercalations. The formation comprises two members: Germik limestone member and overlying Germik gypsum member. The latter is composed of massive, laminated, banded and even nodular gypsum with some dolomitic beds and mudstone-marl interbeds (Güngör *et al.*, 2013, 2017) (Figure 26). The Germik Formation is deposited in an evaporitic environment (lagoon and coastal sabkha) with regression during Middle–Late Eocene and Oligocene time (Çoruh *et al.*, 1997). Most of the time the unit is ductilely deformed and appears as small-scale domes in the outcrop. The thickness of the unit in the study area ranges between 300 m and 400 m.

Miocene starts with red clastic rocks of the Kapıkaya Formation (Perinçek, 1978). The formation is composed mainly of red-brownish conglomerate-sandstone and siltstone-mudstone alternation at the base. Up in the succession, white evaporitic (gypsum) bands/beds intercalations (Derge evaporates) characterize the formation. The uppermost part of the formation is composed of pinkish limestones (Zokayıt limestone); there are red shale intercalations as well. The various lithologies of the formation were deposited in river-flood plain-shallow marine environment whereas the age is, based on fossil content, assigned as early Miocene (Duran *et al.*, 1988, 1999).

The basal transgressive lithologies of the Kapıkaya Formation grades into neritic and reefal carbonates of the Miocene Fırat Formation (Figure 27); the lithological association of the formation is rather consistent through the most part of the southeastern Turkey. These carbonates have been named as the Fırat Formation by Peksu (1969) (in Yılmaz and Duran, 1997). The formation is made up mainly of

shallow-marine (chalky) limestones with some siltstone, claystone, marl and shale interbeds. The carbonates are represented by cream beige colored shallow-marine patch to near reefal massive bioclastic packstone and grainstone. The thickness of the unit in the study area ranges between 50 m and 200 m. The Fırat Formation grades vertically and laterally into the turbiditic sandstone, claystone, mudstone, and gypsum of the Lice Formation. In other areas, Fırat Formation is tectonically overlain by allochthonous units.

AGE			ROCK UNITS		LITHOLOGY	
			GROUP	FORMATION		
QUATERN		HOLOCENE		ALLUVIUM		
TERTIARY	NEOGENE	PLIOCENE		LAHTI		
		MIOCENE		ŞELMO		
					SILVAN	LİCE (evaporitic)
				FIRAT		
		KAPIKAYA				
	PALEOGENE	OLIGOCENE	MİDYAT	GERMİK		
		EOCENE				

Figure 25. Stratigraphic column of the Miocene units in the study area.



Figure 26. A view from an anhydrite quarry within the Eocene–Oligocene Germik Formation near Garzan oilfield (Siyako et al., 2013)

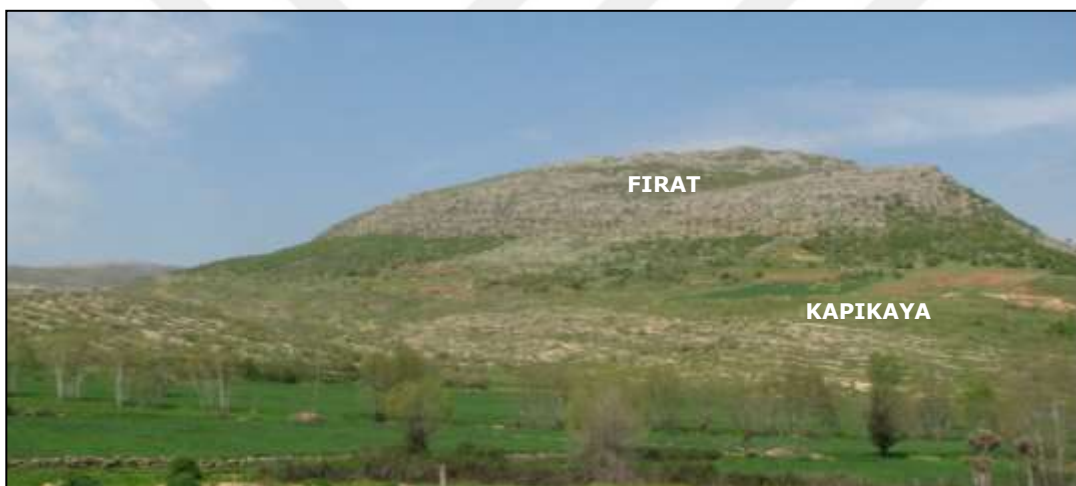


Figure 27. The relationship between the Lower Miocene Fırat Formation and basal conglomeratic Kapıkaya Formation near Kurtalan, Siirt.

Several samples are collected from the limestones of the Fırat Formation along Kayabağlar road and near Kurtalan Cement Factory quarry. The limestones are petrologically described as shallow-marine fossiliferous grainstone, packstone, little benthic foraminiferous pelloidal bioclastic grainstone, little benthic foraminiferous sandy bioclastic grainstone and, pelloidal-little benthic foraminiferous sandy bioclastic grainstone/packstone. The fossil assemblage identified from these samples include *Amphistegina* sp., *B. curdica*, *Borelis cf. curdica*, *Borelis melo*, *Borelis* sp., *Denditrina* sp., *Dentritro* sp., *Elphidium* sp., *Milliolidae*, *Miliolid* form, *Rotalidae*,

Rotalid form, Soritidae, Textularidae, bryzoa, echinoderm, Ostracoda, red algae, little benthic foraminifera and mollusk shell pieces. The age of the Fırat Formation is, based on the fossil assemblage, therefore assigned as early Miocene (TPAO Research Center).

After the deposition of carbonates, while the deep basin environment dominates in the west, evaporitic shallow-marine, playa and fluvial environment controls the deposition in the study area; this time corresponds to the deposition of the Lice Formation. The formation is represented by deep marine turbiditic clastic rocks. As it is summarized in Tuna (1973), the unit is first described and named in Schmidt (1958). The Lice Formation overlies the Fırat Formation conformably. The unit is exposed within a narrow zone, named Lice trough that is located in front of Miocene thrust zone (Rigo de Righi and Cortesini, 1964; Sungurlu, 1974). It is tectonically overlain by the Miocene nappes. The uppermost lithology of the Fırat Formation is clay-rich carbonates and they grade into gray marls and shales of the Lice Formation.

The eastern part of the study area, the Lice Formation was deposited in a rather shallow-water evaporitic environment, where deep marine turbidites are lacking. Yeşilova and Helvacı (2011) considered both the deeper marine shales and the evaporitic shallow-marine section as part of the Lice Formation. In previous studies, the evaporitic shallow-marine unit, which is depositional time equivalent of the Lice Formation, is referred as the Kapıkaya Formation (Perinçek, 1980). Later Siyako *et al.* (2013) named the shallow-marine evaporitic Lice as Kayabağlar Formation and also defined a carbonate deposition (up to 20 m) in the section along the Oyuktaş-Kurtalan Fault. The carbonate section is, however, accepted as part of the Fırat Formation in this study as none of the drilled wells penetrated such carbonate level within the Kayabağlar Formation. Also, B-1 well, drilled in 2013, cuts 13-meter-thick Fırat Formation (Figures 23 & 24), which also supports the contention that this carbonate section belongs to the Fırat Formation rather than the Kayabağlar Formation. The Lice Formation is concordant with the underlying Fırat Formation and overlying Şelmo Formation; it is composed of gypsum, marl, mudstone, siltstone,

sandstone and rare conglomerates (Figure 28). The present work considers evaporates of the Kayabağlar Formation as part of the Lice Formation. The samples were collected near Kayabağlar village from the clastic levels (carbonate-rich claystone, mudstone and marl) of the Lice Formation yielded the following fossils: ?*Artemisia*, *C. macrospecious*, *Cingulatioporites macrospecious*, *Cingulatisporites* sp., *Compositae (liquiliflorae-tip)*, *Compositae* tip pollen, *Dipsacaceae*, *Dinoflagellat*, *Dipsacaceae*, *Echinatisporis* spp., (from Eocene), *Ephedripides* sp., *Gramineae*, *Inaperturopollenites hiatus*, *Keriporopollenites multiporatus*, *Laevigatosporites haardti*, *M. gramineoides*, *M. tranquillus*, *Magnastriatites howardi*, *P. multiporatus*, *P. stigmus*, *Pityosporites* sp., *Polysphaeridium* sp., *Reticulatosporites austroclavidites*, *S. simplex*, *Sparganiaepollenites neogenicus*, *Spiniferites mirabilis*, *Tricolporopollenites* sp., *Umbelliferae*, *V. faus* and *Verucatosporites alienus*. The facies analysis and fossil content suggest a variety of deposition environments, including terrestrial, near shore, shallow sea and lagoon (?) (TPAO Research Center). The age of the Lice Formation is, based on the fossil assemblage, assigned as (Early–Middle) Miocene.

The Lower–Middle Miocene sediments of the Kapıkaya, Fırat and Lice formations are named as the Silvan Group (Tolun, 1960; Duran *et al.*, 1989). Following the deposition of the Lice Formation, continental conditions dominate the entire region and fluvial sandstones of the Şelmo Formation were deposited during late Miocene time. The Şelmo Formation was first named by Gossage (1957) and Bolgi (1961). The formation displays conformable contact relationship with the underlying Lice Formation and is (angular) unconformably overlain by the Lahti Formation in the study area (Figures 29 & 30). It is composed of reddish fluvial clastic rocks, such as conglomerates, sandstone and mudstones. It comprises two members: (i) alternation of sandstone and pebbly mudstone alternation with conglomerate intercalation (Uzunyazı member) and (ii) sandy-muddy conglomerate, cross-bedded sandstone and conglomerate-mudstone alternation (Atabağı member) (Güngör *et al.*, 2012). The coarse lithologies were deposited in a river environment while mudstones are referred to a flood plain.



Figure 28. Field view of the evaporitic Lower Miocene Lice Formation near Kurtalan, Siirt.

Plio–Quaternary Lahti Formation is composed of loose gravel, conglomerate, coarse sandstone and mudstones and overlains unconformably above all older formations. Like the Şelmo Formation, the Lahti Formation is composed of river deposits. The horizontal configuration of the formation is generally interpreted as suggesting that the formation has escaped from deformation. On the other hand, in areas where the Şelmo Formation is exposed within and around strike-slip faults, it is tilted and intensely deformed. The erosional plateaus and terraces of river courses is the most important indicator of the still continuing uplift of the region.



Figure 29. Field view showing relationship between the Upper Miocene Şelmo Formation red clastic rocks and underlying Early–Mid Miocene Lice Formation, Kozluk, Batman (courtesy of İsmail Bahtiyar).



Figure 30. Field view of the angular unconformity between the overlying horizontal Pliocene Lahti Formation and the underlying tilted Upper Miocene Şelmo Formation, Beşiri, Batman (courtesy of İsmail Bahtiyar used in Siyako et al., 2015).

2.2. Depositional System

After the deposition of the Aptian–Turonian Mardin Group carbonates, the Campanian–Paleocene succession started to develop as five different sequences that represent deposition during Middle–late Campanian, late Campanian–early Maastrichtian, Middle–late Maastrichtian, Early–middle Paleocene, and Late Paleocene time intervals, respectively. Each sequence starts with transgression and develops into regression; they therefore form unconformably divided successions if deposited in shallower parts of the basin, whereas deep sea equivalents of these sequences reflect rather continuum of sedimentation (Yeşilova and Helvacı, 2012).

Due to the compressional tectonism, which affected the region during Late Campanian–Early Maastrichtian time interval, a mountain chain of allochthonous units has uplifted in the north. Similarly, eastern and southern parts of the Southeast of Anatolia were also uplifted and emerged above sea level. This mountain range formed the site of erosion, eroded materials were transported to a fore-deep type of trough (the Kastel Formation) and formed turbiditic successions, while pelagic marls (the Bozova Formation) were deposited in more stable areas. When the Kastel trough was rapidly filled up, continental deposition (the Terbüzek Formation) took place with sea level fall. In the meantime, erosional products of calcareous terrain (the Kıradağ Formation) covered the platform areas and prograded with the fall in sea level (Güven *et al.*, 1991).

A new transgressive sequence started to form at the end of Early Maastrichtian, which lead the deposition of shallow-marine carbonates (the Besni, Garzan and Lower Sinan formations). The progressive sea level rise provided room for deposition of pelagic shales and marls (the Lower Germav and Üçkiraz formations). Slope deposits containing calcareous or siliciclastic turbidites (the Haydarlı and Lower Germav formations) were piled up in front of the carbonate platforms and along steep slopes. At the end of Late Maastrichtian, sudden drop in the sea level caused shallow areas to

expose to surface conditions; these areas therefore became source region for continental deposition (the Antak Formation) all over the region.

Another sea level rise started during Early–Middle Paleocene interval and led shallow-marine carbonate deposition (the Upper Sinan and Belveren formations) with evaporitic successions (the Kayaköy Formation) deposited in some parts of the basin. Deposition of pelagic shales, marls and turbiditic successions (the Upper Germav Formation) has continued in deeper parts and along continental slopes. Deltaic successions were deposited contemporaneously in the northern sections and prograded through south near basin center. Middle Paleocene regression has resulted in the deposition of evaporitic and continental deposits (the Kayaköy and Antak formations). Carbonate (the Becirman and Belveren formations) and delta platforms started to dominate when sea level has risen during late Paleocene. Red beds with evaporitic additions were deposited behind carbonate platforms and then prograded to the south. After Late Cretaceous, Southeast Anatolia shelf was deepened in the Campanian, then gained a new morphology during the Maastrichtian. The basin was filled up with carbonate and clastic sediments during transgressive and regressive periods and erosion from rapidly rising northern areas. Then basal clastic rocks (the Gercüş Formation) and platform carbonates (the Midyat Group) were deposited throughout the region during the Eocene transgression.

Early Miocene was the time for the onset of a new transgression period as marked by deposition of basal clastic rocks (the Kapıkaya Formation). The transgressive sequence continued with deposition of shallow-marine carbonates (the Fırat Formation), open marine clastic rocks (the Lice Formation), shallow-marine evaporitic-continental sediments (the evaporitic Lice or Kayabağlar formations) with changing paleo environments. Then, the area was the site of continental and fluvial clastic deposition (the Şelmo Formation) during late Miocene. The study area is evaluated, based on data from surface mapping, wellbores and seismic interpretation study, in two different generalized stratigraphic sections (Figures 31 & 32).

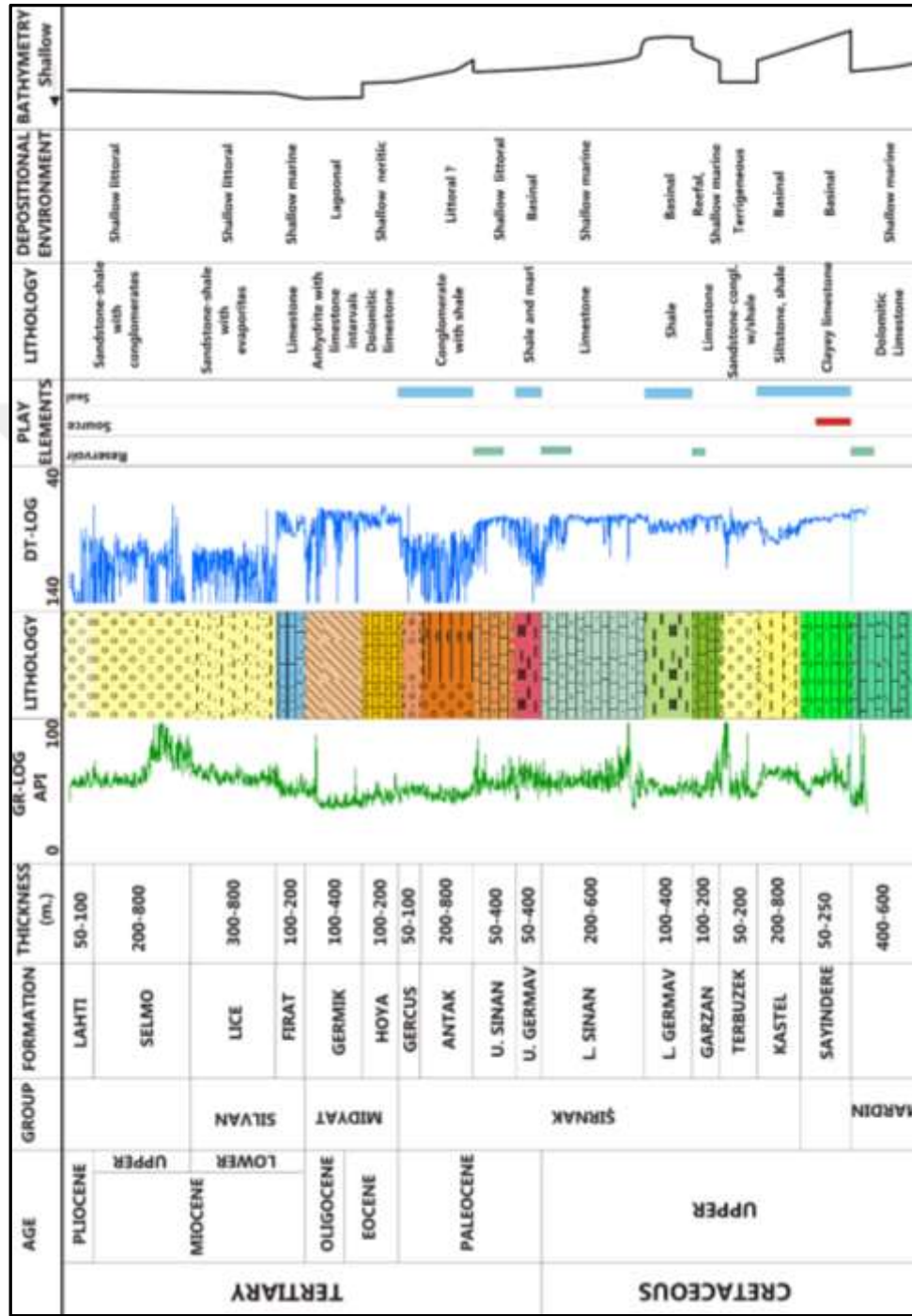


Figure 31. Post-Mardin Group (since Late Cretaceous) generalized stratigraphic section of western part of the study area.

The Mardin Group averages 500 m in thickness and consists of limestones and dolomites; it was deposited almost homogeneously within the study area and neighborhood. Small heterogeneities in reservoir characters stem from secondary diagenetic alterations, such as dolomite generation under deeper burials or right after deposition or karstic porosity developments. This unit has mostly been penetrated in the wells drilled as it forms one of the potential reservoir rocks in the region. It is overlain by another carbonate section (the Beloka Formation) and is interpreted as a reservoir rocks in the central part of the study area. The carbonates are overlain by a clastic sequence in the north and northwest; it has a cap rock and source rock potential (the Sayındere Formation). There are also productive wells from the Beloka Formation porous and permeable carbonates in eastern part of the seismic data. The total reservoir section of the Beloka formation carbonates ranges from 5 m to 15 m.

The Kıradağ Formation comprises sandstone and conglomerates in the northwest but thins and then disappears in the southeast; it becomes a condensed section in the Garzan Formation carbonates towards southeast. This shows that the possible direction of sediment supply was from north and northwest. The Kıradağ and Garzan formations base levels present the cap rock potential for the Beloka Formation. The uppermost part of the Garzan Formation (top section) has a reservoir potential and forms a productive zone in eastern part of the Kozardere 3D seismic data. The reservoir quality depends on fault-related paleo-highs that creates localized high energy environment for carbonate build-up development. The thickness of the Garzan Formation ranges between 100 m and 200 m. After the deposition of the Garzan Formation, sea level deepened during which shale and marls of the Germav Formation started to deposit. The deeper marine deposition was disrupted by carbonate sedimentation in response to sea level changes especially in the western part of the area (the Sinan Formation carbonates). There might be a structural control on this event. Then, terrestrial conditions dominated these environments and thick continental clastics of the Gercüş and Antak formations were deposited. The thickness of this unit is rather uniform throughout the study area. The Eocene–Oligocene section is represented by evaporates and dolomites and thickens towards southeast. The

Miocene sequence commenced with basal conglomerates of the Kapıkaya Formation, and continued with shallow-marine carbonates of the Fırat Formation, and then evaporitic and clastic sediments of the Lice and Şelmo formations. Lower Miocene Lice Formation, contains sandstones and claystones with evaporitic contribution.

The continuum of clastic sedimentation is illustrated by transitional contact between the underlying Middle Miocene Lice Formation and Upper Miocene Şelmo Formation (fluvial deposits). At the top, Plio–Quaternary Lahti Formation alluviums and Quaternary basalts cover the study area. The major regional unconformities occur at top Paleocene and base Miocene. There are also numerous disconformities and depositional gaps within the sequence, such as top Kıradağ, top Beloka formations, and top Mardin Group. Sinan, Garzan, Beloka formations, and Mardin Group are the main reservoir rocks. The main seal/cover rocks are the Antak and Germav formations, while the Sayındere Formation (lateral time equivalent of the Beloka Formation) is the source rock of oil in this region.

2.3. Revised Stratigraphy of the Study Area

During the Campanian and Maastrichtian while pelagic sequences (the Sayındere and Kastel formations) deposited in the deeper parts of the foreland of Arabian Plate, the shallow-marine carbonates (the Beloka Formation) are deposited in the higher parts (forebulge). The study area in the Late Maastrichtian was characterized by sediments of alluvial-fluvial quality (the Antak Formation) in the northwestern areas, while marine facies have been deposited in the southeastern part. The study area is located on the coastal parts of this sea, thus the carbonate sediments dominate (Garzan and Alt Sinan formations) rather than turbiditic/calci-turbidic sequences (Üçkiraz and Germav formations) observed on the east. Continental sediments (Antak Formation) dominated due to the elevation in the northern areas during the Paleocene period, while turbiditic systems (Upper Germav Formation) were deposited in the deep sections of the basin (south). In the Late Paleocene, the

basin became shallow and terrestrial deposits prograded through sea. The system continued with sediments (the Upper Germav Formation), shallow-marine carbonates (Upper Sinan / Becirman Formation), and fluvial-playa (Gercüş Formation) sediments. The entire region gained platform character and the transgression starts in the Lower Eocene. On this platform, firstly massive carbonates (Hoya Formation) were deposited and these units passed through evaporitic deposition (Germik Formation) due to the shallowing of the basin. In the study area, during the Early Miocene, when the closure of the Neotethys gained speed with the placement of the allochthonous nappes, the new transgressional period starts with alluvial-fluvial sediments (Kapıkaya Formation). During this time, the flysch character units (Lice Formation) were deposited in the pit areas of the developing basin (northwest), while the reefal carbonates (Fırat Formation) and the playa facies (Lice evaporitic) were deposited in the shallow parts (southeast). Alluvial-fluvial sediments (Şelmo Formation) from the Middle–Late Miocene have been completely filled basins and then alluvial clasts have been deposited in alluvial basins due to new tectonic regime in the continental-continental collision zone. Also, the volcanic activity gained efficiency through region and volcanics spread around by many ways such as flooding river beds.

The study chronostratigraphy has been framed in-between Cretaceous, the deposition of the Mardin Group (~113 Ma, Late Aptian), and recent. The generalized stratigraphic sections of the western and eastern parts of the study area are shown in Figures 31 and 32. The main difference among two regions can be summarized as (i) the eastward thinning of the Paleocene Upper Sinan and Cretaceous Lower Sinan members; and (ii) the deposition of the deeper marine Kastel and Sayındere formations in the Habandere sub-basin located in west.

The Cretaceous succession commenced with the Mardin Group and continued with the deposition of the Sayındere Formation in the west, and the Beloka Formation in the east. The Beloka limestone is overlain by the shales and marls of the Kastel Formation in the west, and shales and sandstones of the Kıradağ Formation in the east.

The Kıradağ Formation is thicker in the west and represented by sandstone, conglomerate and shales, named as the Terbüzek Formation; it is overlain by the Garzan Formation in the whole study area. The Kıradağ Formation has an eastward thinning trend. The Garzan limestones are overlain by time equivalent shales and marls of the Germav Formation. The Germav Formation is interbedded with the Sinan Formation. Paleocene succession starts with the Upper Germav Formation, which is overlain by the Upper Sinan Formation limestones, and then continues with clastics of the Antak Formation. The Antak Formation is overlain by conglomerates of the Gercüş Formation; it is overlain by the Eocene–Oligocene Midyat Group. The Midyat Group is composed of the Hoya Formation dolomites and limestones, and then top Germik Formation evaporates and shales. Miocene units starts with basal clastics of the Kapıkaya limestone and continues with the Lower–Middle Miocene Fırat Formation limestones and then with the Lice Formation evaporitic sandy units. Upper Miocene is represented by the Şelmo Formation clastic section. At the top, the Plio–Quaternary Lahti Formation alluviums cover the study area.

2.4. Well Log Correlation

Digital logs of four wells in the 3D survey area and one well from outside the surveys have been used in this study (Figure 33). All of the wells have caliper, gamma-ray, and sonic porosity logs. The stratigraphic markers have been picked in the well logs with the help of drilling cuttings from composite well sections generated by TPAO (Figure 34).

The well log correlation is very important to determine the structural and stratigraphic distribution in time and to prepare the structural cross sections. Gamma-ray (GR) and sonic porosity (DT) well log correlation of the five wells reveal a pronounced change from northwest to southeast across the region (Figure 35). From northwest to southeast these wells are K-1, KP-1, BA.-1, A-1 and B-1 (Figure 33).

The distance between wells is also shown in correlation. The vertical scale is in 1 cm to 100 m. GR log is located on the first track, stratigraphy is on the second and DT log is located on the third track (Figure 35). All the well log data have been loaded in Petrel 2016 and well tops have been interpreted by using Software's Well Correlation module.

After picking the formation tops, wells are automatically correlated by flattened from sea level. Yellow colored section represents the Miocene package, Oligocene–Eocene is red, Paleocene is green, and Cretaceous is blue (Figure 35). While the Miocene and Cretaceous packages have a thinning trend to southeast, the Eocene–Oligocene and Paleocene section become thicker. The difference is attributed to activity of the major fault systems. For example, the Kumlupınar Fault is located between Ko-1 well and other wells.

Thus, both the Miocene section and Cretaceous units are thicker and also lithologically different than other wells in the east. B-1 well, which is located outside of the study area, does not have the Upper Miocene Şelmo Formation as it is next to the Oyuktaş-Kurtalan Fault System and close to the Eski Garzan-Reşan Anticline crest.

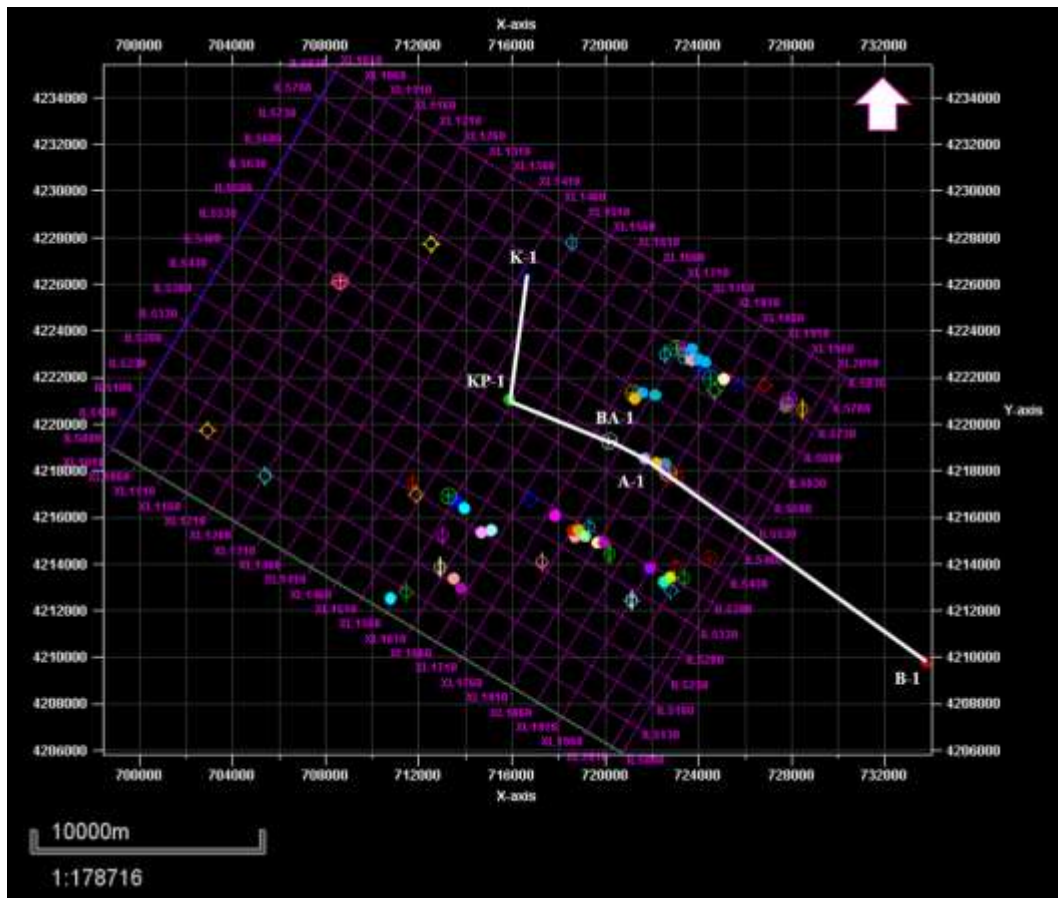


Figure 33. 2D Map view showing 3D survey profile and wellbore locations, the well correlation path shown in Figure 35.

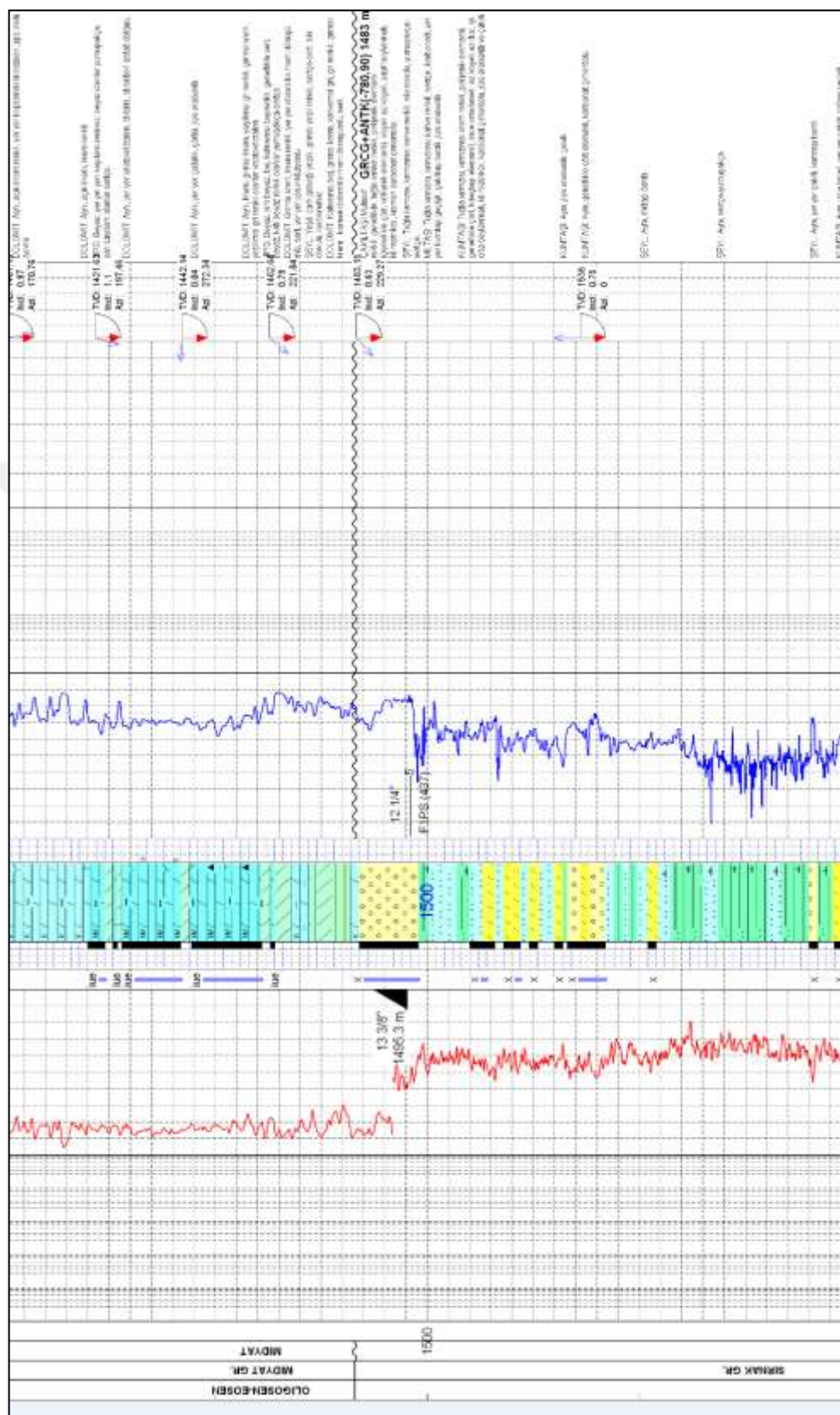


Figure 34. Example from a partial composite section of A-1 well (TPAO database) showing GR log (red), lithology, and DT-sonic log (blue).



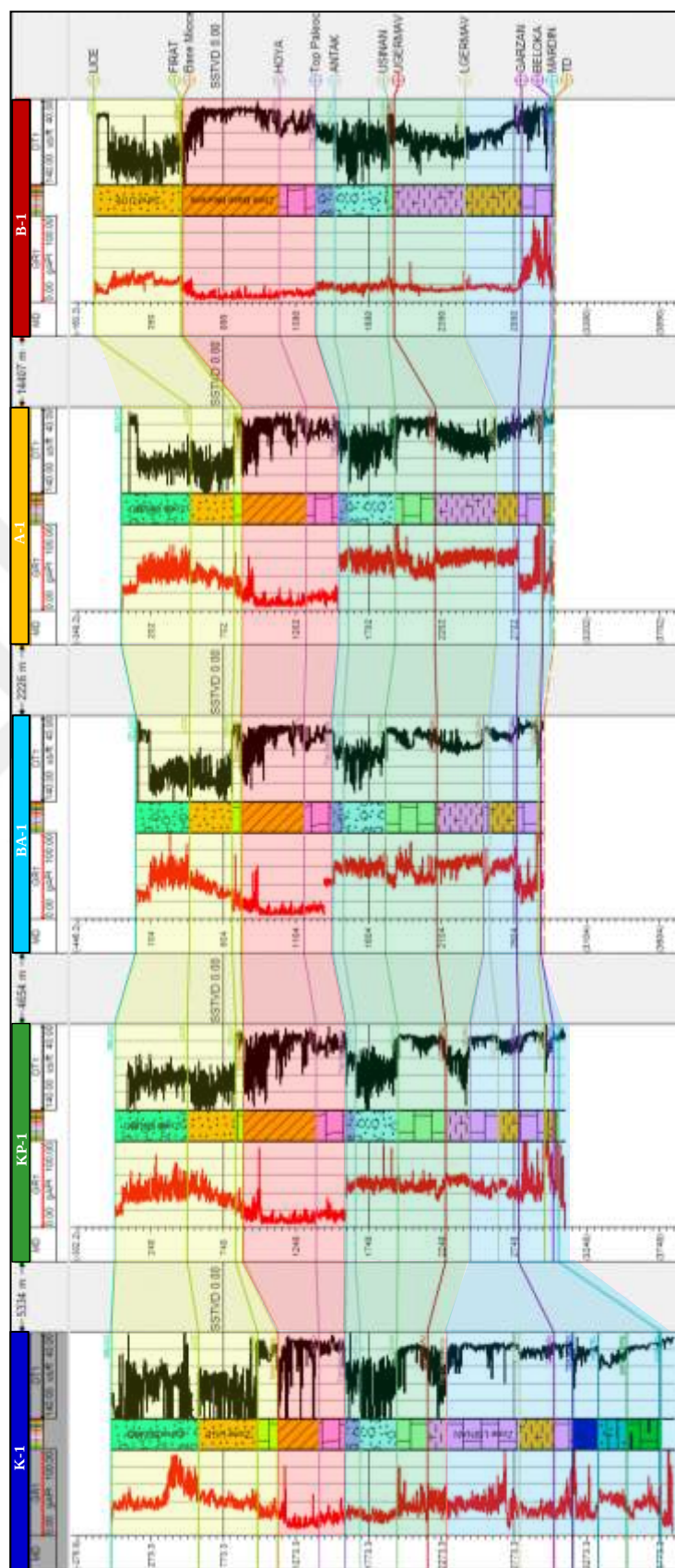


Figure 35. NW-SE-directed GR-DT well-log correlation in the study area. Yellow horizon represents the Miocene package; Oligocene-Eocene is red, Paleocene is green, and Cretaceous is blue in color.



2.5. Discussion

As it is shown in the generalized stratigraphic columnar section of Southeast Anatolia, the Lower Miocene Lice Formation is represented with deep-marine turbiditic facies (Figure 36). It is deposited in a narrow belt, which developed in front of the Miocene allochthonous units around Lice-Kulp (Rigo de Righi and Cortesini, 1964; Sungurlu, 1974). This unit has taken its material from the allochthonous units of uplifted area in the north. The basin starts with clayey, sandy and fossiliferous limestones, alternating with thin shale / marl and silt levels. The turbiditic sandstones and shales that overlie them form the main section of the formation. Starting with fine-bedded divergent turbidites, this section coarsens upward and migrates to convergent turbidites and channel conglomerates (Sungurlu, 1974; Aıkbař and Bařtuę, 1975; Perinek, 1978b; Prosecutor and Dlger, 1980).

Through southeast thinner, shallower water sediments become dominated, and the Lice Formation is represented by marls and shales near Silvan-Malabadi. In the study area, southern Kozluk evaporitic, lagoonal, and then fluvial environment begins to emerge (Figure 36). Another important aspect is the deposition of the first product of the Miocene transgressional event called the Kapıkaya Formation. Lithologically, about 30–50-meter-thick Kapıkaya Formation commences with erosional materials from especially the Germik Formation and consists mainly of conglomerates, sandstones and mudstones. The carbonate ratio increases towards the upper levels and then grades into the carbonates of the Fırat Formation. The Eocene–Oligocene deposition starts with Lower Eocene basal clastics of the Gercř Formation in the study area. The Midyat Group consists of Kavalky, Hoya, Gaziantep, Havillati and Germik formations, which show both lateral and vertical passages to one another. The Lower Eocene–Lower Oligocene and locally chert-containing fossiliferous subfacies deposited near shelf edge (Duran *et al.*, 1988, 1989).





Middle Eocene–Oligocene dolomitic intercalated evaporites of the Germik Formation are abundant unit in the study area. Around Adıyaman-Gaziantep region, the same unit is called the Gaziantep Formation, which is composed of conglomerate, marl and clayey limestones. The Germik Formation display discordant relationship with the overlying Kapıkaya Formation. The basin analysis studies demonstrated that the maximum oil generation and migration of the region occurred during Middle–Upper Miocene time after the Miocene overthrusting (Akçay *et al.*, 2009). In this study, the petroleum system is interpreted according to the burial history of K-1 well, which was drilled in the deepest part of the basin in the modeled area (Figure 33, 37). According to this study, the Mardin Group settled with a slow sedimentation between 113 Ma and about 81 Ma. After that date, the rate of burial/deepening of the basin has accelerated and the source, reservoir and seal rocks were all deposited between 81 Ma and 50 Ma. Between about 50 Ma and 15 Ma the burial rate began to slow down; by then another period of sudden burial commenced. The erosion has started by 7 Ma BP and still continues. In Ko-1 well, the hydrocarbon generation in the source rock has started at ca. 12 Ma and then continued with expulsion after saturation at ca. 9 Ma (Akçay *et al.*, 2009) (Figure 37).

This result emphasizes the importance of re-evaluating the geological and structural development of the region. The field observations were therefore concentrated on the Miocene and Paleocene successions and related structural features. The major transgression occurred during Middle Eocene time, by the Late Eocene regression started to be effective in both the study area and all over the Southeast Anatolia (Duran *et al.*, 1988). The facies associations demonstrates the effects of north through south migrating sea as demonstrated by shallowing carbonate deposition in the same direction. The regressive deposition continued until Late Oligocene time and while the succession continued with shallow-marine carbonate deposition in the western part of Southeastern Turkey; evaporitic and dolomitic units were deposited in the eastern section, including the present study area. There is an erosional contact between the Midyat Group and the Silvan Group carbonates (Duran *et al.*, 1988; Perinçek *et al.*, 1991).

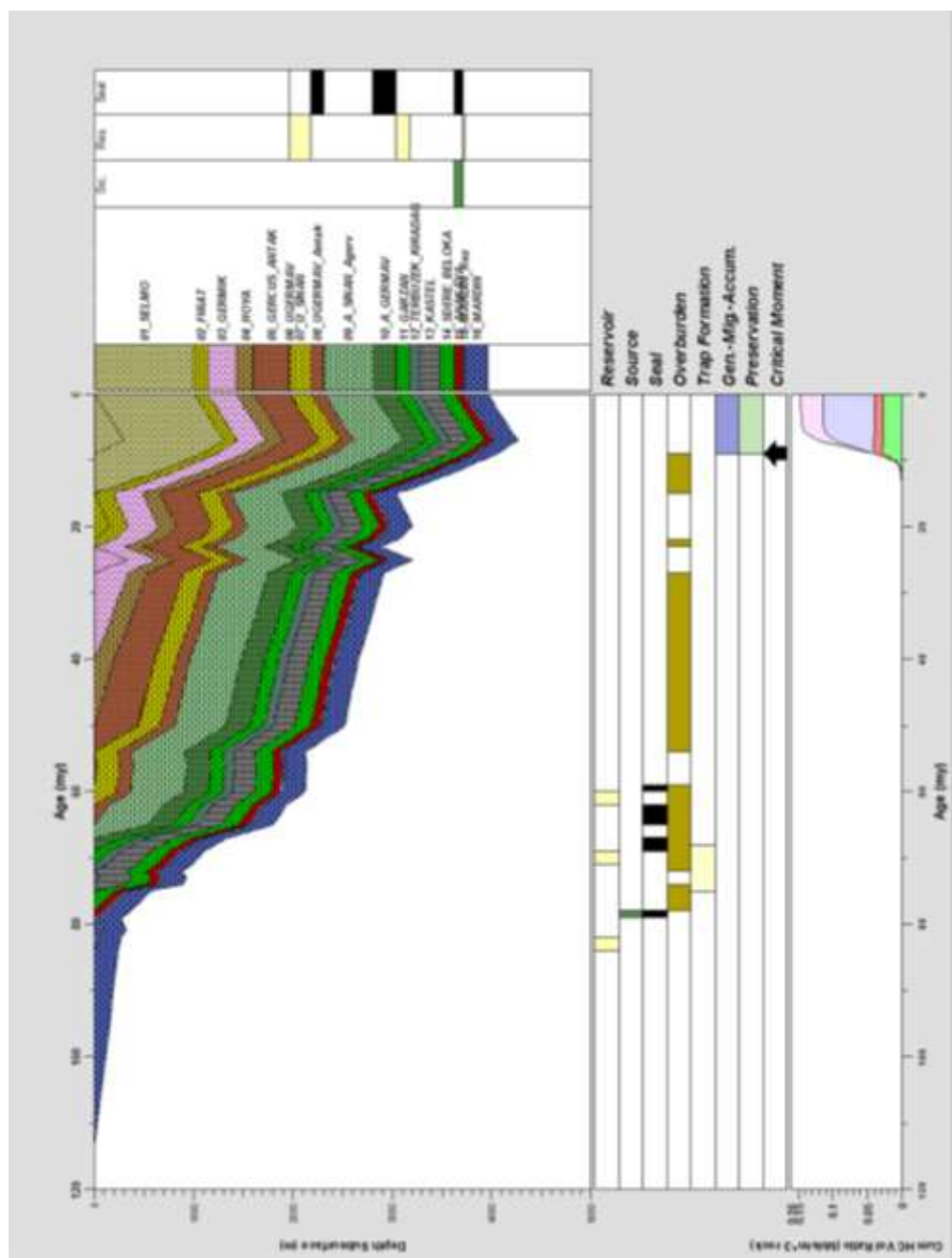
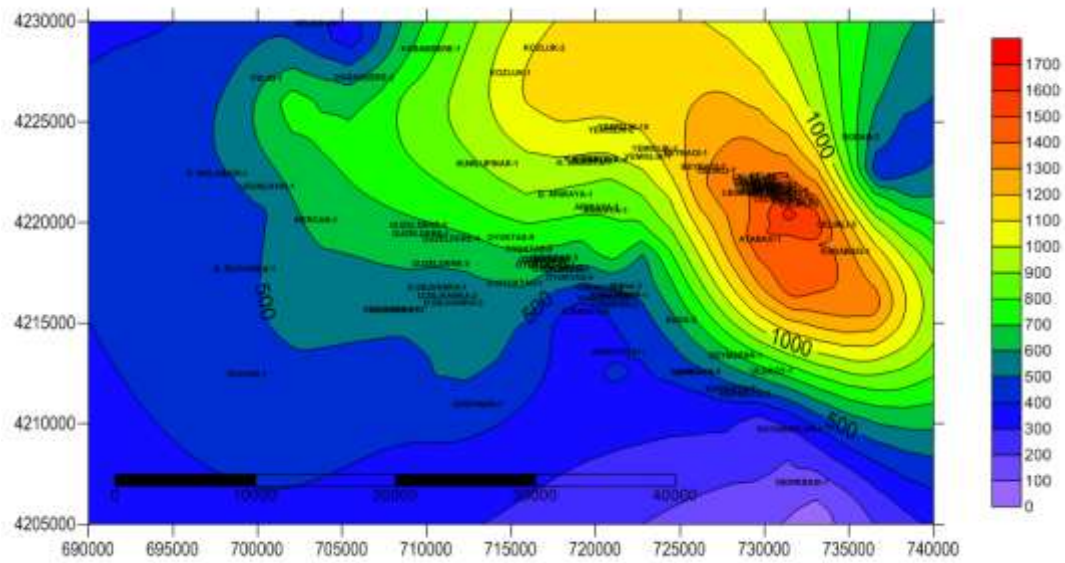


Figure 37. Burial history and petroleum system of the K-1 well (Akçay *et al.*, 2009).

Near Lice-Ergani and eastern Siirt, the deepening Fırat Formation is overlain by the turbiditic facies of the Lice Formation. Along the Hazro-Siirt trend, the evaporitic fluvial Lice Formation overlies the Fırat Formation. While the Eocene–Oligocene succession is composed of characteristic regressive Midyat Group units all over the Southeastern Turkey, the lithology of the Lower Miocene Silvan Group varies from one region to another. The dramatic changes of the Miocene depositional environments indicate severe tectonic influences during this time. Perinçek (1980) stated that the intense deformation has started during Middle Miocene in the west (Maraş-Gölbaşı area) of SE Anatolia and continued until the end of Late Miocene in the east (Siirt-Baykan area). Duran et al. (1987) interpreted, based on rock and clay mineralogy of the Lower Miocene Lice Formation, that content of korensit and serpentine minerals were most probably sourced from erosion of the ophiolitic Miocene allochthonous.

Figure 38a, prepared from the wells given in Figure 33, illustrates variation in the thickness of the Miocene succession (up to 1700 m.) through study area and surroundings. The thickness increases towards northeast and it is perpendicular to major Miocene NW–SE structural trend. The map also indicates dramatic thickness change along Oyuktaş-Kurtalan fault zone. Figure 38b, prepared from the wells given in Figure 33, shows the thickness variation of the Eocene–Oligocene succession (the Midyat Group) throughout study area and its neighborhood; it ranges between 280 m and 700 m. The thickness is about 580–700 meters in the most part of the study area, except for the northeastern part, which seems to be controlled by the faults.

(a)



(b)

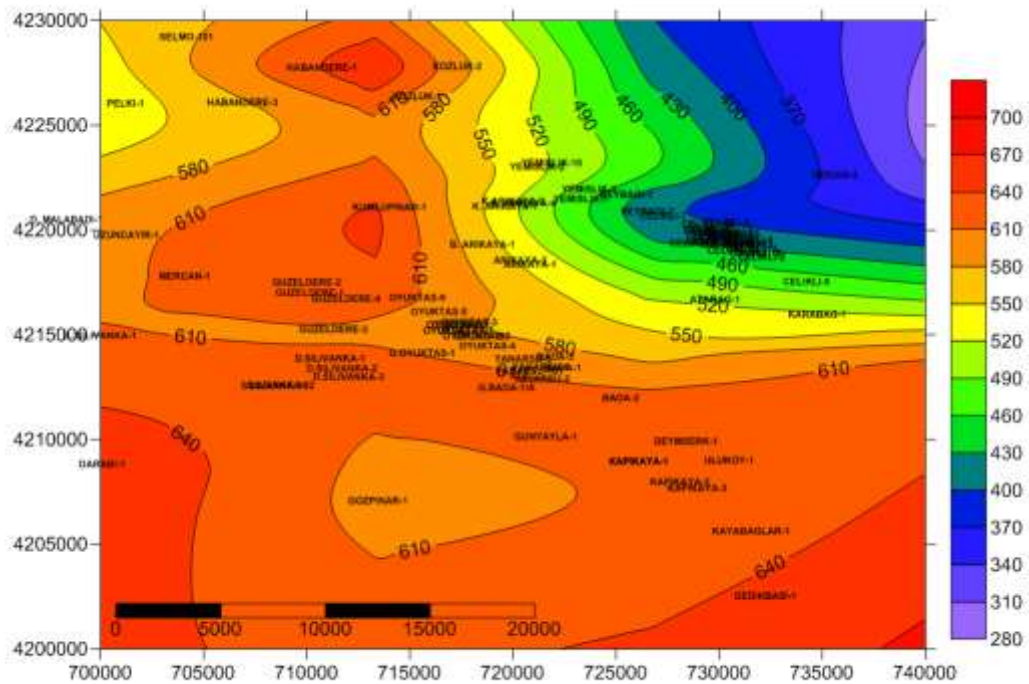


Figure 38. (a) Maps showing variations in thickness of the Miocene and (b) Eocene–Oligocene successions (Midyat Group) throughout the study area and its surroundings.

CHAPTER III

STRUCTURAL SETTING

The continental collision of the African-Arabian Plate with the Eurasian Plate resulted in a tectonic complexity in eastern and southeastern Anatolia. The complex geology of the region is expressed by several tectonic units: (i) the eastern Rhodope-Pontide Arc in the north; (ii) the East Anatolian Accretionary Complex, consisting of an ophiolitic mélange and overlying Paleocene to upper Oligocene sediments; and (iii) the Bitlis-Pötürge Massif tectonically above the northern part of the Arabian margin (Figure 1) (e.g., Şengör and Yılmaz, 1981; Yılmaz 1993; Robertson, 2000; Şengör *et al.*, 2003; Agard *et al.*, 2005). The continent-continent collision zone between Arabian Plate in the south and Eurasian Plate in the north is marked by zone of high strain and rapid uplift, and is represented by an areally extensive deformation zone along the Bitlis-Zagros Suture Zone; the present-day convergence rate is ca. 18 ± 2 mm/year (McClusky *et al.*, 2000). Bitlis-Zagros fold and thrust belt trends roughly northwest–southeast and accommodates the convergence by widespread thrusting and folding (Figure 2). Along the northern Arabian margin, the Zagros becomes the uplifted belt of the Eocene–Miocene Bitlis Suture of the Eurasian and Arabian plates (Hempton, 1985). This collision manifests the active transform and convergent plate boundaries that currently surround southeastern Turkey (Figure 1). To the northwest of the Arabian Plate, the Mio–Pliocene active strike-slip fault zones, namely the right-lateral North Anatolian and the left-lateral East Anatolian fault zones accommodate westward movement/escape of the Anatolian Plate from the convergence zone (McKenzie, 1970). The two major structures meet in the Karlıova in eastern Turkey. The overall convergence between Arabia and Anatolia is taken up motion along these strike-slip fault zones.

Similar to the East Anatolian Fault, the north–south-striking Dead Sea Fault Zone is located on the south, and extends as far as the Red Sea in the south, and forms

the boundary between Arabian Plate in the east and the African Plate in the west. It is a sinistral transform fault and accommodates differential northward motion between these plates. There also several other strike-slip faults in Southeast Anatolia, such as the Kozluk-Narlı Fault, Oyuktaş-Kurtalan Fault, Çelikli Fault, Bozova Fault, Adıyaman Fault Zone, Lice Fault, Kalecik Fault and Şemdinli Fault Zone. There are also structural highs, like Mardin and Hazro and they are all aligned parallel to NW–SE-oriented Bitlis-Zagros collision zone (Figures 2 & 10).

The study area is in the fold and thrust belt zone located on the foreland area of the Bitlis-Zagros Suture Zone to the north of the Arabian Plate (Açıkbaş *et al.*, 1981). The area has been experiencing intense deformation during several phases since the Paleozoic time and is therefore characterized by several structural elements. The present morphology is the manifestation of deformation commences at the end of the Miocene and during the Pliocene. The Miocene allochthonous units are exposed about 7 km further north of the study area. Although the Bitlis-Zagros trend has been considered as one continuous orogenic belt, there are major contrasts in structural style in different parts of the belt due in part to the nature of the lithologic packages involved and in part to differences in the tectonic levels exposed at the surface.

Faults, anticlines and fault-related monoclines form the major structural elements of the study area and trend parallel to (similar) structures within the Bitlis-Zagros Suture Zone. Major folds are Dodan, Hazro, Garzan-Germik, Kentalan, Reşan, Şelmo, West and East Raman anticlines. Many anticlines are characterized by fold axes trending in northwest–southeast direction parallel to the Bitlis-Zagros Suture Zone but there are also east–west-trending anticlines (such as East Raman and West Raman anticlines) as well. The anticlines vary in geometry; the Şelmo anticline display a very low structural relief at the surface, while the Dodan anticline, in contrast, is marked as a high sharp feature (Figures 2, 3 & 39).

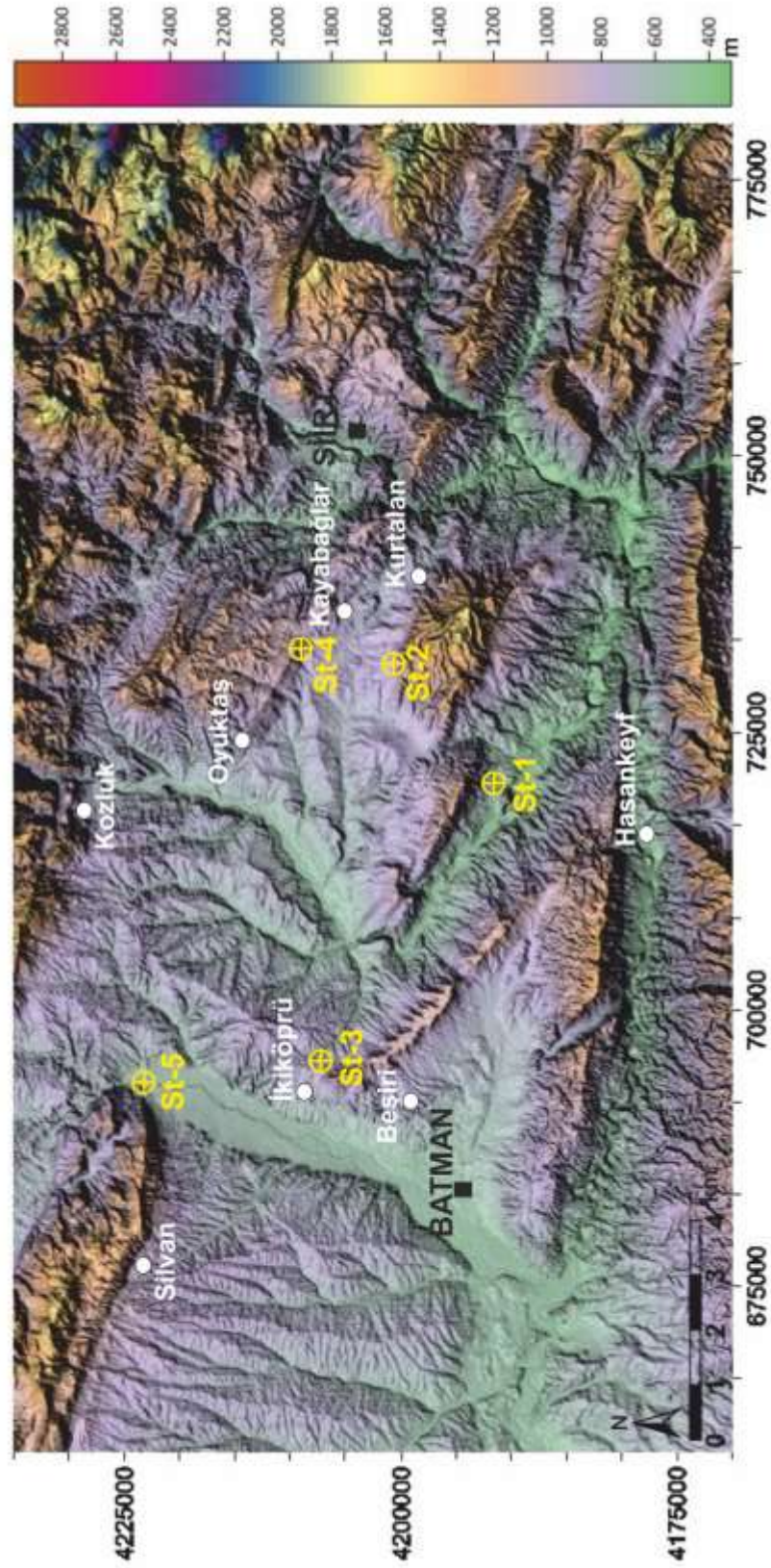


Figure 39. Digital Elevation Model (DEM) of the study area and its surroundings. The elevation ranges between 400–2400 meters. The yellow ones represents field observation stations, white dots show towns of cities Batman and Siirt.

The folds vary in length, some being little more than elongate domes while others can be traced for up to 50 kilometers along fold axis. Most folds are overturned toward south with a few exceptions. Eski Garzan-Reşan Fold forms one of these exceptions. These folds have been interpreted as flexures on north-dipping reverse faults rooted in the basement (e.g., Perinçek and Çemen, 1991; Bozdoğan and Erten, 1990). The northwest-southeast-trending Hazro uplift (anticline) forms the major structural element located in northwest of the study area (Figure 2). The prominent morphological elements, such as Kozluk-Narlı Fault Zone, Oyuktaş-Kurtalan Fault Zone, Çelikli Anticline, west banks of the Reşan and Dodan Anticlines, are visible in DEM data (Figures 2, 39).

In the northern part of the study area (Kozluk, Batman), the Miocene thrust front is placed further south than the Cretaceous thrust front (Figure 2 & 3). West of the Sason River valley (Hazro uplift and its western section) the autochthonous section is marked by well-developed anticlines with thrust or reverse faulted southern flanks. The deformation pattern becomes complex through west. The Çüngüş wildflysh cover its overlying Bitlis-Maden sedimentary package and steps back to the north and there is evidence that it never did advance over the Hazro uplift fold complex. Movement of the plate was motivated by gravity and was accomplished partly by detachment and shear at the top of the Çüngüş and partly by shear at the Çüngüş-Lice contact. As the allochthonous plate moved, becomes broken and rafts on the ductile flysh, much like floating ice floes. The pile-up of the mountain front indicates that this is also the structural front and that the Bitlis thrust probably did not once continue southward over the anticlines of the foothills belt. The present mountain front is not simply a topographic scarp formed by retreat of the eroded edge of the Bitlis-Maden thrust plate, but is the exhumed structural front marking the farthest southward advance of the thrust (Figure 2).

The data gathered from almost 15 wells indicate that the Lower Miocene Lice Formation underlies the Çüngüş Flysch unit in the thrust zone. The Lice Formation evaporitic salty units was deposited in the northern and northeastern parts of the study

area, while deeper marine sediments along the western section. Figure 40 shows the reverse relationship between the thickness of salt, which acted as a detachment surface and flysch above. The data is collected from wells drilled on allochthonous region. The graph indicates the mobility of salt with the increasing thickness of the flysch pile. Upper Miocene Şelmo Formation and Plio–Quaternary Lahti Formation is located on south right in front of the allochthonous section, the thrust zone.

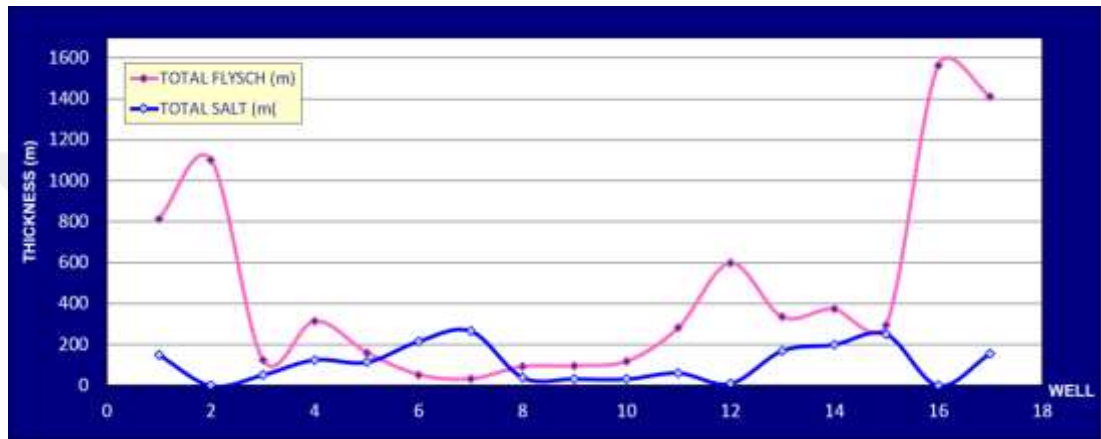


Figure 40. The comparison between total thickness of the salt of evaporitic Lice Formation and the Çüngüş Formation flysch (data is taken from drilled wells of TPAO).

The Kozluk-Narlı Fault Zone is located in the north of the study area. It is characterized by several branching and discontinues strands along the mountain front in the area between Sason River in the west and Dodan Anticline in the east (Figure 2). The segments of the fault zone are marked by deformation of the Şelmo Formation where beds are sharply up-turned to a vertical attitude (Masson, 1986).

The ‘Eski Garzan-Reşan Anticline’, the main structural element of the study area, starts around east of N–S-trending Garzan River and runs eastward outside the study area. Its apparent length is about 50 km and only 12 km western part is located in the study area (Figure 2). The NW–SE-trending anticline is conformable with the regional structural trends. N–S-trending Başur River cuts through the anticline and expose rock units within this structure. While the Paleocene units outcrop in the core,

Eocene, Oligocene and Lower Miocene units occur in the flanks. The core of the anticline is however located outside the study area. The NW–SE-trending Oyuktaş-Kurtalan Fault is related with the northern flank of the Eski Garzan-Reşan Anticline (Figure 2). The field observations on these major structural elements will be summarized in the following sections.

3.1. Field Observations

Field observations were made to investigate especially the Oyuktaş-Kurtalan Fault, the Çelikli Fault, the Kozluk-Narlı Fault Zone and related outcropping units (Figure 41) along road cuts in the area between the towns Beşiri and Kurtalan, then from Kurtalan through Kozluk. The Oyuktaş-Kurtalan Fault is a strike-slip fault with a normal component and trends in WNW–ESE direction (292°N). It has a pronounced morphological expression and runs mostly within the Şelmo Formation but there are areas where juxtaposition of several different units marks the location of this structure: juxtapositions of the Şelmo-Lahti formations, the Fırat-Lice formations or the Lahti-Lice formations. The fault also cuts and displaced the Eski Garzan-Reşan anticline. The dextral nature of the fault zone is, based on the seismic data, recognized for the first time during this study.

The Çelikli-Habandere Fault is a dextral structure trending in 295°N. It runs within the Şelmo Formation. The surface expression is limited and the fault is mainly recognized in seismic sections. The dextral nature of this fault also is recognized during this study. Kozluk-Narlı Fault is a subvertical NW–SE-trending (300°N) dextral fault. The western part starts from north of Silvan and forms the southern boundary of the allochthonous units (Figure 41). The fault zone runs through the Şelmo Formation but in places it is marked by the juxtaposition of the Lice Formation in the northern footwall and the Şelmo Formation in the southern hanging wall blocks. The fault zone is also marked by salt extrusions at several locations along Diyarbakır-Bitlis highway. Dextral nature is defined by Perinçek *et al.* (1987).

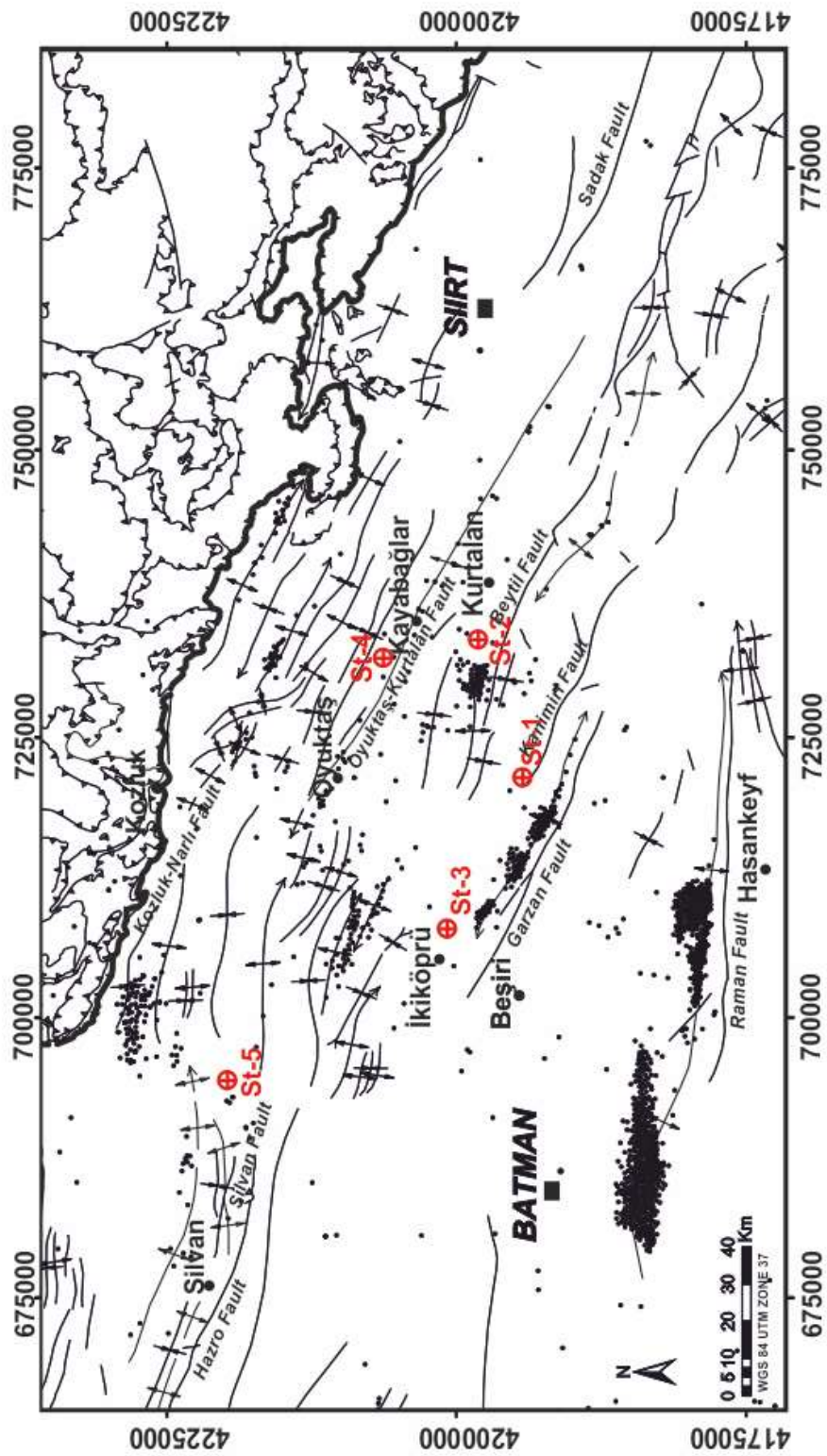


Figure 41. Location map showing field study observation stations (red), major faults and drilled wells near Batman and Siirt. The black dots are drilled wells. The trends of the oil fields are parallel with major faults and mostly trending NW–SE.

The Kozluk-Narlı Fault comprises several branching and discontinues strands along the mountain front from the Sason River to Dodan Anticline (Figures 2 & 41). Horizontal and/or gently dipping Şelmo Formation sands become tilted and then vertical abruptly within the fault zone. Main fault is traced by brine springs and gypsiferous soil in most places. In profile, the fault zone is recognized as a closed anticline.

Previous studies reported fault planes with strong coarse horizontal slickenline in vertical sand beds; chatter marks on fault planes indicate right-lateral shear at a locality north of study area (Kozluk, Batman). The salt horizons that belong to the Lice Formation are exhumed and exposed along and within the fault zone; most salt occurrences are exploited by locals. The Kozluk-Narlı Fault segments are located in the north of study area and belong to a right-lateral fault system, which runs for about 300 km along strike (Perinçek *et al.*, 1987). The Kozluk-Narlı Fault is detected as a vertical fault located in front of the onset of allochthones over thrust units in 2D seismic sections.

The observations at the field stations are mostly concentrated around and along large faults. These faults are NW–SE-directed Oyuktaş-Kurtalan Fault, Kanimiri Fault, Silvan Fault and Beytil Fault. The field observations have been conducted in five stations (Figures 41). The deformation along the Kanimiri Fault is well expressed along Batman-Siirt highway road cut (Station 1). The Kanimiri Fault is a N60°W-trending fault and is tracked on the surface near the southern boundary of the Kentalan Anticline (Figure 41). There, there are several small-scale normal faults mapped in this particular location and they all occur within the Upper Miocene Şelmo Formation (Figure 42).

Fault segments are characterized by smooth, polished and fresh slip surfaces; most planes strike in NW–SE and dip northeast or southwest and define a well-developed conjugate fault pattern. The parallel fault segments have an overall strike ranging between 225°N and 348°N and average dips of between 52° and 73°NE or

SW (Table 4). The data from the striated slip surfaces are analysed in order to determine the kinematics of the faulting. Analysis are performed by using the stress inversion method of Angelier (Angelier, 1984, 1991, 1994), and computed using the software T-Tecto 3.0 developed by Zalohar and Vrabec (2007). The computed results of the inverse analysis of fault-slip measurements define almost horizontal σ_1 (02°) but steeply plunging (almost vertical, 86°) (Figure 47).



Figure 42. Field view of normal faults in the Upper Miocene Şelmo Formation along the Batman-Siirt Highway road-cut. Note that conjugate normal faults define an outcrop-scale horst-and-graben structure (Station 1).

An inverted fault can also be observable along the road-cut on Batman-Siirt highway near Gürgöze Village (322°/44°E 78°N; strike/dip amount and direction, rake) at Station 2 (Figure 43). The deformation pattern is marked by the displacement of the Upper Miocene Şelmo Formation clastic layers first by normal then reverse component along the fault. This fault can be related with the Beytil Fault, which also controls the northern boundary of the Kentalan Anticline. There are numerous faults observable near the western end of the Kanimiri Fault at Station 3. These faults are both observable in the Şelmo and Fırat formations (Figures 44 and 45).

There are also both syn-sedimentary and post-sedimentary deformation patterns observed within the Upper Miocene Şelmo Formation in the study area (Figure 46). The fault-plane measurements major trend is NW–SE as observed in stereoplots (Figure 47). The details of the measurements are shown in Table 4.

The Oyuktaş-Kurtalan Fault can be best observed near Kayabağlar Village (N68°W/75° NE). The Lower Miocene Fırat Formation (Tf) carbonates in the foreground occurs on the southern block and NE–SW-trending Lice (Tl) and Şelmo (Tş) formations are exposed along the fault zone. These units dips to 45–55° to northeast along fault zone (Figures 48–54). Seismic sections also confirm the geometry of fault and tilted beds (Figures 51 & 52).



Figure 43. Field view from an inverted fault in the Upper Miocene Şelmo Formation, near Gürgöze village, Kurtalan (322°/44°E, 78°N). (Station 2).

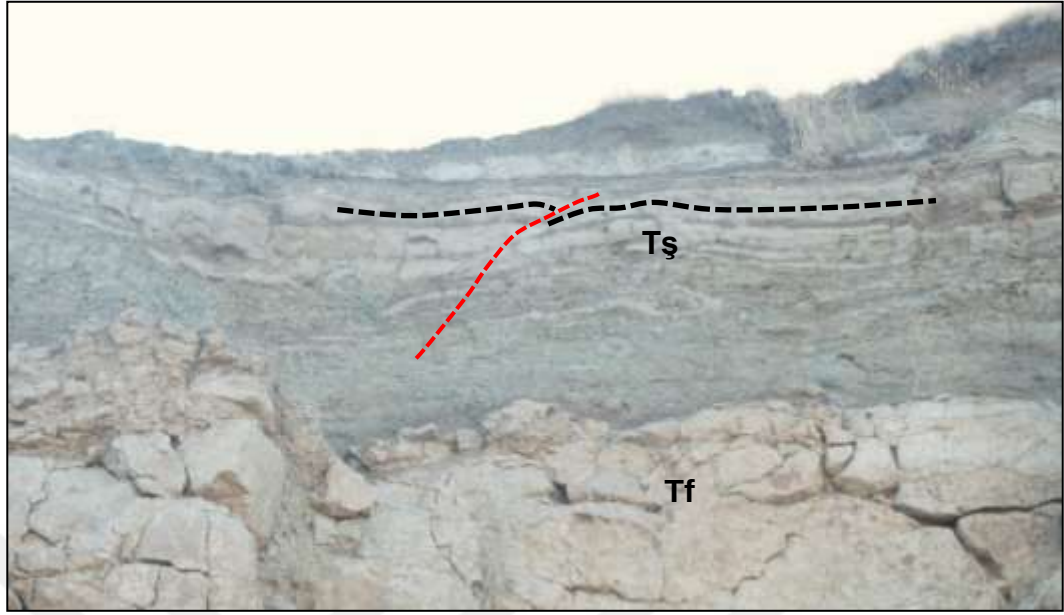


Figure 44. A field view from a fault in the Upper Miocene Şelmo Formation (Tş) near İkiköprü, Batman (340°/45°W, 42°S). The underlying massive lithology is carbonates of the Lower Miocene Fırat Formation (Tf) (Station 3).

The geology map in Figure 53 shows the Oyuktaş-Kurtalan Fault and related outcropping units along fault system and the location of outcrop samples, which have been collected to identify the formations near Zokpirt village. Figure 54 is the field view from the north–south-trending section A–A’.

Figure 55 demonstrates the pond along the Oyuktaş-Kurtalan Fault Zone, near Oyuktaş village Batman. Ancient pond has hot water spreading points and the NE–SW-trending elevation profile taken from Google Earth shows that the pond is 612 meter and the river is 587 meter above sea level, which indicates that the pond is topographically located above the Garzan River (Figure 56). Thus, these findings might shows that the pond formation is strongly related with the mechanism of faulting in the area.



Figure 45. Field views from the faults deforming the Lower Miocene Firat Formation near İkiköprü, Batman (see Table-4 for measurements) (Station 3).

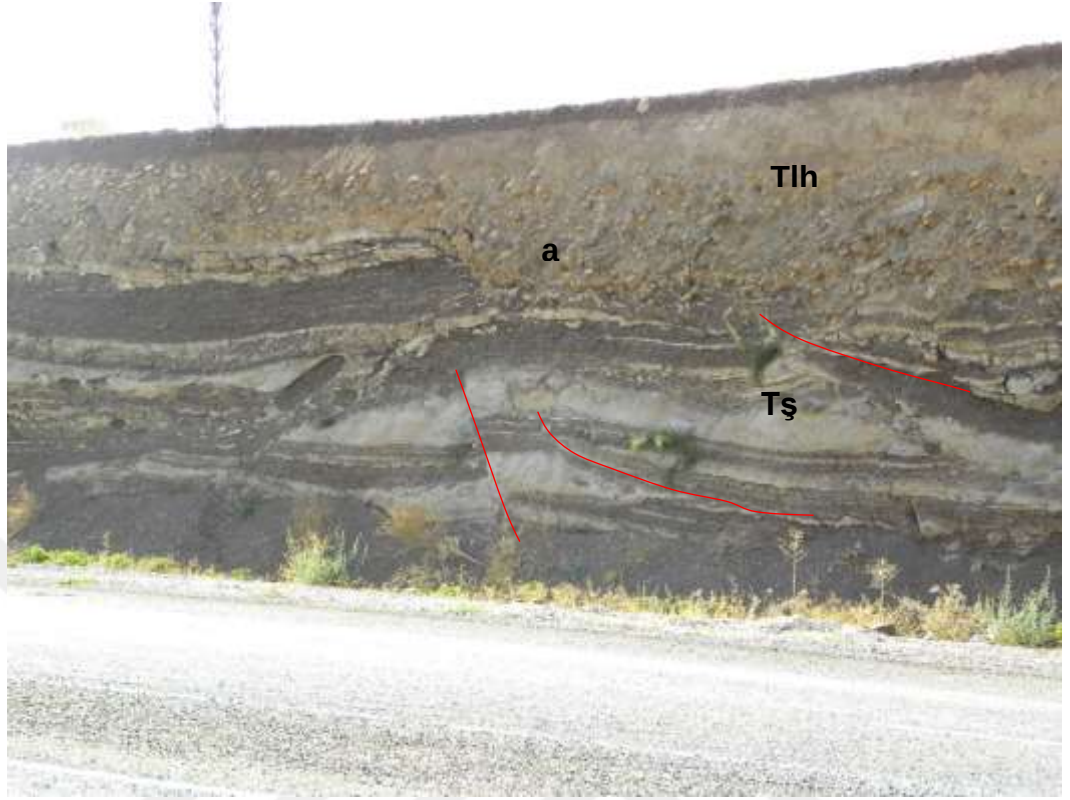


Figure 46. Field view from syn-sedimentary reverse faults deforming the Upper Miocene Şelmo Formation (Tş), Beşiri, Batman. Note that the faults do not disturb/cut a thin bed (labelled 'a'). The conglomerates of the Plio–Quaternary Lahti Formation (Tlh) overlies unconformably the Şelmo Formation with a pronounced erosional surface (courtesy of İsmail Bahtiyar used in Siyako et al., 2015).

The Habandere-Çelikli Fault is located north of the study area near Beybağı village Batman (Figure 57). While the structure is observable as a NW–SE-trending nearly vertical strike-slip fault in seismic sections, it is represented by structural elements related with strike-slip fault system, such as horse tails, normal and reverse faults mostly developed only in the Miocene units on the surface.

Table 4. Measurements of strike/dip amount and direction, rake of the faults

No.	Strike (°)	Dip amount & direction (°N)	Rake (°)	Sense	Principal stress axes	Ø
<i>Station-1</i>						
1	274	58K	80D	Normal		
2	166	62D	80K	Normal		
3	295	73G	80B	Normal		
4	315	71G	81D	Normal		
5	158	58K	72K	Normal		
6	126	59G	77B	Normal		
7	127	54G	81B	Normal	$\sigma_1 = 2^\circ/86^\circ$ $\sigma_2 = 128^\circ/2^\circ$ $\sigma_3 = 219^\circ/3^\circ$	0.1
8	115	73K	87B	Normal		
9	105	67G	86B	Normal		
10	348	62D	70K	Normal		
11	325	63B	85G	Normal		
12	45	52D	82K	Normal		
13	145	72K	80B	Normal		
14	302	65K	77B	Normal		
<i>Station-2</i>						
1	322	44D	78K	Normal & Reverse	$\sigma_1 = 30^\circ/13^\circ$ $\sigma_2 = 121^\circ/2^\circ$ $\sigma_3 = 220^\circ/77^\circ$	0.4
<i>Station-3</i>						
1	340	45B	42G	Reverse	$\sigma_1 = 15^\circ/02^\circ$ $\sigma_2 = 284^\circ/12^\circ$ $\sigma_3 = 114^\circ/78^\circ$	0.1
2	35	36B	0	Reverse	$\sigma_1 = 175^\circ/65^\circ$ $\sigma_2 = 52^\circ/14^\circ$ $\sigma_3 = 317^\circ/20^\circ$	0.6
3	10	32B	16G	Reverse		
4	165	66B	32G	Reverse		
5	152	47B	40G	Reverse		
6	148	60B	33G	Normal		
7	177	72B	0	Normal	$\sigma_1 = 297^\circ/2^\circ$ $\sigma_2 = 189^\circ/84^\circ$ $\sigma_3 = 27^\circ/6^\circ$	0.9
8	160	40B	34G	Normal		
9	170	50B	14G	Normal		

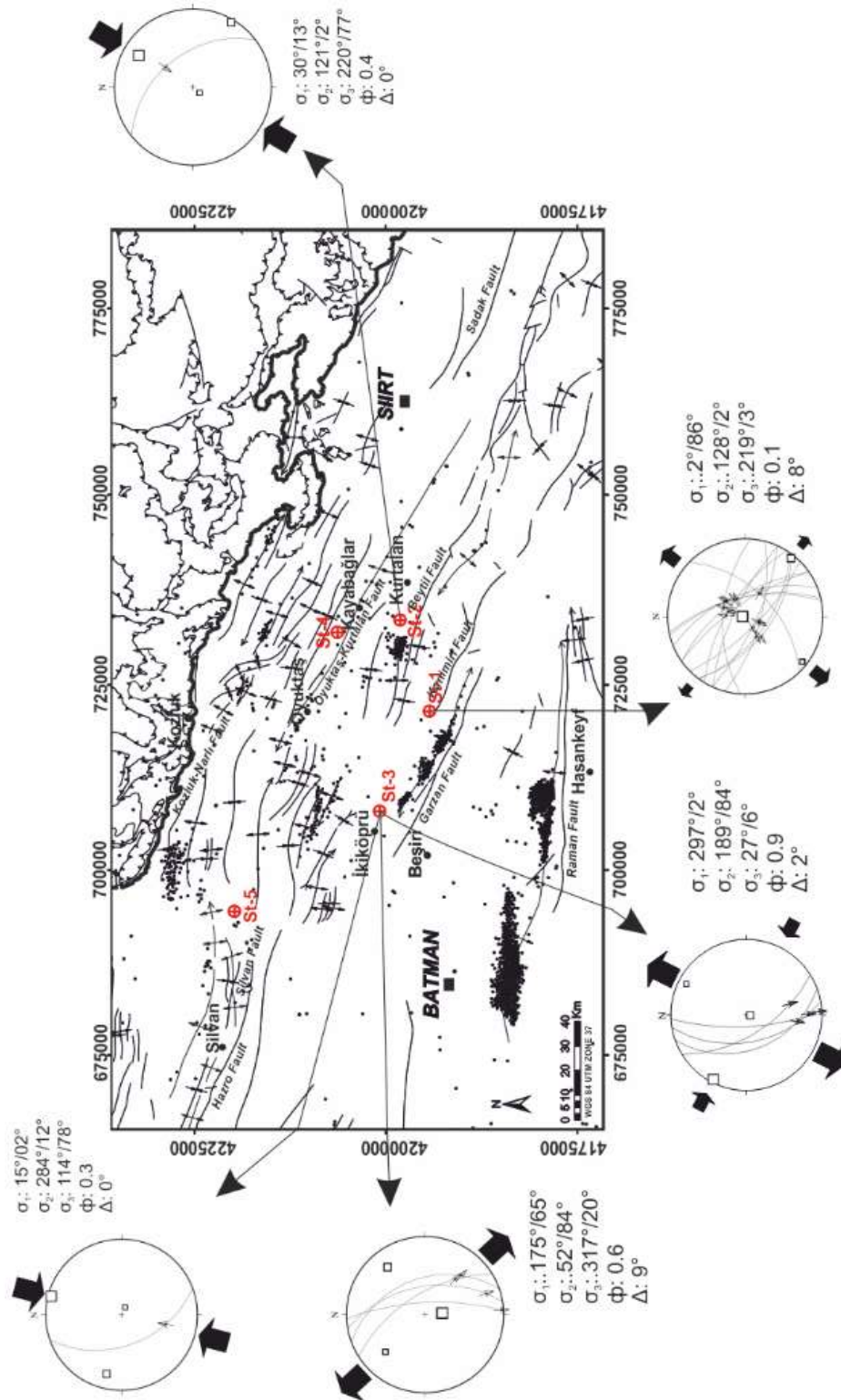


Figure 47. Spatial variation of the stress field at field observation stations. The data was taken from measurements done in the Miocene strata. Analyses are performed by using the stress inversion method of Angelier (1984, 1991, 1994), and computed using the software T-Tecto 3.0 developed by Zallohar & Vrabec (2007).





Figure 49. Field view from the Oyuktaş-Kurtalan Fault Zone (N68°W/75°NE), view from east near Kayabağlar village, Batman. Red line represents the location of the fault. Ductile deformation of folded Kapıkaya Formation and brittle deformed, highly fractured, Fırat Formation can be observed on the northern block (Station 4).

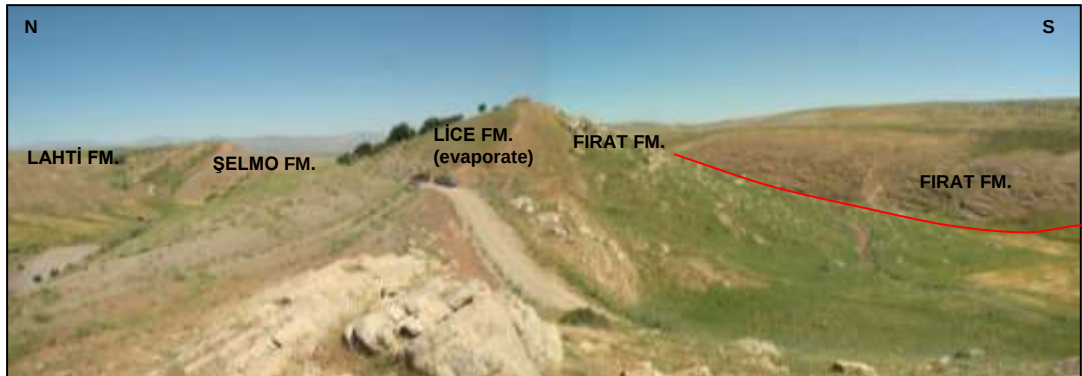


Figure 50. Oyuktaş-Kurtalan Fault Zone, view to east, near Yanarsu village, Batman. Lice and overlying Şelmo formations display transitional contact relationship. From north to south: Pliocene Lahti Formation, Upper Miocene Şelmo Formation, Lower Miocene Lice Formation evaporitic member (Kayabağlar Formation) and Lower Miocene Fırat Formation bioclastic reefal carbonates. The Şelmo and Kayabağlar formations steeply dip north at 70–80°. Red line represents Oyuktaş-Kurtalan Fault.



Figure 51. Field view of the Oyuktaş-Kurtalan Fault Zone and river terrace near Yanarsu village. The lower diagram is the seismic section along the same locality, showing the location of the fault zone. Note tilted sediments both in photo and seismic section.

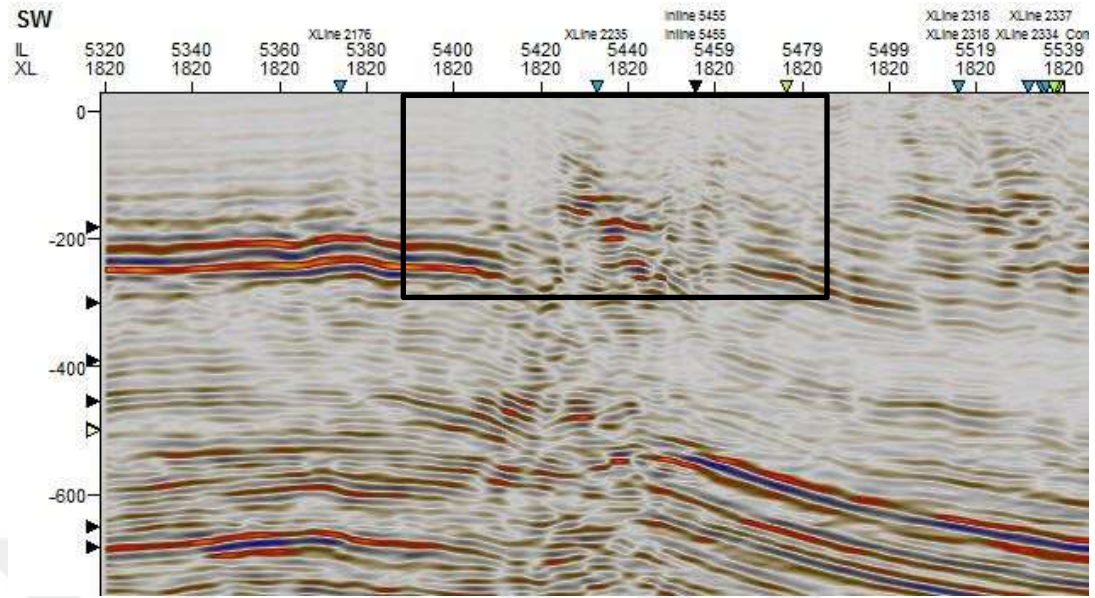


Figure 52. Seismic section, showing the presence and location of the Oyuktaş-Kurtalan Fault. Note that the fault zone is marked by disturbed seismic reflections and sudden termination of stratal reflections. Black rectangle shows approximate location of the area in Figure 53.

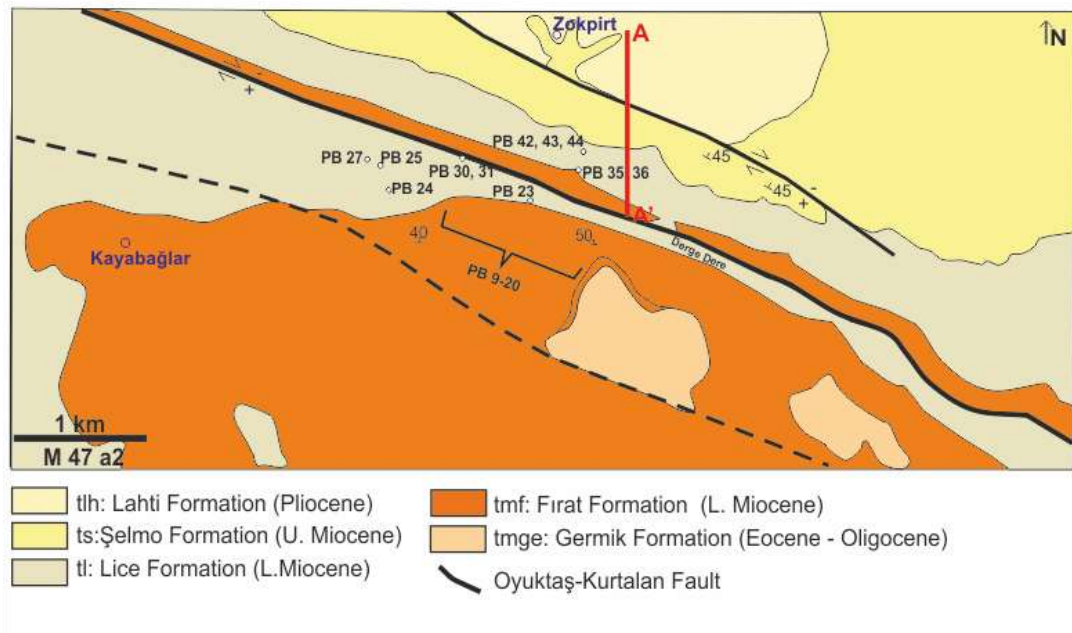


Figure 53. Geology and sample location map, near Kayabağlar village (generated by field studies during this research and observations from Siyako *et al.*, 2013). The formations related with the Oyuktaş-Kurtalan Fault. Section A-A' demonstrated in Figure 54.

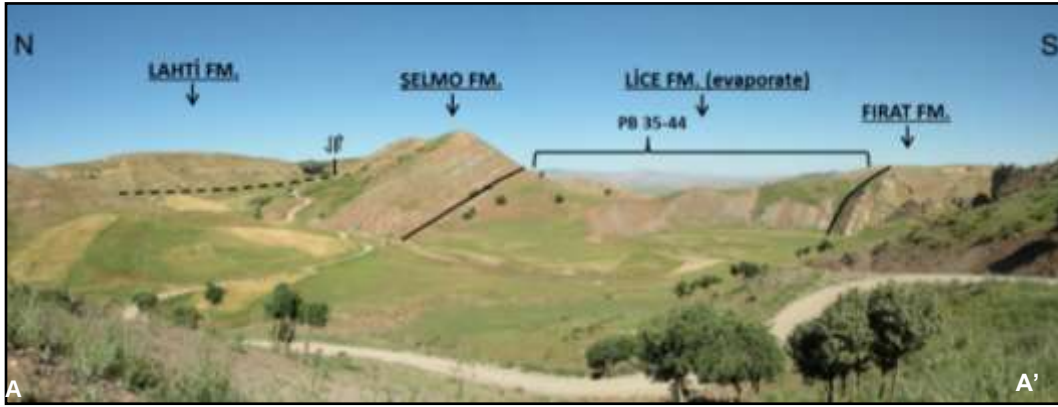


Figure 54. Field view of the flank of Reşan Anticline and distribution of the Silvan Group (Firat, Lice and Şelmo formations) from northwestern flank of the Reşan Anticline, Kayabağlar village (section A-A'). Oyuktaş-Kurtalan Fault (dashed line) forms the boundary between the Miocene formations in the southern block and the Lahti Formation in the northern block. PB-35-44 shows location of samples taken from the Lice Formation (from Siyako et al., 2013).



Figure 55. The Oyuktaş-Kurtalan Fault related water spring/pond near Oyuktaş village Batman.



Figure 56. Google Earth satellite view of the Garzan River and historical pond. The red line represents the location of NW–SE directed elevation profile through river and pond.



Figure 57. Field view from the Çelikli-Habandere Fault and related surface structures near Beybağı village Batman, view to east (courtesy of İsmail Bahtiyar).



Figure 58. A view from the NE-SW-trending Silvan Fault exposed near Malabadi Bridge, Batman, view to north. Note overturned anticline deforming the Lice Formation. The anticline is associated with the fault (Station 5).



Figure 59. Silvan Fault near Malabadi Bridge, Batman. The moderately southeast-dipping fault is almost a pure dip-slip reverse structure. Note that the rocks in the southeastern hanging-wall block is nearly horizontal while they are overturned and steeply dips southeast in the northwestern block.

The surface and subsurface correlation of faults is a critical issue to understand their roles in petroleum migration and trapping mechanism. To solve this problem it is very important to understand the relationship between timing of the tectonic events. The modeling of the structural elements could help especially to figure out the effect of inversion tectonics on pre-existing faults. By combination between the field data with existing well information and high resolution 3D seismic data the study was able to help better understand the tectonostratigraphic evolution and petroleum system of the region.

3.2. Structural Cross Sections

Two NE–SW-directed geological cross sections were generated through study area (Figure 60). The cross sections show the formations deposited since the Late Cretaceous time. The Cretaceous units are represented by greenish color, while the Tertiary units by yellow and red tones. The interpreted seismic lines are composite lines, which were obtained by merging 3D seismic sections with 2D seismic lines to demonstrate the structural relationships between foreland and foothills areas.

Figure 61 shows a SW–NE-trending structural cross section on the western part of Garzan River. The section demonstrates the position of the Kozluk-Narlı Fault, which lies in front of allochthonous units, and the borders of the Kastel Basin that was opened during Early Campanian by numerous normal faults. And also the structural settings of foreland region platform areas compartmentalized by nearly vertical oblique strike-slip faults.

Figure 62 shows a SW–NE-trending structural cross section on the eastern part of Garzan River. The section demonstrates the preserved structural styles beneath allochthonous units and shows the flank of Dodan Anticline, the Çelikli-Habandere Fault, and the Oyuktaş-Kurtalan Fault.

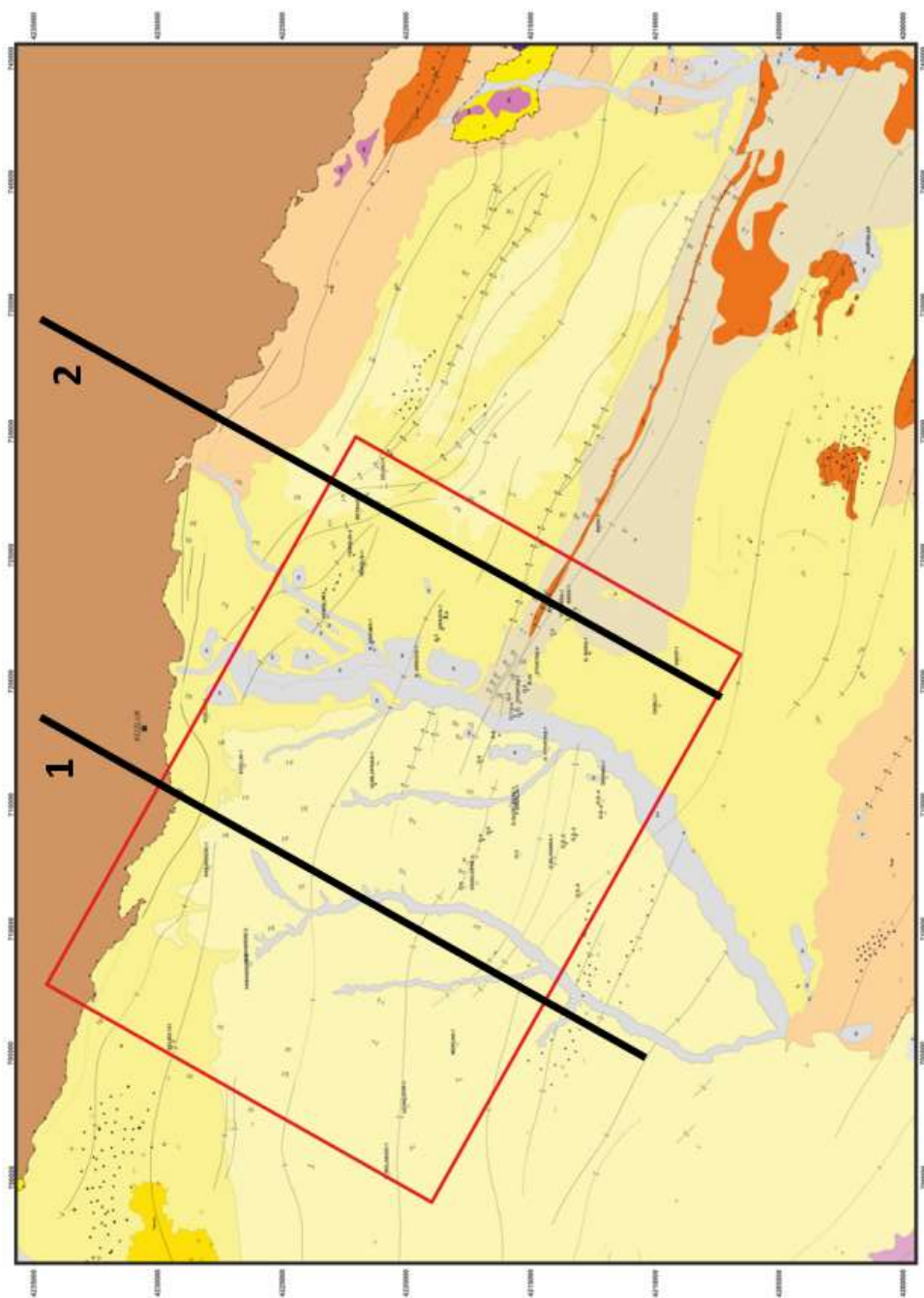


Figure 60. Geology map showing the location of NE–SW-trending structural cross sections shown in Figures 61 & 62.

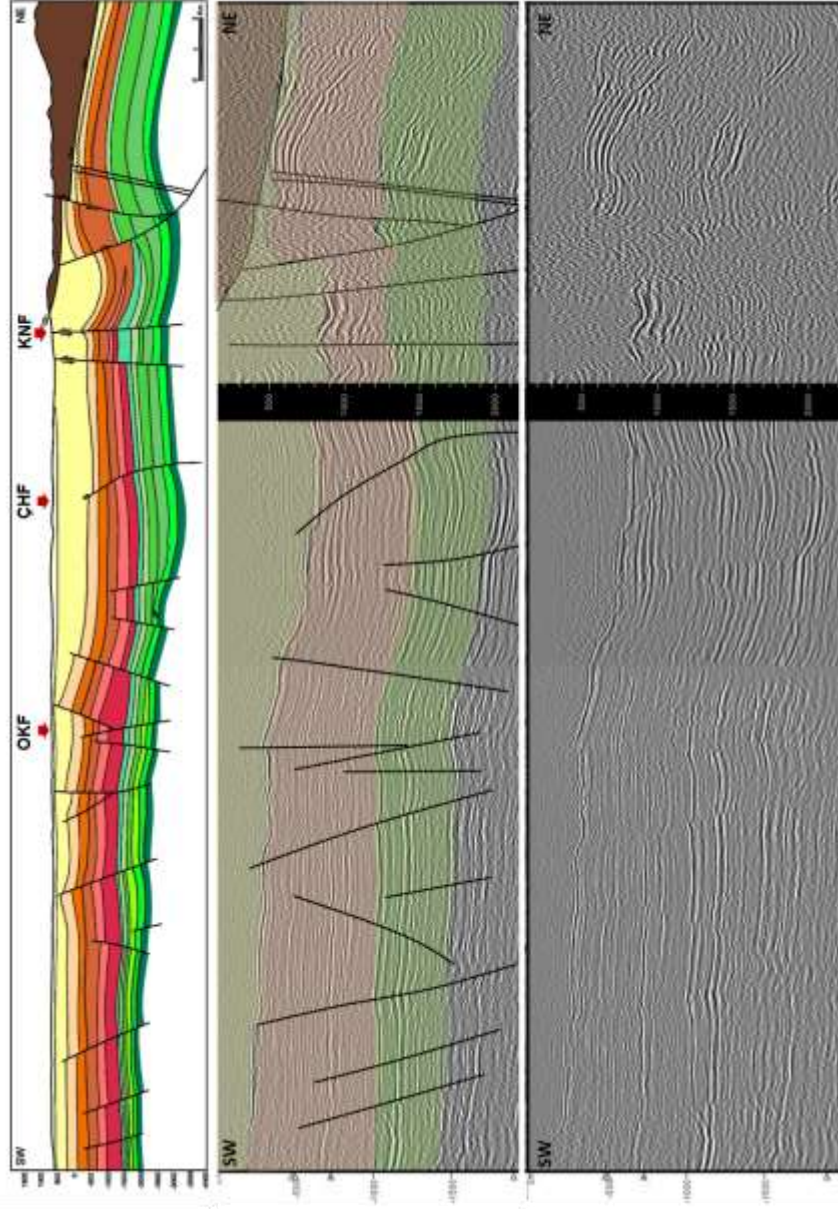


Figure 61. NE-SW-trending structural cross section 1 (upper diagram) and the representative seismic section (lower diagram) that shows the western part of the study area (for reference see Figure 60). The 39 km long section shows up to 4000 meter depth below sea level. Tertiary succession is represented by color scale from yellow to red, greenish colors shows the Cretaceous rocks and the brown color is for the Miocene allocthonous units located on north in the cross section. Oyuktaş-Kurtalan Fault (OKF); Çelikli-Habandere Fault (CHF), and Kozluk-Narlı Fault (KNF) are shown on the section.



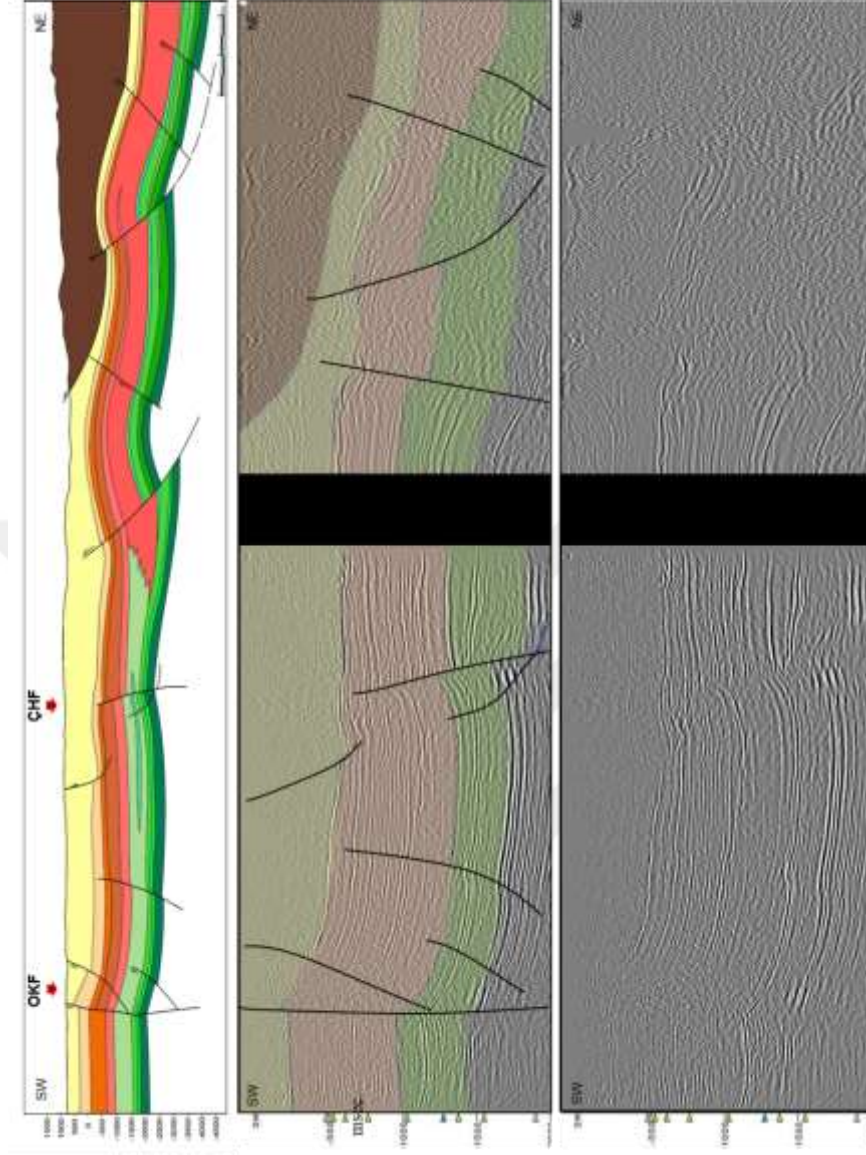


Figure 62. NE-SW-trending structural cross section 2 (upper diagram) and the representative seismic section (lower diagram) that shows the eastern part of the study area (for reference see Figure 60). The 24,5 km long section shows up to 4500 meter depth below sea level. Tertiary succession is represented by color scale from yellow to red, greenish colors shows the Cretaceous rocks and the brown color is for the Miocene allochthonous units located on north in the cross section. Oyuktaş-Kurtalan Fault and Çelikli-Habandere Fault (CHF) are shown on the section



3.3. Seismicity of the Area

Several seismic catalogues are examined to study the seismic activity in the region. The catalogues include USGS (<http://earthquake.usgs.gov/earthquakes/eqarchives/>), International Seismological Center (<http://www.isc.ac.uk/search/bulletin/>), Boğaziçi University Kandilli Observatory and Research (<http://www.koeri.boun.edu.tr>) and Global CMT (<http://www.globalcmt.org/CMTsearch.html>) are studied. The results are summarized in the following paragraphs.

Figure 63 shows the earthquakes occurred in the time interval from 1900 to 2017 in and around the study area. Earthquakes occurred along western part of the Oyuktaş-Kurtalan Fault in 2002 (M: 3.2), 2004 (M: 3.0) and 2007 (M: 3.6). This may indicate westward migration of the earthquakes. The ancient civilizations were settled down near Garzan River. There are many findings about Erzen Antique city civilization were developed near Oyuktaş, Batman since 2000 BC. The city is also named as demolished city. In historical records, it is written that the city was destroyed and could not be built again. Also, Dilmaçoğulları principality was developed in and around this area in the years between 1085 and 1192. The Oyuktaş-Kurtalan Fault could have been played a role on the destruction of these ancient cities. Also the recent earthquakes near Beyçayırı and Durucak implies the existence of seismically active faults (NW trending Beyçayır and Beytil Faults?), which have to be mapped in active fault map of Turkey (Figure 63).

Figure 64 illustrates fault plane solutions of earthquakes with focal mechanisms along the East Anatolian Fault and within the Bitlis-Zagros Suture Zone just to the north of the study area. The data from reverse to thrust faulting is consistent with almost N–S-oriented compressional stresses; the faults with reverse component indicate the existence of transpressional structures, some of which might have been linked with folding in the region. It is also worth to mention that several earthquakes in front of these folds are most probably associated with blind thrusts, tipping out of strike-slip faults with reverse components. Therefore, the distribution of earthquake epicenters does not necessarily define a long linear trending in the region.

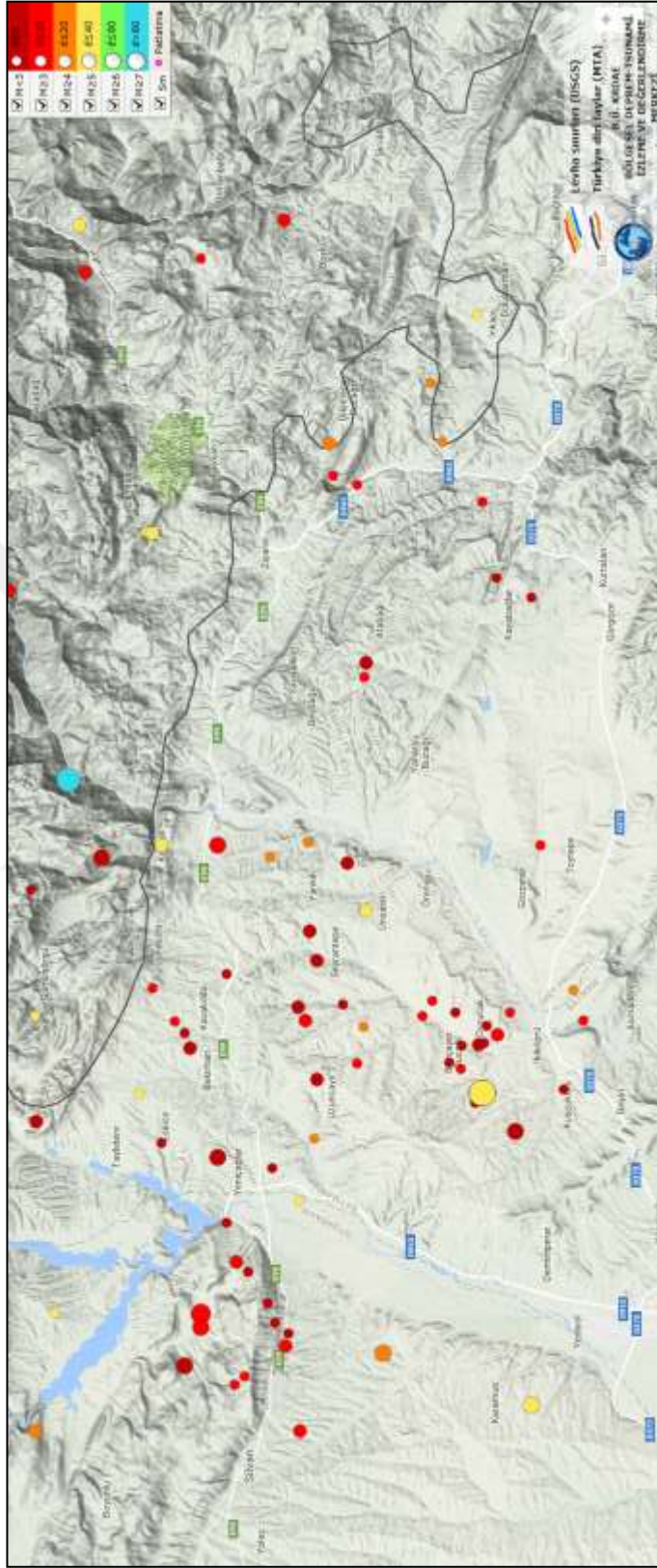


Figure 63. Earthquakes occurred since 1900 in the study area and its neighboring (data from web page of B.Ü. Kandilli Rasathanesi, <http://udim.koeri.boun.edu.tr/zeqdb/>)

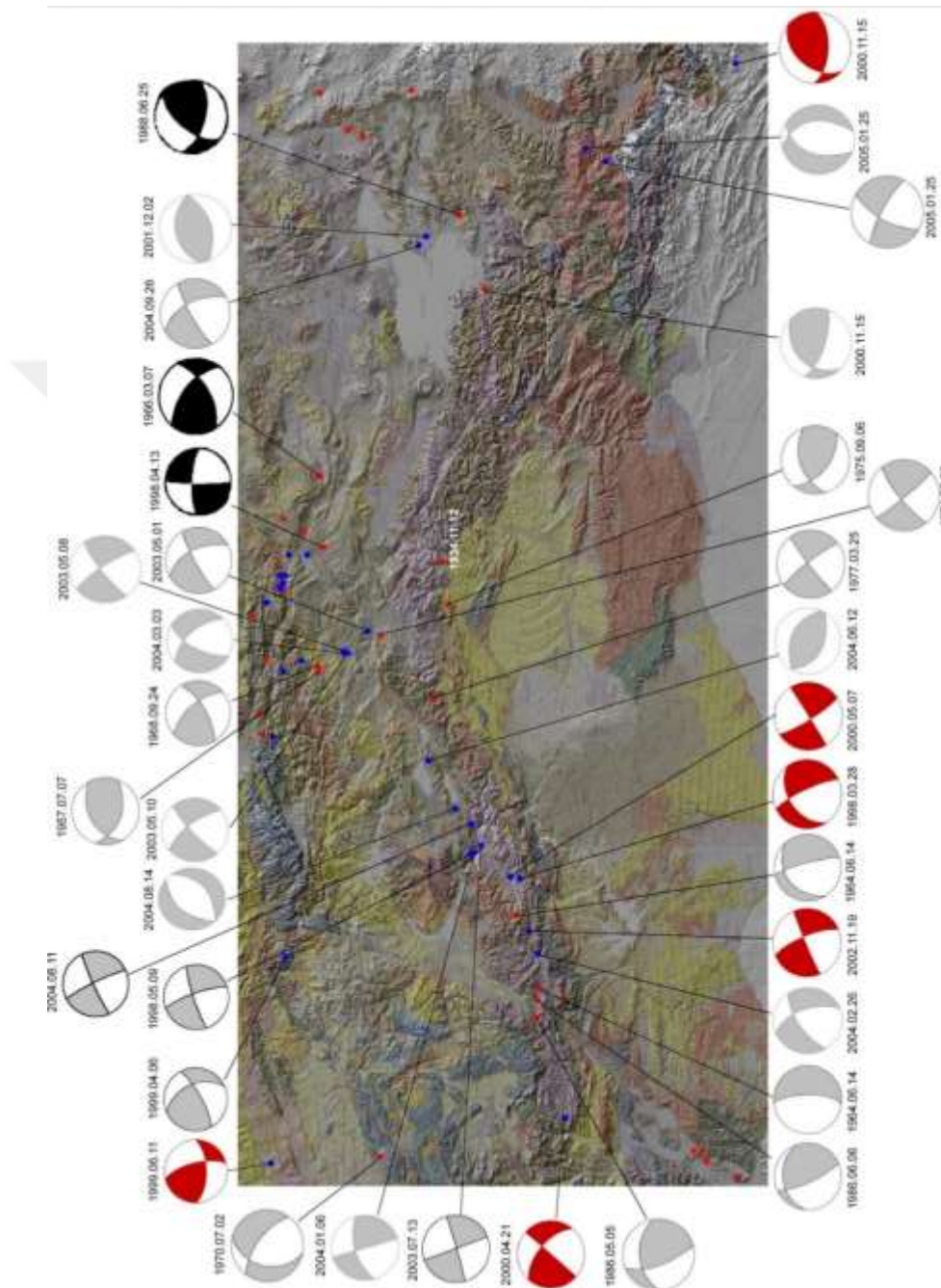


Figure 64. Fault plane solutions from earthquakes with focal mechanisms on the north and within the Bitlis-Zagros suture zone to the north of the study area (courtesy of Prof.Dr. Bora Rojay). Blue dots– reverse/thrust faulting, red dots– strike-slip faulting.

Figure 65 illustrates fault plane solutions of earthquakes with focal mechanisms in northern Iraq within the suture zone (area between 36° to 38° latitudes and 42° to 45° longitudes) during 1980 to 2010 (Table 5). The results clearly demonstrate a structural pattern within the study area and its surroundings and suggests, based on earthquake fault plane solutions, strike-slip faulting where two sets of (conjugate?) faults are NW–SE right-lateral and NE–SW left-lateral strike-slip faults (Figure 65). The other common conclusion is that there are no earthquake fault plane solutions depicting pure normal or reverse/thrust faulting.

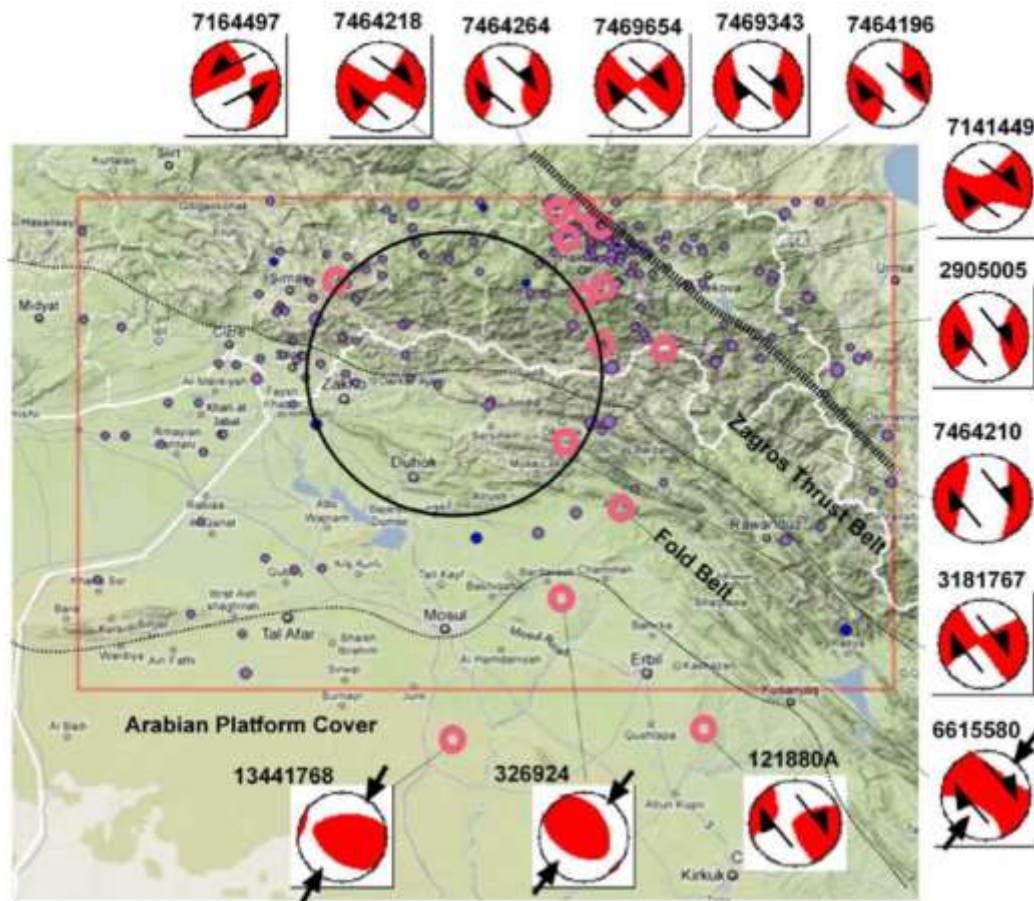


Figure 65. Fault plane solutions from earthquakes with focal mechanisms in an area between 36° to 38° latitudes and 42° to 45° longitudes in northern Iraq during 1980 to 2010 (courtesy of Prof.Dr. Bora Rojay). See Table 5 for more details.

Table 5. Earthquakes with fault plane solutions with possible tectonic sources (see Figure 65 for location of earthquakes. Courtesy of Prof.Dr. Bora Rojaj.

No	Date/ Time	Depth (km)	Lat. (°)	Long. (°)	Mw	Fault Plane 1	Fault Plane 2	Reference	Beachball	Tectonic Source
121880A	1980/12/18 12.34	15	35.89	44.25	6.1	Strike: 247 Dip: 74 Rake: 12	Strike: 154 Dip: 79 Rake: 163	Global CMT Catalog		Right-lateral strike-slip faulting beneath platform cover
326964	1991/07/24 09.45	15	36.40	43.77	5.4	Strike: 335 Dip: 44 Rake: 121	Strike: 116 Dip: 53 Rake: 64	Int. Seismo. Centre (HRVD)		Thrust with right-lateral strike-slip components „ beneath platform cover
2905005	2002/02/28 00.45	18	37.28	44.14	5.0	Strike: 317 Dip: 89 Rake: 172	Strike: 47 Dip: 74 Rake: 1	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
3181767	2002/05/03 02.18	24	36.92	43.65	4.7	Strike: 146 Dip: 88 Rake: 173	Strike: 237 Dip: 83 Rake: 2	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
6615580	2003/03/16 09.06	15	36.68	43.87	5.1	Strike: 88 Dip: 74 Rake: 37	Strike: 346 Dip: 54 Rake: 160	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting with reverse components
7164497	2003/10/23 17.24	15	37.52	42.66	4.8	Strike: 251 Dip: 83 Rake: -27	Strike: 344 Dip: 64 Rake: -172	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
7464196	2005/01/25 15.24	27	37.56	43.78	5.2	Strike: 115 Dip: 86 Rake: -167	Strike: 24 Dip: 77 Rake: -4	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
7464210	2005/01/25 16.32	10	37.37	43.76	4.8	Strike: 201 Dip: 54 Rake: -69	Strike: 349 Dip: 41 Rake: -116	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
7464218	2005/01/25 16.44	24	37.62	43.70	5.9 (?)	Strike: 304 Dip: 88 Rake: 175	Strike: 34 Dip: 85 Rake: 2	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting

7464264	2005/01/25 17.52	12	37.79	43.61	4.6	Strike: 31 Dip: 86 Rake: 11	Strike: 300 Dip: 79 Rake: 176	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
7469343	2005/02/02 23.26	14.1	37.72	43.85	4.6	Strike: 39 Dip: 69 Rake: -24	Strike: 138 Dip: 67 Rake: -157	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
7469654	2005/02/04 00.19	21	37.76	43.74	4.8	Strike: 136 Dip: 88 Rake: 178	Strike: 226 Dip: 88 Rake: 2	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
7141449	2005/06/05 03.45	24	37.52	43.82	4.7	Strike: 33 Dip: 88 Rake: -7	Strike: 123 Dip: 83 Rake: -178	Int. Seismo. Centre (ZUR RMT)		Right-lateral strike-slip faulting
13441768	2009/07/18 20.33	12	35.90	43.19	5.1	Strike: 132 Dip: 50 Rake: 128	Strike: 262 Dip: 53 Rake: 53	Int. Seismo. Centre (GCMT)		Thrust with right-lateral strike-slip components , beneath platform cover

CHAPTER IV

INTERPRETATION OF SUBSURFACE DATA

4.1. 3D Seismic Interpretation

This study aims to develop structural and stratigraphic models of the subsurface data by using seismic reflection, well data and field observations. The seismic interpretation of horizons and faults was performed manually. Picked horizons are interpolated and converted to surface models. Fault models were generated from fault sticks that are picked on vertical planes (inlines/crosslines). In order to check the validity of fault and horizon model interpretations, time-slice data are used as quality control tools. A seismic interpretation work flow presented below (Figure 66).

Seismic interpretation process is composed of five steps: (i) determination of lithological changes and identification of key stratigraphic horizons by using GR and DT logs of the existing wells; (ii) tying of wells A-1, K-1, KA-2, Y-3 and O-10 check shot data and synthetic seismic data to seismic cubes; (iii) picking of identified horizons throughout the seismic data; (iv) calculation of variance cubes for each seismic reflection data, and (v) fault interpretation by using seismic and variance cubes (Figure 66).

Three dimensional surfaces of the horizons are created by both manual interpretation and interpolation methods implemented in Petrel software. Faults are picked manually in 3D seismic volumes as discontinuities in seismic sections. The validity of fault interpretations was tested on both time slices of amplitude and variance cubes.

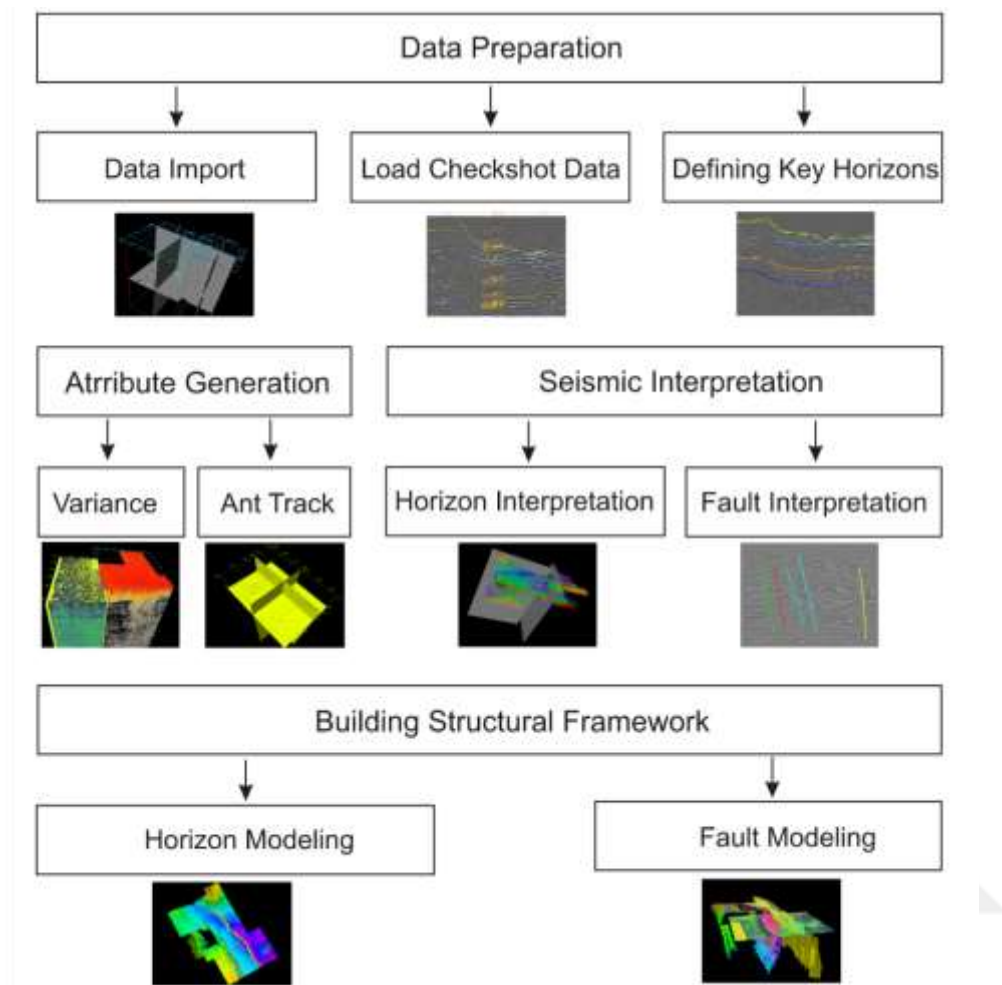


Figure 66. Flowchart showing workflow of seismic interpretation.

4.1.1. Horizon Interpretation

4.1.1.1. Check-shot Data and Syntethic Seismograms

In seismic exploration, the information contained in well-log measurements is used to verify and calibrate seismic data at several stages during processing and interpretation (Figure 67). The information in the well-logs should be aligned with the seismic data before the well-log information is used (Figures 67 & 68). This process is called **well-tying**, and includes the conversion of the well-log measurements from depth to the time domain (Figure 69). It is often observed that a

discrepancy occurs between the travel-times from the seismic measurement and the travel times computed from the P-wave velocity measurements in a given well. Commonly this difference is in the order of a few percent's, but can occasionally reach up to five to ten percent. One of the most important reasons for this difference is the different frequency range at which the well-log and the seismic measurements are performed; well-log measurements are performed using acoustic signals with a much broader frequency spectrum, especially towards the higher frequencies. Small-scale layering will have a different effect at these different frequency ranges. From a review of literature, it was found that the ration between the scale of the measurement and the scale of the small-scale layering is an important factor.

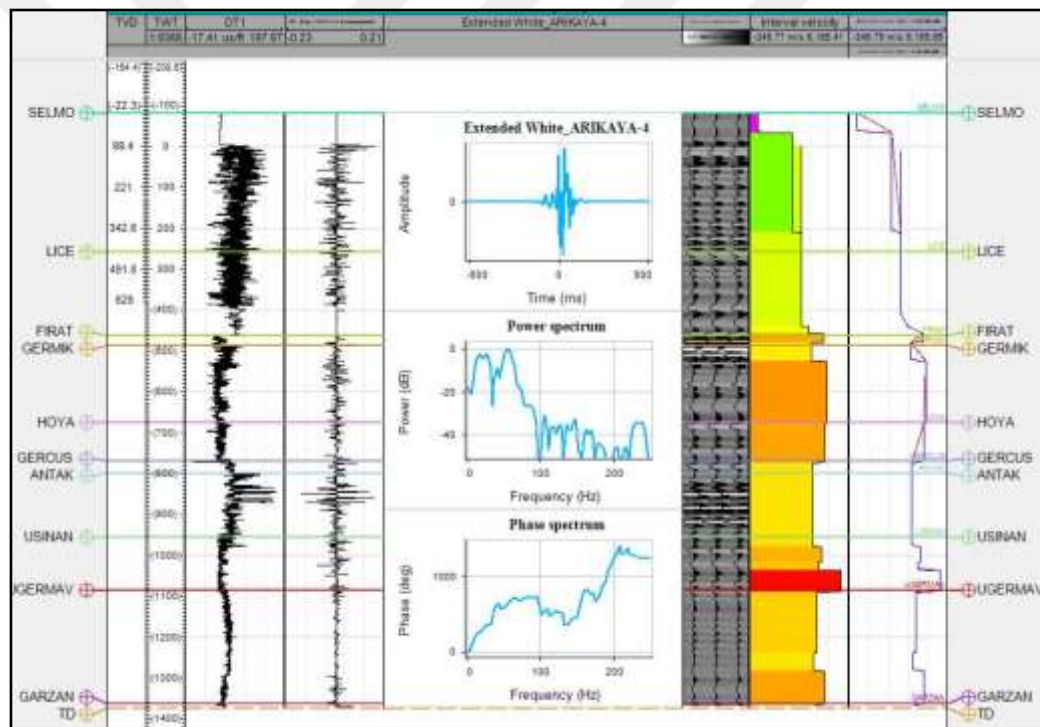


Figure 67. Synthetic seismogram calculated by using check shot data and sonic log for the well A-4. TVD, True vertical depth; TWT, Two way Time; DT1, Sonic log; RC, Reflection coefficient. The formation contacts have been identified by using both cutting samples and well log information gathered from well.

Subsurface discontinuities form reflections in seismic attribute data and these surfaces can be interpreted as structural and stratigraphic markers because they create interfaces with impedance contrasts (Figure 68). Five different levels – Base Miocene,

Top Paleocene, Top Cretaceous, Top Campanian and Base Cretaceous – have been picked and mapped by using Schlumberger product Petrel version 2016 (Figure 69).

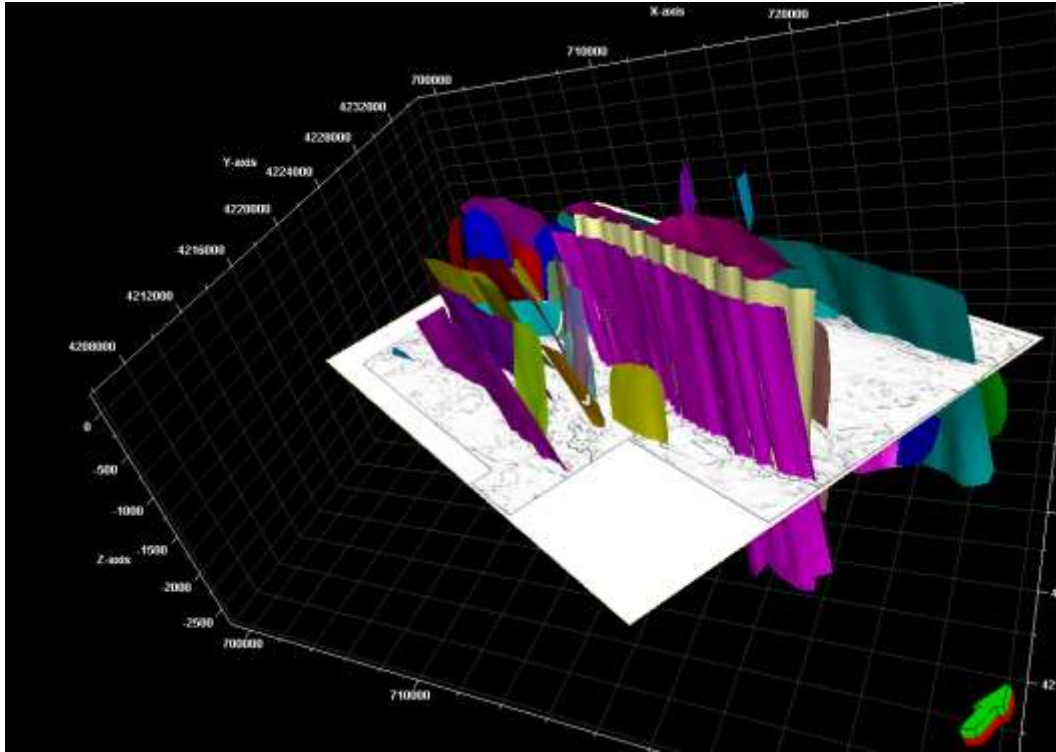


Figure 68. Representative fault interpretations on time slices of amplitude and variance cubes.

The horizons were identified on all interpreted seismic profiles in the 3D volume and picked every 10 lines with the help of well data: (i) **Base Miocene** remarks the base of the Fırat Formation and is represented with a peak. It was picked with low confidence around fault zones. (ii) **Top Paleocene** is represented by top Gercüş Formation, which was picked with a through; (iii) **Top Cretaceous** is defined by top of Lower Sinan Formation, (iv) **Top Campanian** is referred to top Beloka and top Sayındere Formations that is represented by a pick and (v) **Base Cretaceous** is the base of the Mardin Group, which is represented by strong peak amplitudes in seismic sections. Various seismic qualities made the picking process and correlation difficult, thus, the confidence of the picked horizons increases further away from faults and sharp anticlines.

Some of the interpreted lines are shown in Figures 70 and 71. Base Miocene or Base Fırat Formation is a major unconformable transgressive surface that is represented by carbonate deposition with a marine flooding on top of Germik evaporate deposition that was related with major uplift of Arabian Plate. Also Miocene succession is dissected by many faults that are related with strike-slip regime, thus Base Miocene has been chosen as a key level to be interpreted. As the Mid–Late Eocene is the onset of subsidence and transgression in the study area and continues with the deposition of the Midyat Group carbonates, Top Paleocene emphasizes a good correlative surface. Cretaceous is a remarking period as its base represents one of the major unconformity of the Arabian autochthon succession and its top is an easily trackable reflection in seismic data. Especially Top Campanian is an important marking level in the study area, as the Mid-Late Campanian time is represented by the development of series of block faulting and also deformation along existing faults that controls the basin evolutions, their deposition and stratigraphy (Figures 70 & 71).

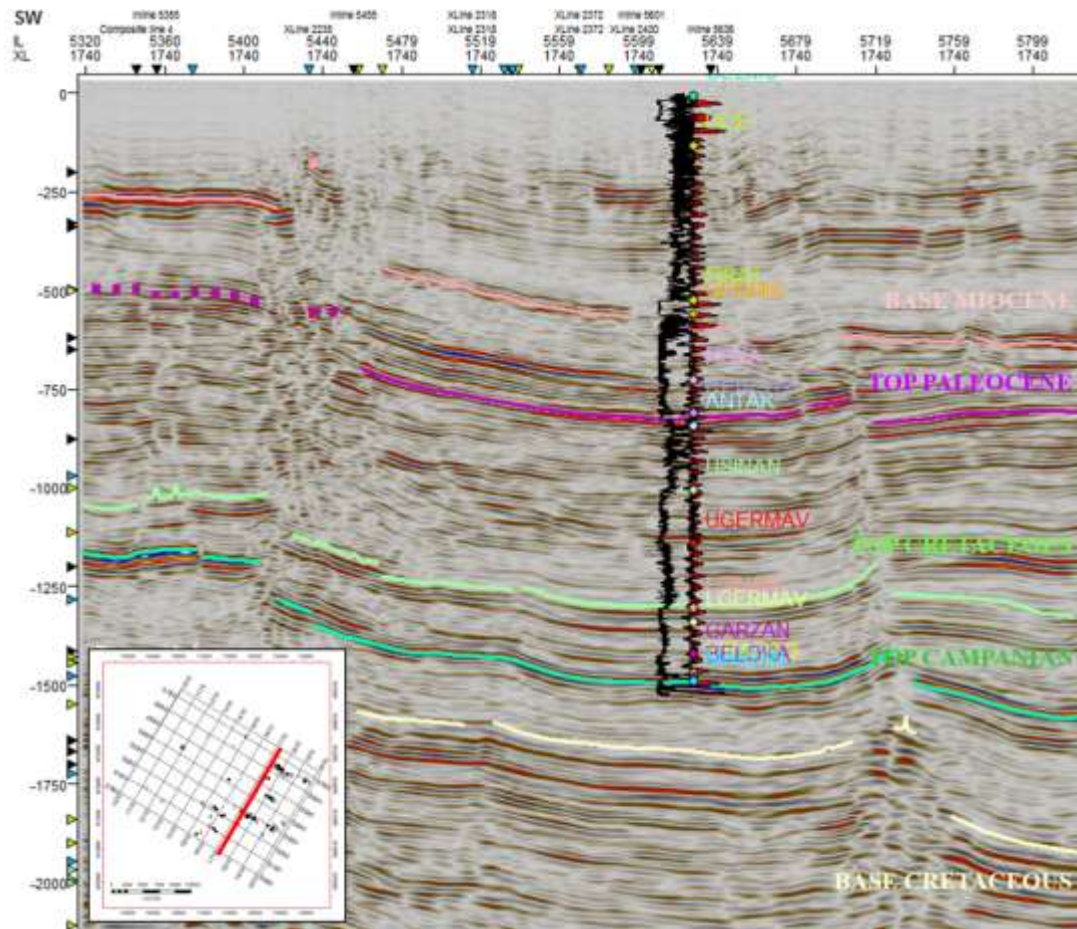


Figure 69. Horizon picks based on synthetic seismogram calibrated by sonic log and check-shot data on well KA-1 in inline 1738. Formation tops are calibrated with well-log information to interpret key horizon levels of Base Miocene (Top Germik Formation), Top Paleocene (Top Gercüş Formation), Top Cretaceous (Top Lower Sinan Formation), and Top Campanian (Top Beloka Formation).

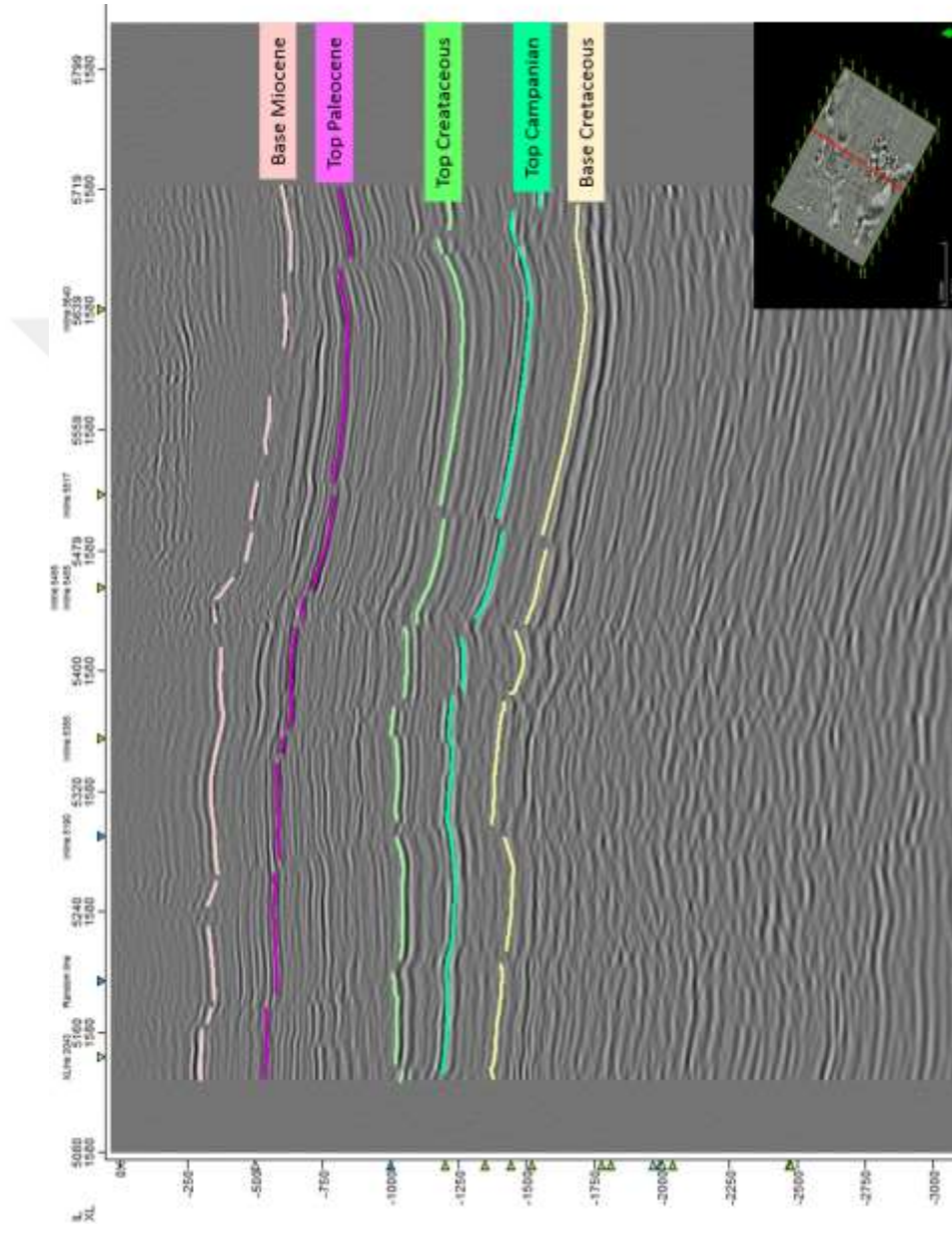


Figure 70. NE-SW-directed seismic crossline showing the interpretation of key stratigraphic horizons. Base Miocene (light pink), Top Paleocene (pink), Top Cretaceous (light green), Top Campanian (green), and Base Cretaceous (yellow) seismic horizon interpretations on crossline 1580 in Kozardere 3D seismic data.

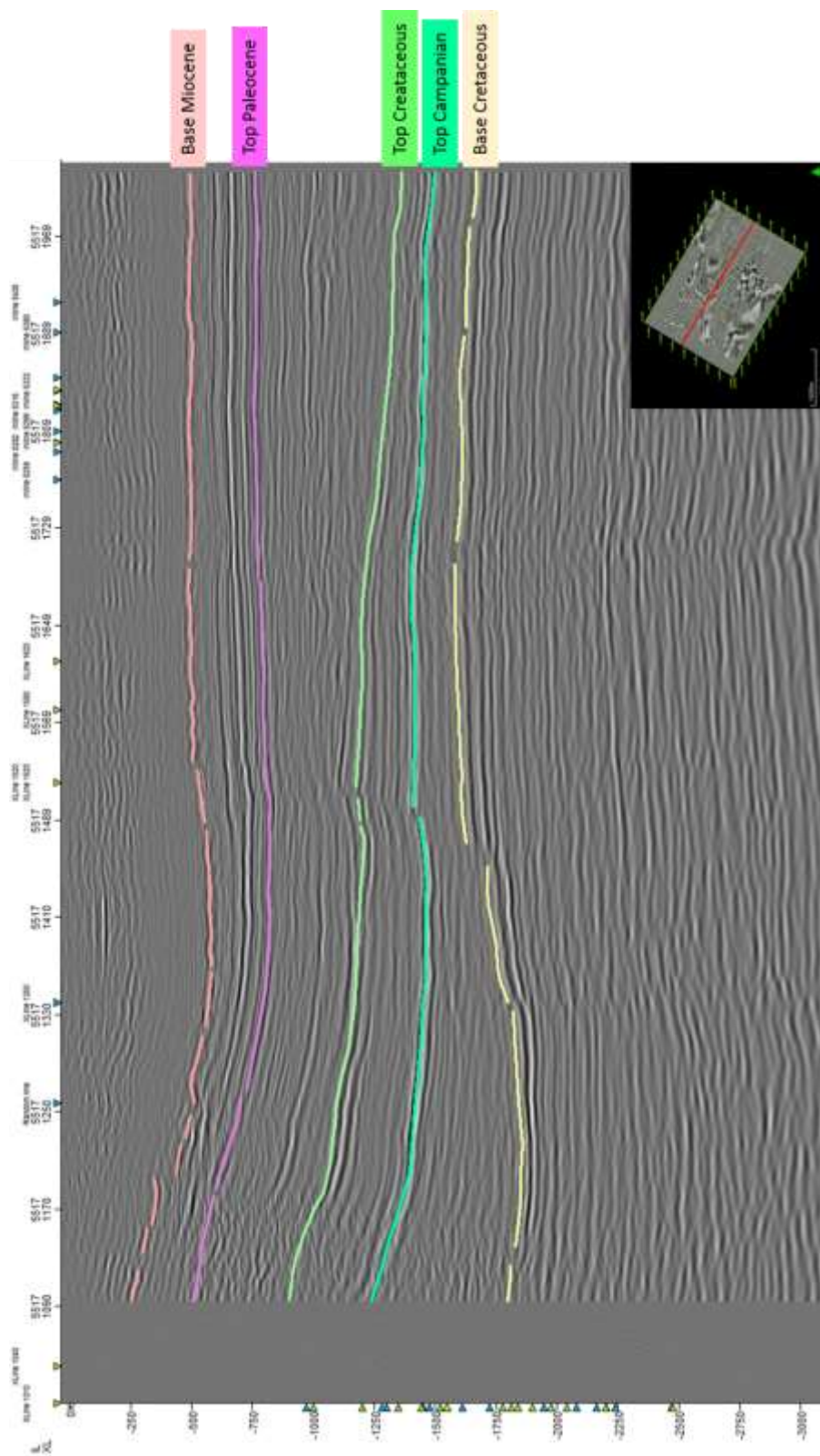


Figure 71. NW–SE-directed seismic inline showing the interpretation of key stratigraphic horizons. Base Miocene (light pink), Top Paleocene (pink), Top Cretaceous (light green), Top Campanian (green), and Base Cretaceous (yellow) seismic horizon interpretations on inline 5517 in Kozardere 3D seismic data.

4.1.2. Fault Interpretation

4.1.2.1. Ant Track Workflow

Due to severe tectonic deformation, the study area is marked by the occurrence of abundant faults. Before picking the faults on the 3D volume, Petrel Ant Tracking cubes and variance cubes were generated in order to obtain an idea about the trends of the faults. Because of the dominant structural trends, the fault interpretation was easily tracked in crosslines of the Kozardere 3D. Their consistency with the other lines is also taken into consideration during the interpretation process.

The three dimensional seismic cubes are very important for understanding earth's subsurface and also form important aspects of oil and gas exploration. As there is a growing volume and resolution of the seismic data, image processing becomes a crucial aspect of the seismic data evaluation. The coherency cube is an important tool for the detection of faults and other geological features in 3D seismic volumes. Coherency is measured by the geometric mean of maximum time-lagged cross-correlation along x and y directions (cf. Bahorich and Farmer, 1995). As the **voxel intensities** indicate sharp contrasts across fault and fracture surfaces, those regions become distinct in the coherency cubes. In this study, the data is loaded into, and the finalized by, using Petrel E&P Software v. 2016. The program allows extracting faults and fractures with a special technique called **ant tracking**. The algorithm resembles the colonies of ants in nature, and imitates these ants as they are looking for food by using pheromones to mark their paths in order to optimize the search for food. Similarly virtual ants are put as seeds on a seismic discontinuity volume to look for fault zones during the process. At the end of the process, an attribute volume has been generated which shows fault zones sharp and detailed. The ant-tracking process steps are listed as follows:

- (1) Create attribute cubes as pre condition to the Ant-tracking cube;
 - a. Structural smoothing with edge enhancement;
 - b. Chaos or variance;
- (2) Generate ant-tracking cube and fault patches;
- (3) Edit the fault patches;
- (4) Convert fault patches to fault interpretation.

This technique helps to obtain better and more accurate interpretation of faults once the manual interpretation is combined together with the realized attribute cube (Figure 72). Before picking the faults on the 3D volume, Petrel Ant Tracking was performed to obtain an idea of the trends of the faults and fractures in the 3D area.

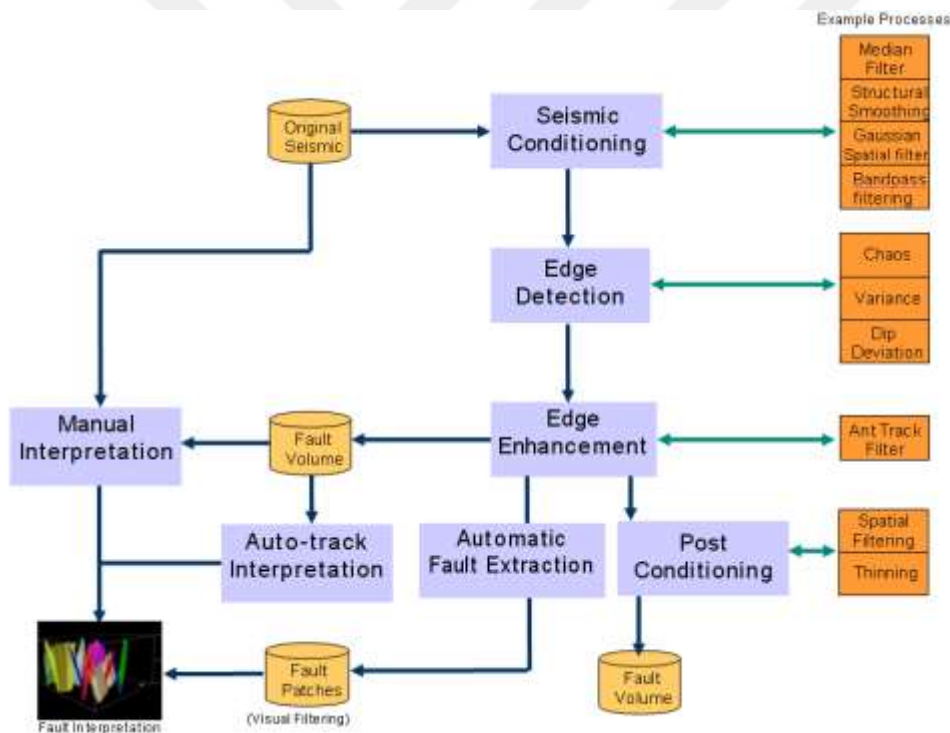


Figure 72. Ant track workflow for the creation of an ant track attribute volume and generating fault patches.

Based on ant tracking results, many faults are identified in 3D seismic data. These are the Oyuktaş-Kurtalan Fault Zone (OKFZ), the Habandere-Çelikli Fault (HÇF), the Kumluşınar Fault (KF), and the Arıkaya Fault (AF) form the major

structures identified in the ant track and variance volumes. All of the faults trend NW–SE direction except for the Kumlupınar Fault (KF). There are also many NW–SE-trending faults and other younger faults visible in the Kozardere 3D volume (Figure 73).

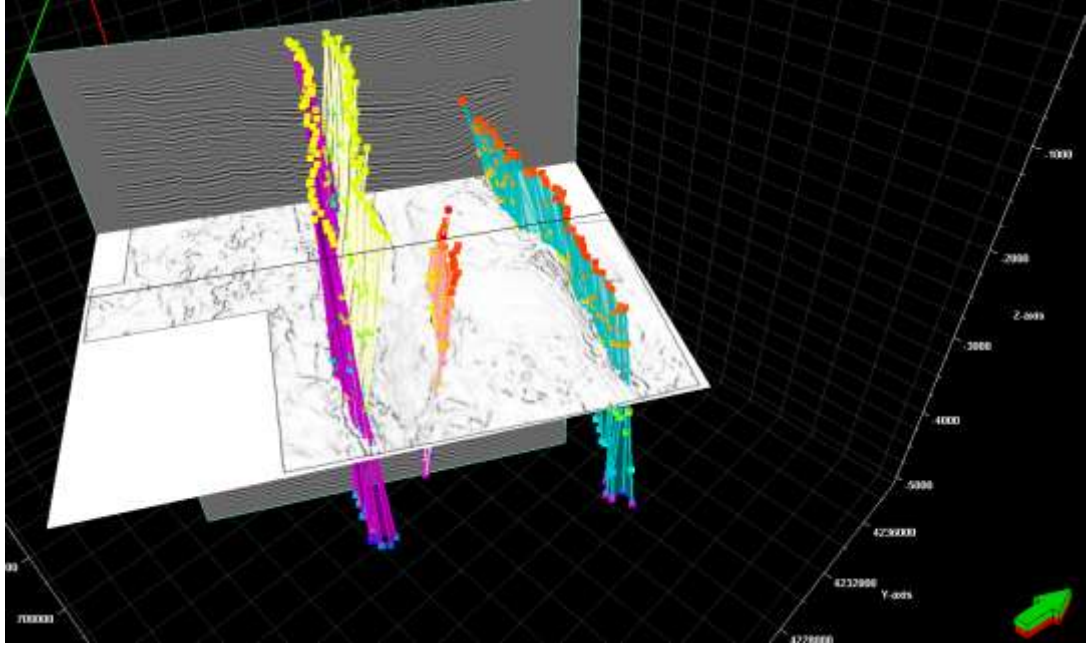
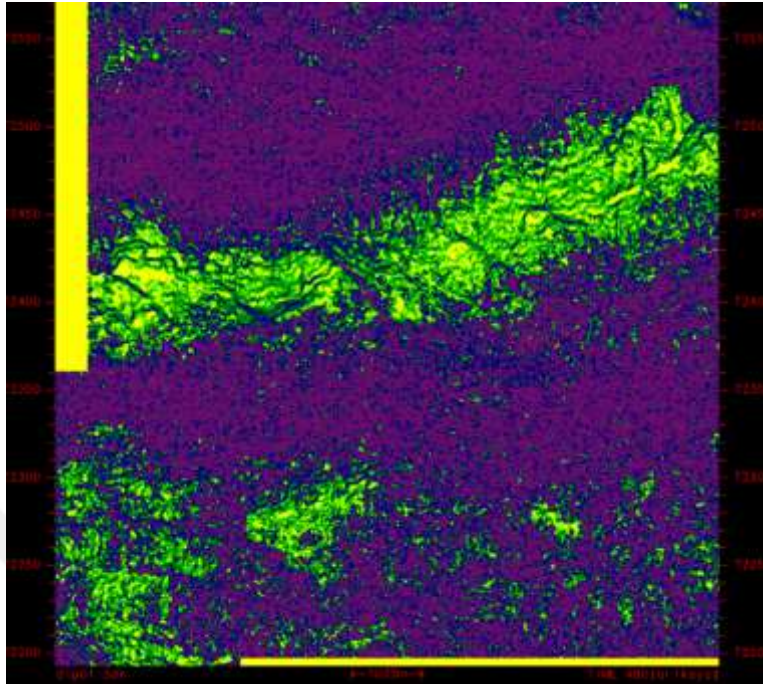


Figure 73. The slice of ant-track cube and Kozardere x-line 1670 with the view from east to west. The faults from left to right: OKFZ, Oyuktaş-Kurtalan Fault Zone (purple and yellow surfaces), AF, Arıkaya Fault (pink), CHF, Çelikli-Habandere Fault (blue).

4.1.2.2. Variance Attribute and Slice Mapping

Variance attribute (edge method) evaluates the similarity of waveforms or traces neighboring in lateral or vertical windows. Thus, it can image discontinuity of structural or stratigraphic features in the seismic data. Variance attribute is mainly successful on imaging faults and channels both in vertical or time slices (cf. Pigott *et al.*, 2013). Figure 74 represents variance slice from 480 msec (section in the Miocene strata) near the Çelikli-Habandere Fault (CHF). Figure 74 also shows the un-interpreted data (a) and represents the interpreted variance slice with the strain ellipsoid (b). The Miocene channel appears to be displaced in a right

(a)



(b)

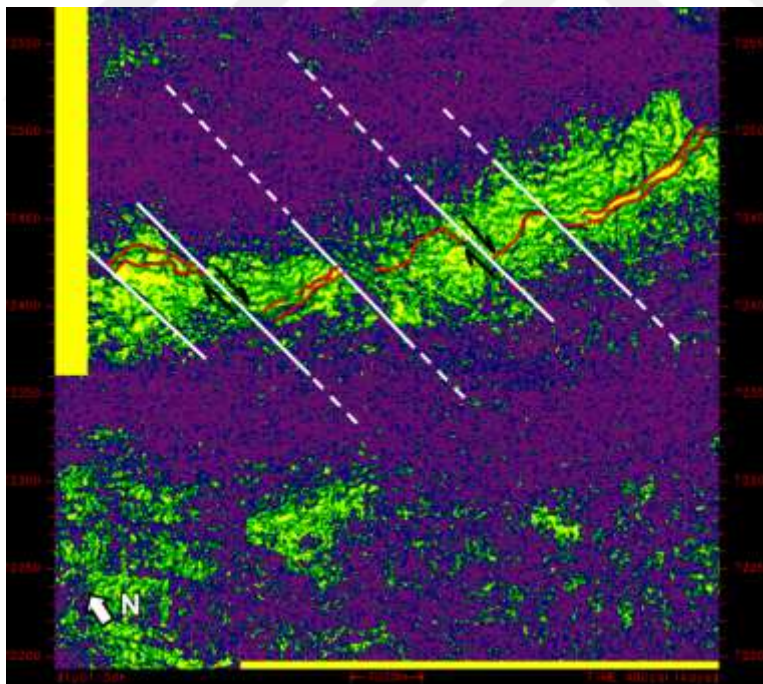


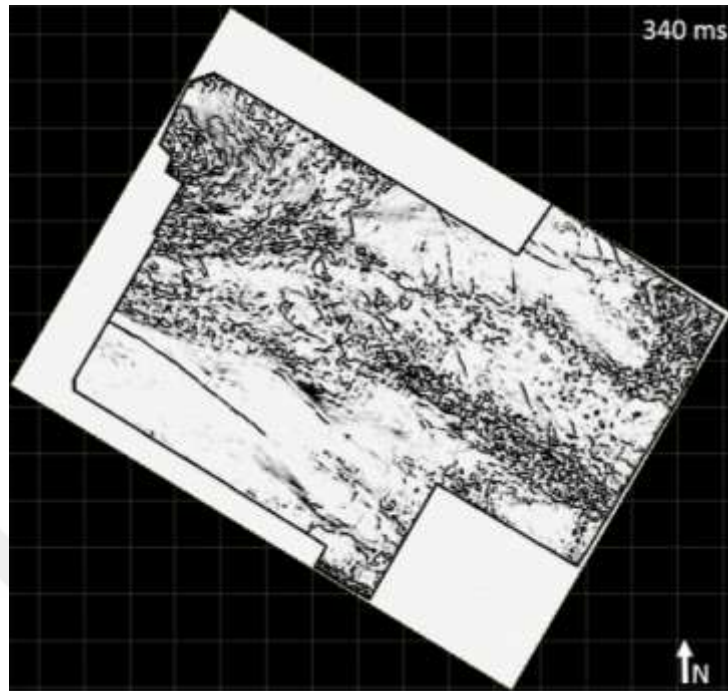
Figure 74. Variance slice from 480 msec from Arikaya 3D Data (some part of Kozardere merge data). **(a)** Un-interpreted data; **(b)** interpreted data that shows an ancient river course (red line) deformed (cut and offset) by faults that are related to younger strike-slip regime. Synthetic faults displaced the river course in a right-lateral sense.

lateral sense by a series of faults. The faults trend in N15°W and are interpreted as synthetic Reidel shears in a strike-slip fault zone; they are therefore interpreted to indicate a maximum shortening (contraction) direction (σ_1) of N05–10°W during this deformation. The synthetic faults are developed in 2.5 km distance apart. The horizontal displacements along these faults range between 100 and 600 meters.

Figures 75 to 84 demonstrate both un-interpreted and interpreted variance slices of the Kozardere 3D seismic variance cube in certain time intervals (340, 380, 530, 620, 840, 920, 1020, 1230, 1400, and 1450 msec). These time slices were chosen because they showed changes in structural elements and these elements are interpreted with red lines. There are several NW–SE-trending faults dominated in 340–380 msec variance slice sections taken in the Miocene strata. While the major faults trend N60°W (such as OKF), N10°–25°W-trending faults are also observable in relation with the major faults. The NE–SW-trending faults are visible in the 530 msec variance slice section with a number of N45°W-trending smaller faults. Section also shows a pronounced meandering channel as represented in blue color (Figure 77). The N20°–25°W-trending fractures/faults are visible in the northern part of the seismic data (northeastern corner in 640 msec time variance slice section) and they are attributed to the Şelmo High (Figure 78).

Also NE–SW-trending Şelmo faults are remarkable features in this slice. The NE–SW-trending Kumlupınar Fault (N50–60°E) becomes clearly visible in 840 msec variance slice section (Figure 79). The Kumlupınar Fault trend is conformable with Late Permian–Early Triassic structural trends in and around the study area (Figure 79). In this time interval, Kumlupınar Fault and similarly trending faults, however, demonstrate segmented and fragmented geometries due to disturbance of NW–SE-trending fault segments. There is a quite remarkable fault linkage profile along the Çelikli-Habandere Fault in the north in 920 msec variance slice (Figure 80).

(a)



(b)

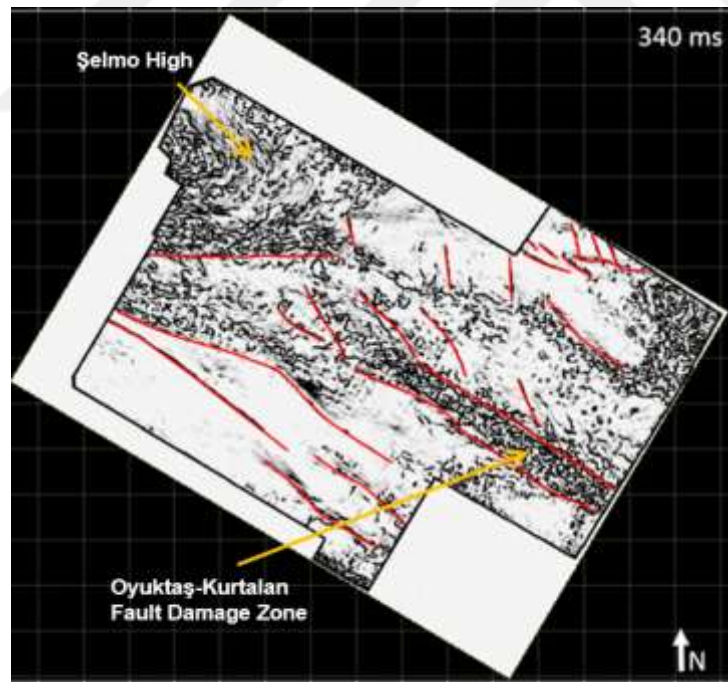
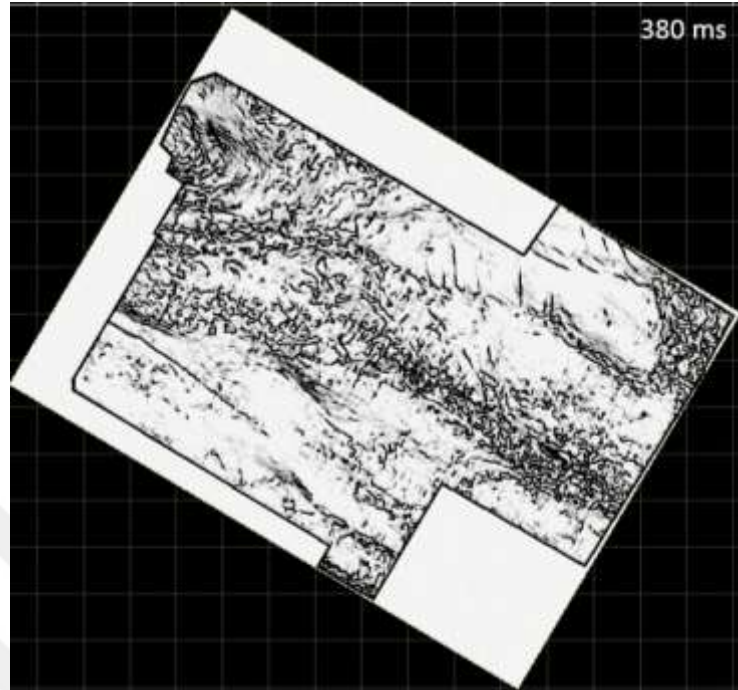


Figure 75. Variance cube time slices from 340 msec. **(a)** Un-interpreted data; **(b)** interpreted data that shows major faults and fractures with red lines. NW–SE-trending Oyuktaş-Kurtalan Fault damage zone is trackable from southeast through middle parts of study area. Şelmo High is located on the northwestern corner of the 3D seismic data.

(a)



(b)

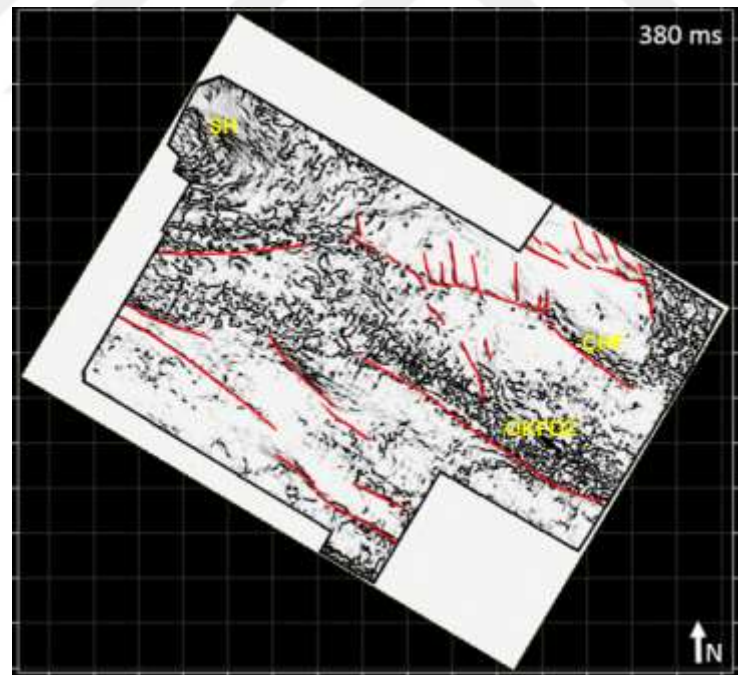


Figure 76. Variance cube time slice from 380 msec. **(a)** Un-interpreted data; **(b)** interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault damage zone (OKFDZ), Çelikli-Habandere Fault (ÇHF).

(a)



(b)

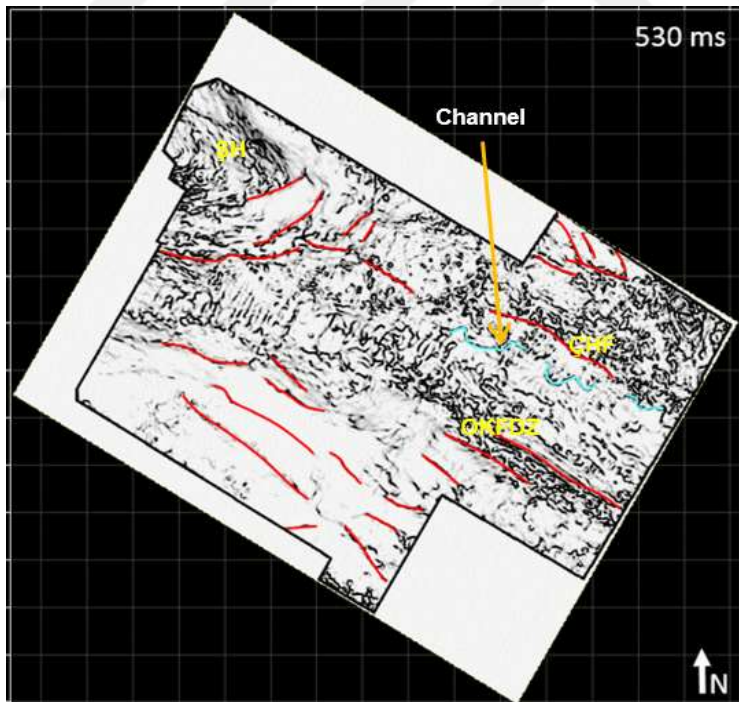
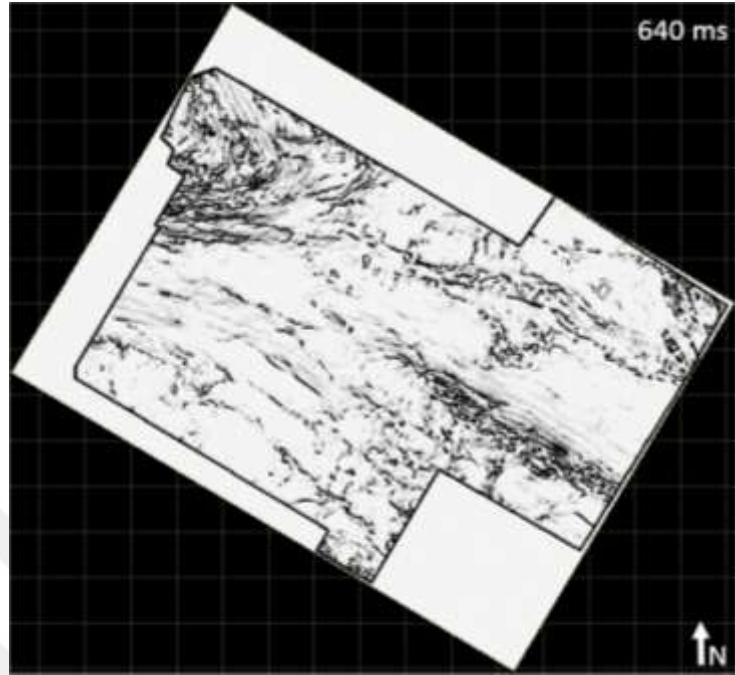


Figure 77. Variance cube time slice from 530 msec. **(a)** Un-interpreted data; **(b)** interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault damage zone (OKFDZ), Çelikli-Habandere Fault (ÇHF). Blue lines represent Miocene river channel.

(a)



(b)

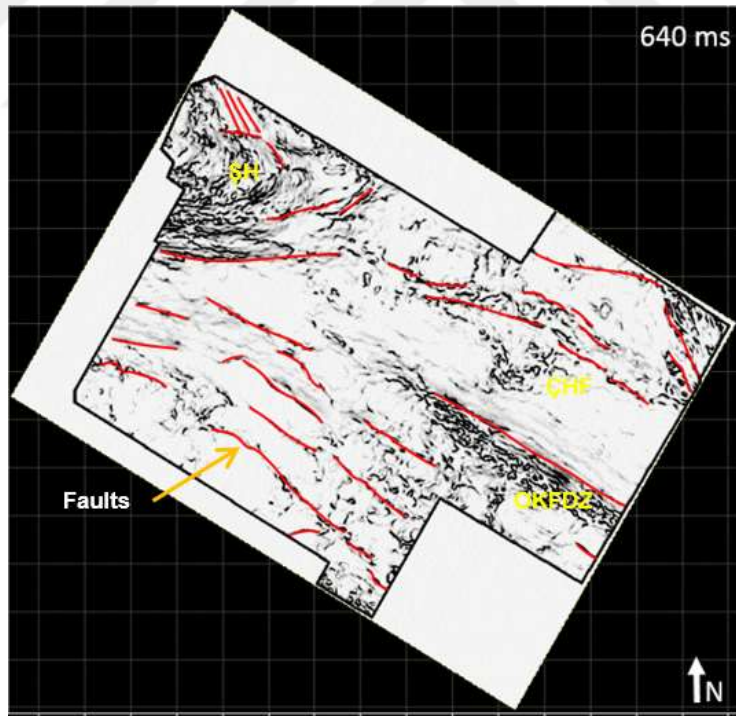
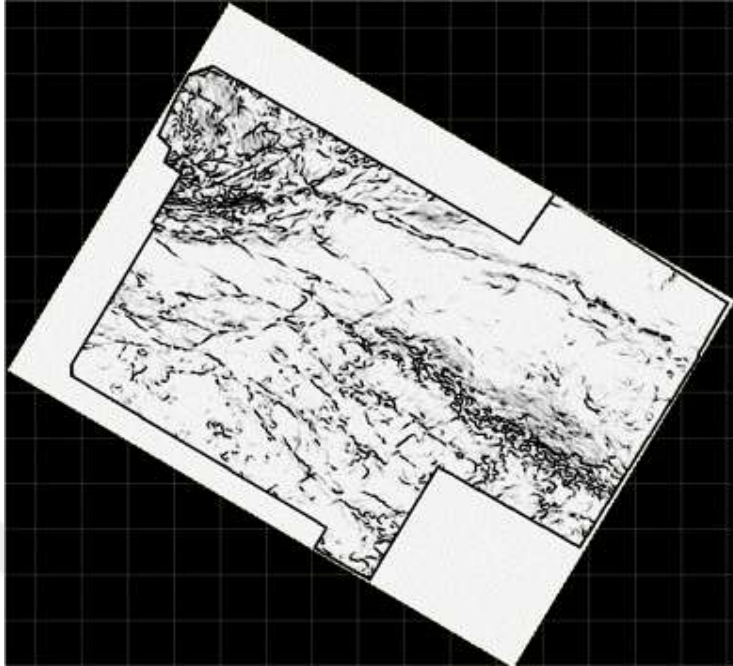


Figure 78. Variance cube time slice from 640 msec. **(a)** Un-interpreted data; **(b)** interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault damage zone (OKFDZ), Çelikli-Habandere Fault (CHF). NW–SE-trending many faults are visible in the south of time slice section.

(a)



(b)

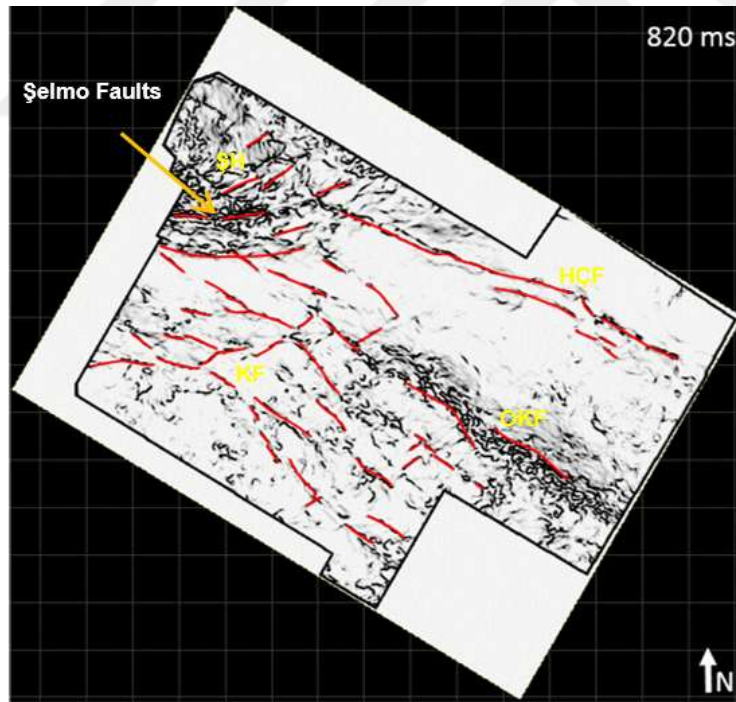
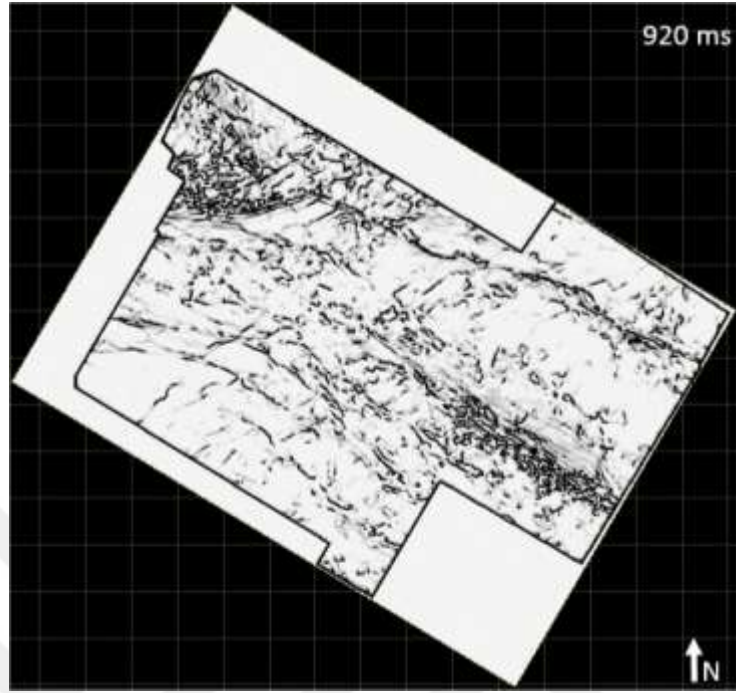


Figure 79. Variance cube time slice from 820 msec. **(a)** Un-interpreted data; **(b)** interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault (OKF), Kumlupınar Fault (KF), Çelikli-Habandere Fault (CHF). Faults that control the Şelmo high is visible on the slice.

(a)



(b)

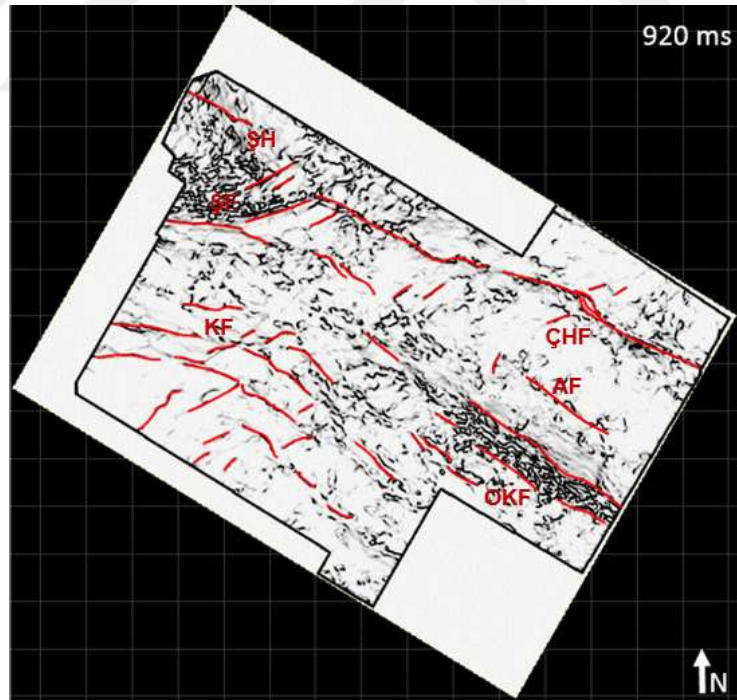
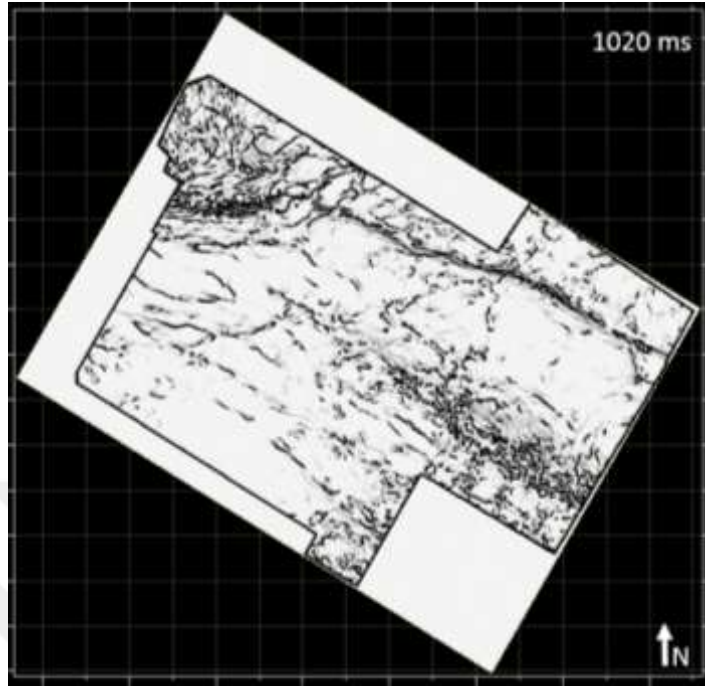


Figure 80. Variance cube time slice from 920 msec. **(a)** Un-interpreted data; **(b)** Interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Şelmo Faults (ŞF), Oyuktaş-Kurtalan Fault (OKF), Çelikli-Habandere Fault (CHF), Kumlupınar Fault (KF), Arıkaya Fault (AF).

(a)



(b)

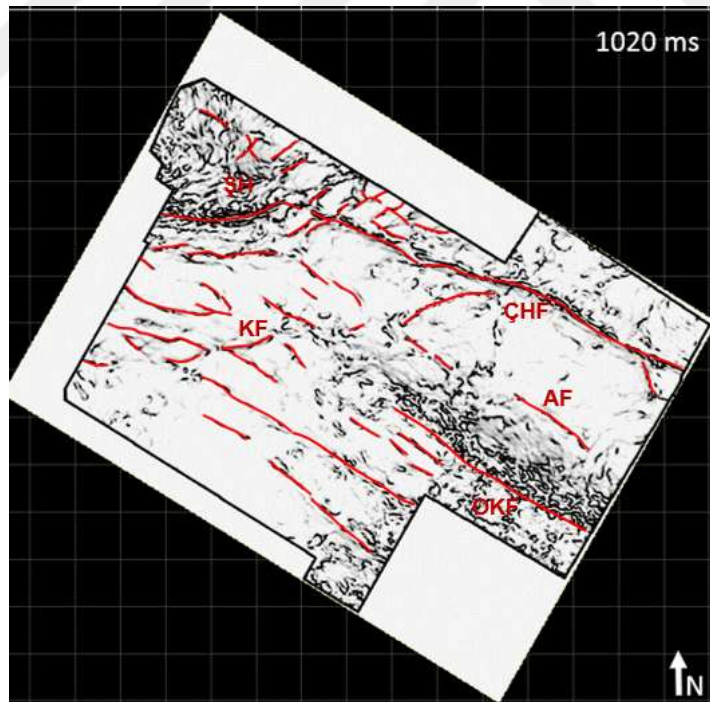
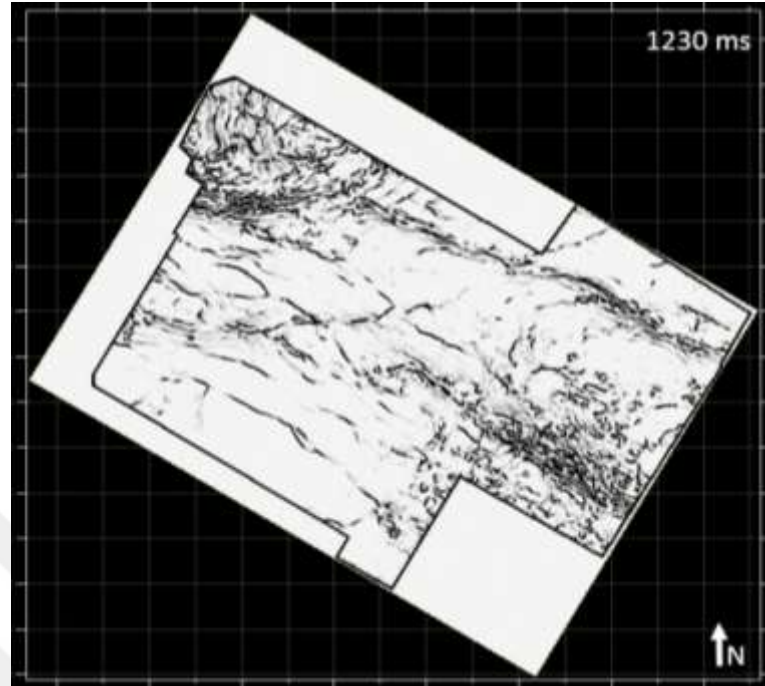


Figure 81. Variance cube time slice from 1020 msec. **(a)** Un-interpreted data; **(b)** Interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault (OKF), Çelikli-Habandere Fault (CHF), Kumlupınar Fault (KF), Arıkaya Fault (AF).

(a)



(b)

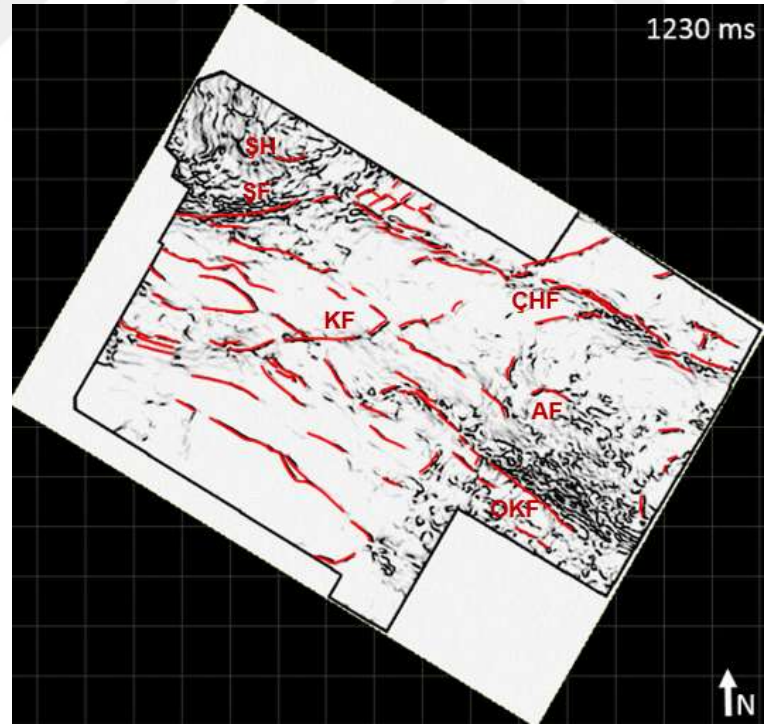
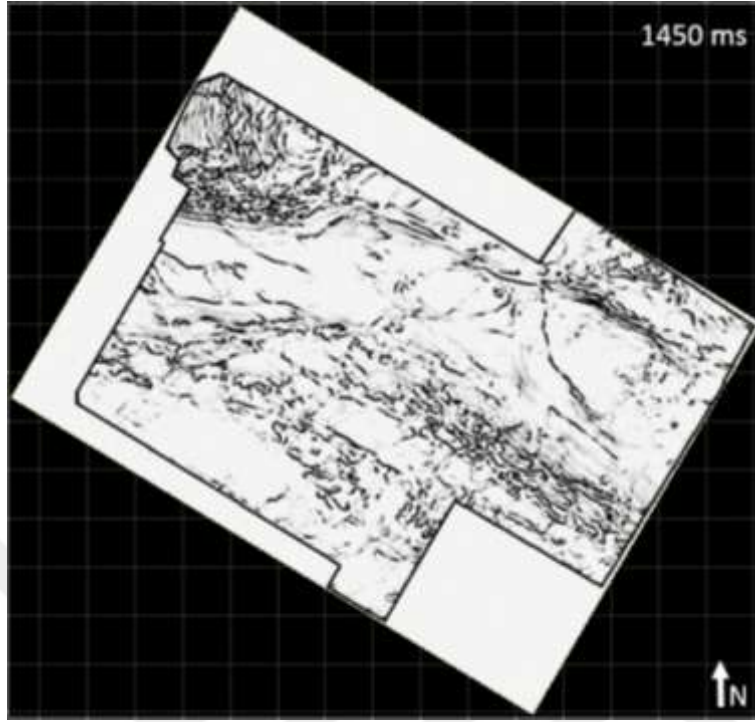


Figure 82. Variance cube time slice from 1230 msec. **(a)** Un-interpreted data; **(b)** Interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault (OKF), Çelikli-Habandere Fault (CHF), Kumlupınar Fault (KF).

(a)



(b)

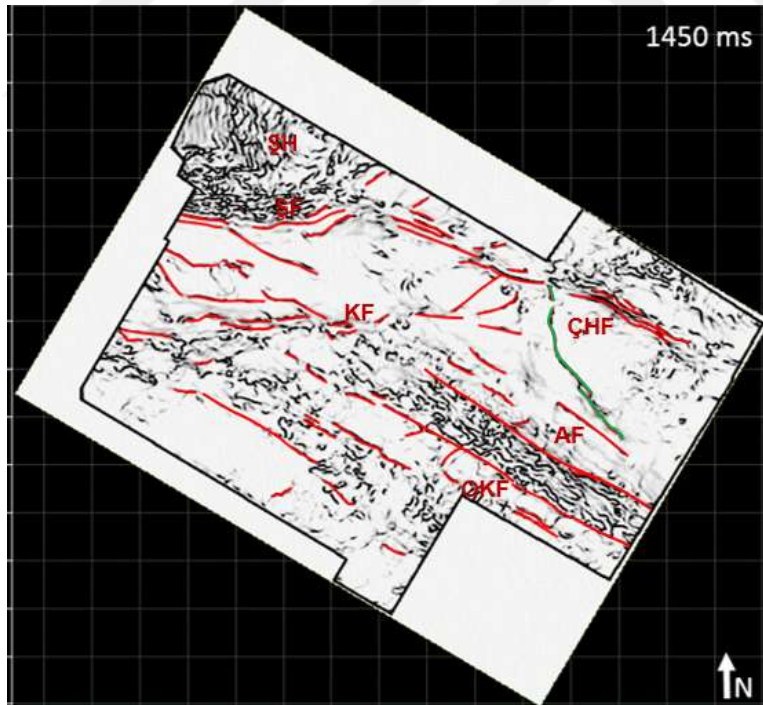


Figure 83. Variance cube time slice from 1450 msec.(a) Un-interpreted data; (b) Interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault (OKF), Çelikli-Habandere Fault (ÇHF), Kumlupınar Fault (KF), Arıkaya Fault (AF).

(a)



(b)

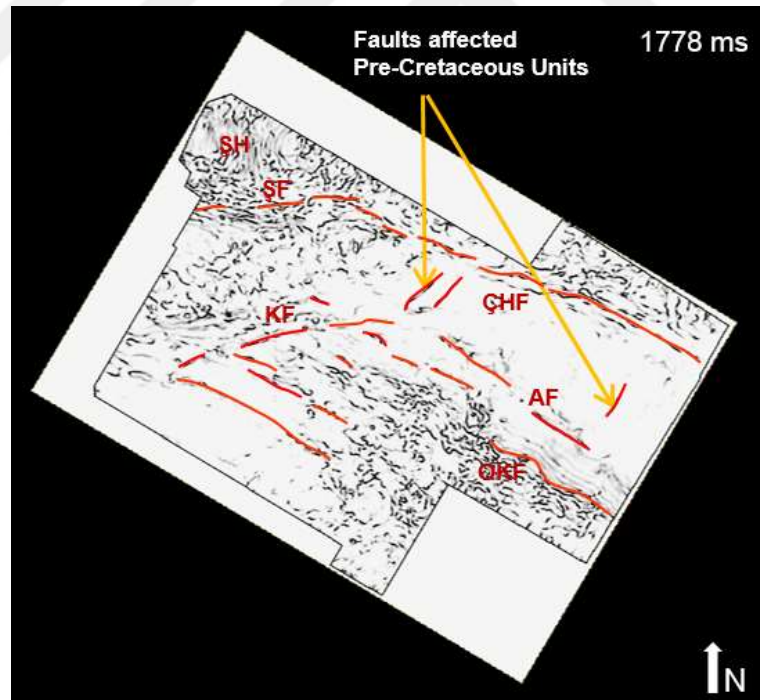


Figure 84. Variance cube time slice from 1778 msec. **(a)** Un-interpreted data; **(b)** Interpreted data that shows major faults and fractures in red lines. Şelmo High (ŞH), Oyuktaş Kurtalan Fault (OKF), Çelikli-Habandere Fault (ÇHF), Kumlupınar Fault (KF), Arıkaya Fault (AF).

The Oyuktaş-Kurtalan Fault damage zone can also be described very clearly in this slice. The Habandere-Çelikli Fault and the fault controlling southeastern flank of the Şelmo High can be connected in 1020 msec variance slice (Figure 81). The Kumlupınar Fault is identified as a much better plane and appears to continue as northern part of the Çelikli-Habandere Fault in 1230 msec variance slice. In 1400 and 1450 msec variance slices, deformation patterns are clearly described and faults are represented by moreless continuous single lines.

In 1450 msec variance slice section, there is a curved trend between the Çelikli-Habandere Fault (ÇHF) and the Arıkaya Fault (AF) against the common structural trends (Figure 83). This can be interpreted as a stratigraphic border developed during Maastrichtian carbonate deposition time. These trends are also observable in other 3D seismic cubes for the same lithological interval. The N30°E-trending normal faults are visible in 1778 msec variance slice (Figure 84). Also structural anomalies can be observed around these faults in the Campanian age succession. These anomalies can be attributed to highly fracture porous zones, dolomitization or karstification (Figure 85).

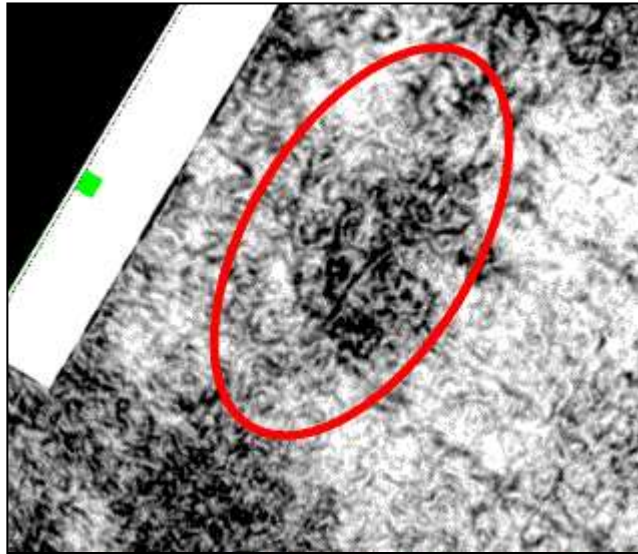


Figure 85. Seismic anomalies can be observed around faults in the Campanian succession. These anomalies can be attributed to highly fracture porous zones, dolomitization or karstification.

Figure 86 illustrates the faults and horizons interpreted in the crossline of 1600- in Kozardere 3D seismic line. The major faults Oyuktaş-Kurtalan and Çelikli-Habandere Faults are visible in section. Many faults have been interpreted and then used to map key horizon levels.

When a smaller area is cropped and a variance attribute is created in the 3D seismic dataset, details of the discontinuities and their intersection points can be more clearly observed. The snapshot in Figure 87a is developed by focusing the vicinity of the Kumlupınar Fault area in the time section of 1532 msec; and shows how NE–SW-trending Kumlupınar Fault (KF) cut and displaced by NW–SE-trending younger faults. Similar Figure 87b is obtained by focusing the vicinity of the Çelikli-Habandere Fault (ÇHF) in the time section of 868 msec; and shows how NE–SW-trending older faults cut and displaced by NW–SE-trending Çelikli-Habandere Fault (ÇHF).

Similar observations can be traced east of the study area along 3D seismic data variance map sliced from 1388 msec that represents Permian section; the NE–SW-trending older faults are cut and displaced by NW–SE-trending younger faults. The right-lateral movements can be observed along younger faults (Figure 88). These faults may have lateral displacements up to 250 meters in this region. Also, the prints of left-lateral displacement along NE–SW-trending faults can be observable in time slices of Kozardere 3D data as shown in Figure 89. There are also fault linkage and pull-apart formation observable in a neighbouring 3D seismic data 1160 msec variance slice (Upper Cretaceous section) located 10 km south of the study area (Figure 90). The fault linkages are very common phenomena between NW–SE-trending faults in the study area and its surroundings. Faults grow into large structures, up to hundreds of kilometers along strike, by linkage of several smaller fault segments. The displacement variations along fault linkages can be related to many parameters such as lithology, deformation patterns, and fault profiles (cf. Peacock, 1991).

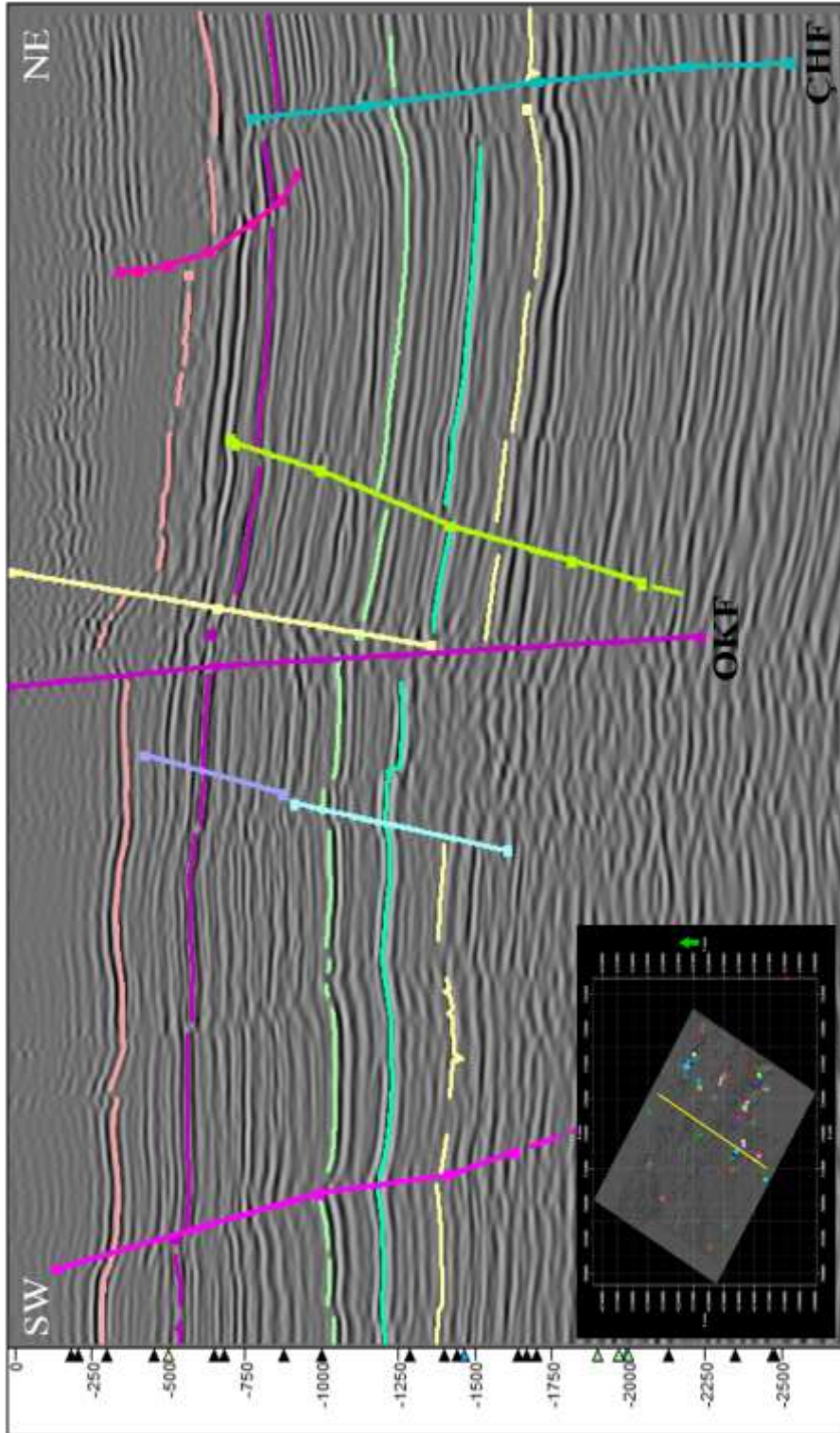
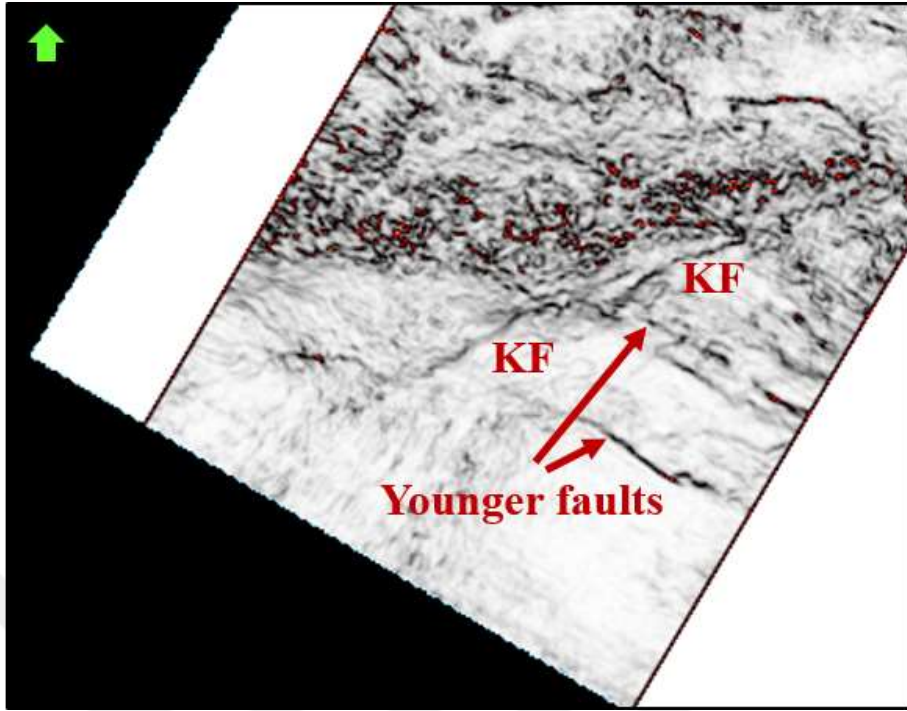


Figure 86. NE-SW-directed seismic crossline shows the interpretation of faults and key stratigraphic horizons. Base Miocene (light pink), Top Paleocene (pink), Top Cretaceous (light green), Top Campanian (green), and Base Cretaceous (yellow) seismic horizon interpretations and the major fault Oyuktaş-Kurtalan (OKF) and Çelikli Habandere (ÇHF) faults are marked in crossline 1600- Kozardere 3D seismic data.

(a)



(b)

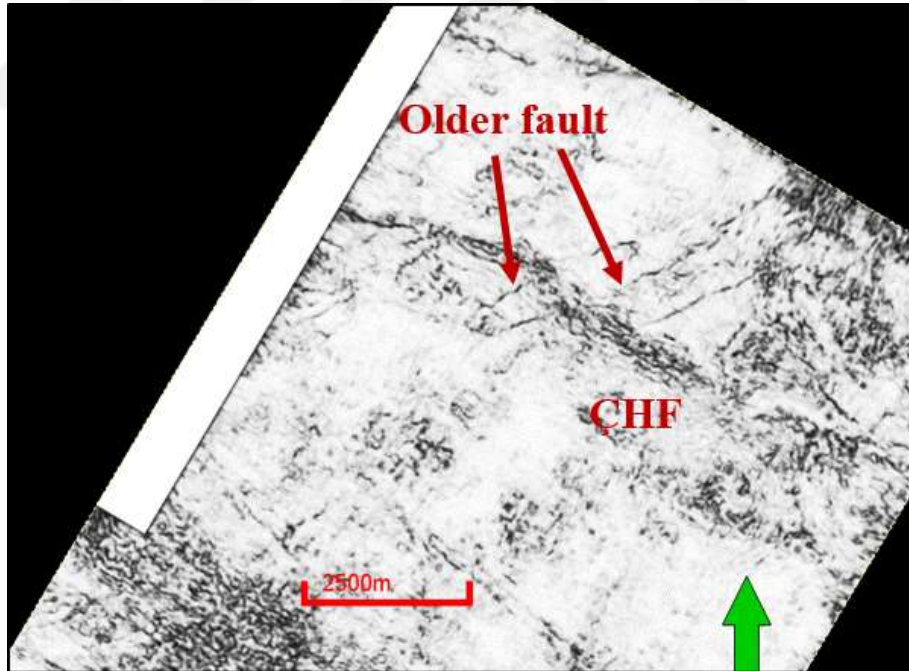


Figure 87. (a) NE–SW-directed Kumlupınar Fault (KF) is cut and displaced by NW–SE-trending younger faults, Kozluk 3D variance cube slice from 1532 msec. **(b)** NE–SW-trending older faults cut and displaced by NW–SE-trending Çelikli-Habandere Fault (CHF), Arıkaya 3D variance cube slice from 868 msec.

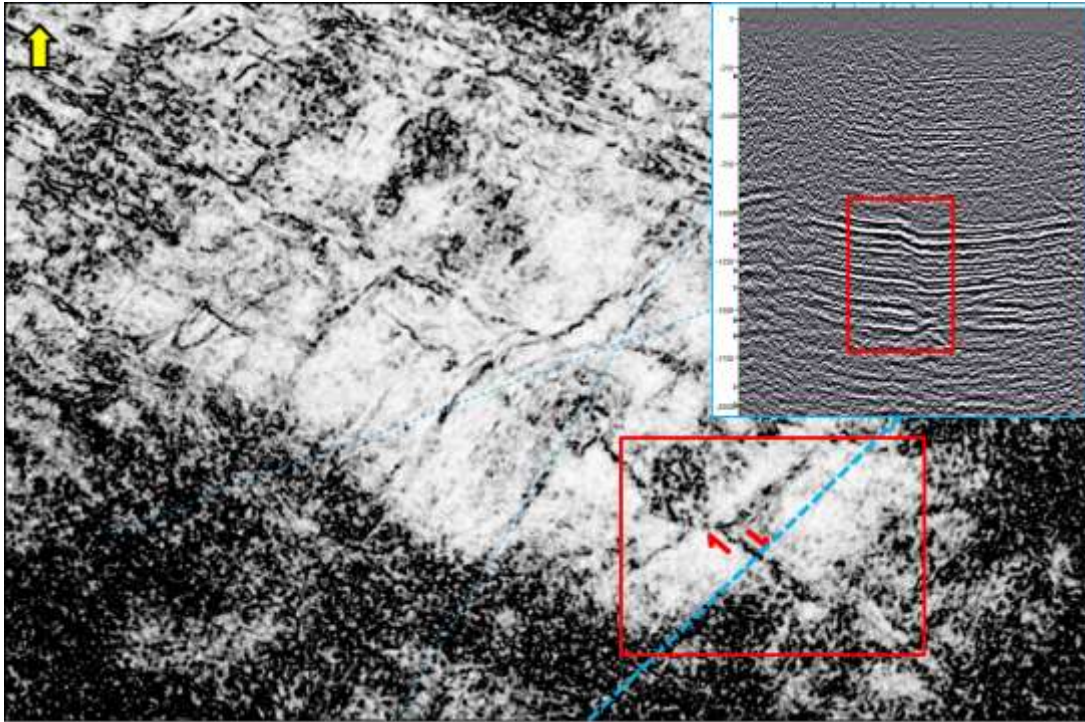


Figure 88. Variance map from 1388 msec variance slice (Permian section) from south of the study area. NE–SW-trending ($N45^{\circ}E$) faults are cut and displaced by NW–SE-trending younger faults. The lateral displacement is 250 meter in the area marked by red box. The dashed blue line represents the direction of seismic section. The yellow arrow indicates north.

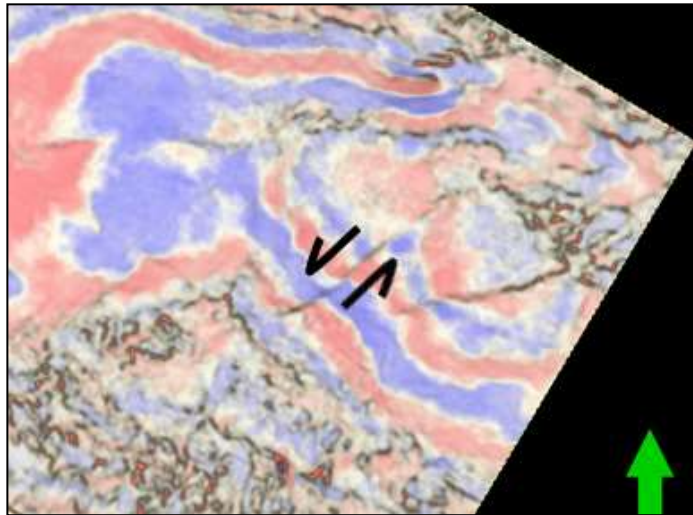


Figure 89. Kozardere 3D time slice from 1495 msec illustrates a NE–SW-trending fault located north of the Çelikli-Habandere Fault. The left-lateral movement is obvious.

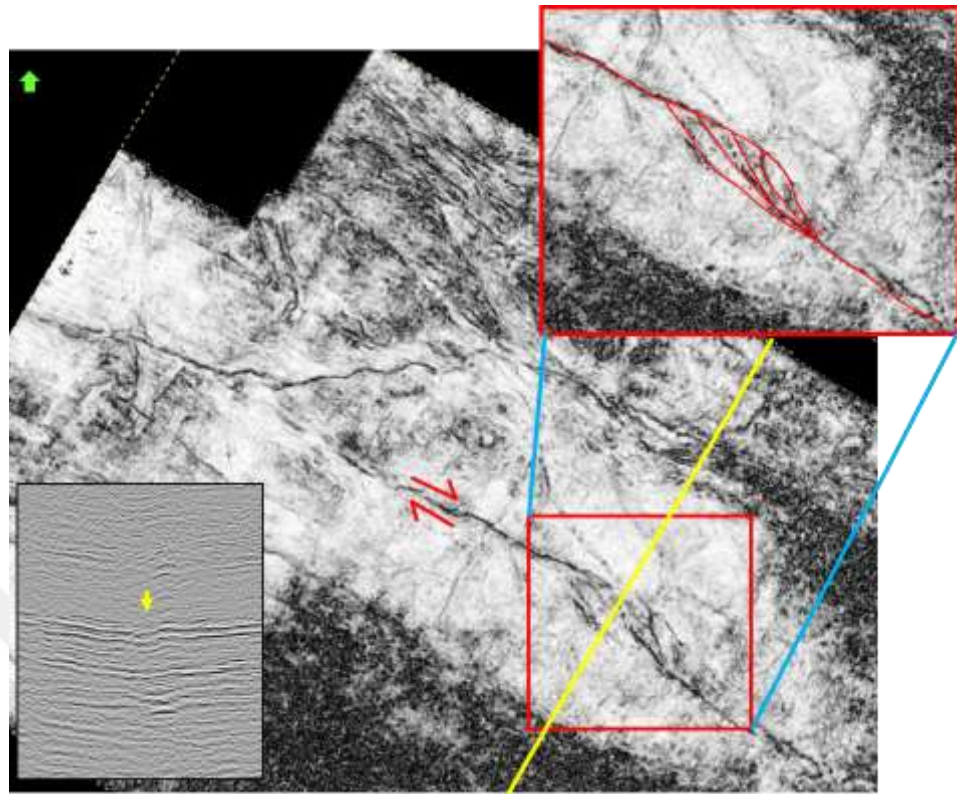


Figure 90. Variance map from 1160 msec variance slice (Upper Cretaceous section) from south of the study area. On the left side of the map, the NE–SW-trending older fault is cut, displaced and gains rugose shape due to strike-slip deformation by younger faults (blue box). The red box shows the linkage between NW–SE-trending right-lateral oblique faults. The linkage area creates a zone of extension or releasing bend.

4.1.3. 3D Horizon and Fault Models

In the 3D survey area, the fault and horizon surfaces are used to construct a geologically realistic 3D model. For each horizon – Base Miocene, Top Paleocene, Top Cretaceous, Top Campanian and Base Cretaceous – 3D horizon models are built and are then employed to investigate topographic highs and lows, depo-centers, and faults that cut through the structural features in the depth domain of each horizon. Fault models are, based on picks on the 3D survey, generated and they mainly trend in NW–SE direction. Combined inline, crossline, time-slice, and variance cube data

are used to evaluate the consistency and thoroughness of the fault models across the 3D survey.

First, the surface maps of each horizon have been generated by using horizon and fault picks. The convergent interpolation algorithm is used for mapping with 25 meter grid increment both in time and depth domains. The convergent interpolation is a control point oriented surface gridding and smoothing algorithm and is used especially for (i) building a structural model, (ii) creating single surface model and (iii) smoothing a grid. The time to depth conversion is applied by converting the RMS velocity model cube into average velocity model. While hot colors (yellow to red) represent topographically high areas, cold colors, topographic lows (blue to purple) in maps (Figures 91 & 92).

There are minor differences between time and depth maps for each horizon intervals. There is a distinct trough area bounded by NW–SE-trending Çelikli-Habandere Fault in the northern part of the study area as illustrated in time and also depth maps (Figures 91 & 92). The depocenter area expands southward and becomes an area delimited by the Oyuktaş-Kurtalan Fault in the south and the Şelmo High in the northwest (see Top Paleocene horizon maps in Figures 91 & 92). In addition, the Top Paleocene and Top Cretaceous maps serve to visualize the effect of intense faulting as illustrated by a dense fault pattern (Figures 91 & 92). These faults mostly trend in NW–SE direction; the NE–SW-trending Kumlupınar Fault is also detectable in these maps. The formation of a significant deposition area on the western part of the mapped region can be followed in the Base Cretaceous maps (Figures 91 & 92). This can be related with the activity of the Kumlupınar Fault and the fault that controls the southern margin of the Şelmo High. Also the NW–SE-trending smaller faults can be definable in the Base Cretaceous time and depth maps (Figures 91 & 92). The horizon depth surfaces, depth converted fault interpretations (Figure 93 & 94), and zones are used to develop final 3D geological structural model (Figures 95 – 101).

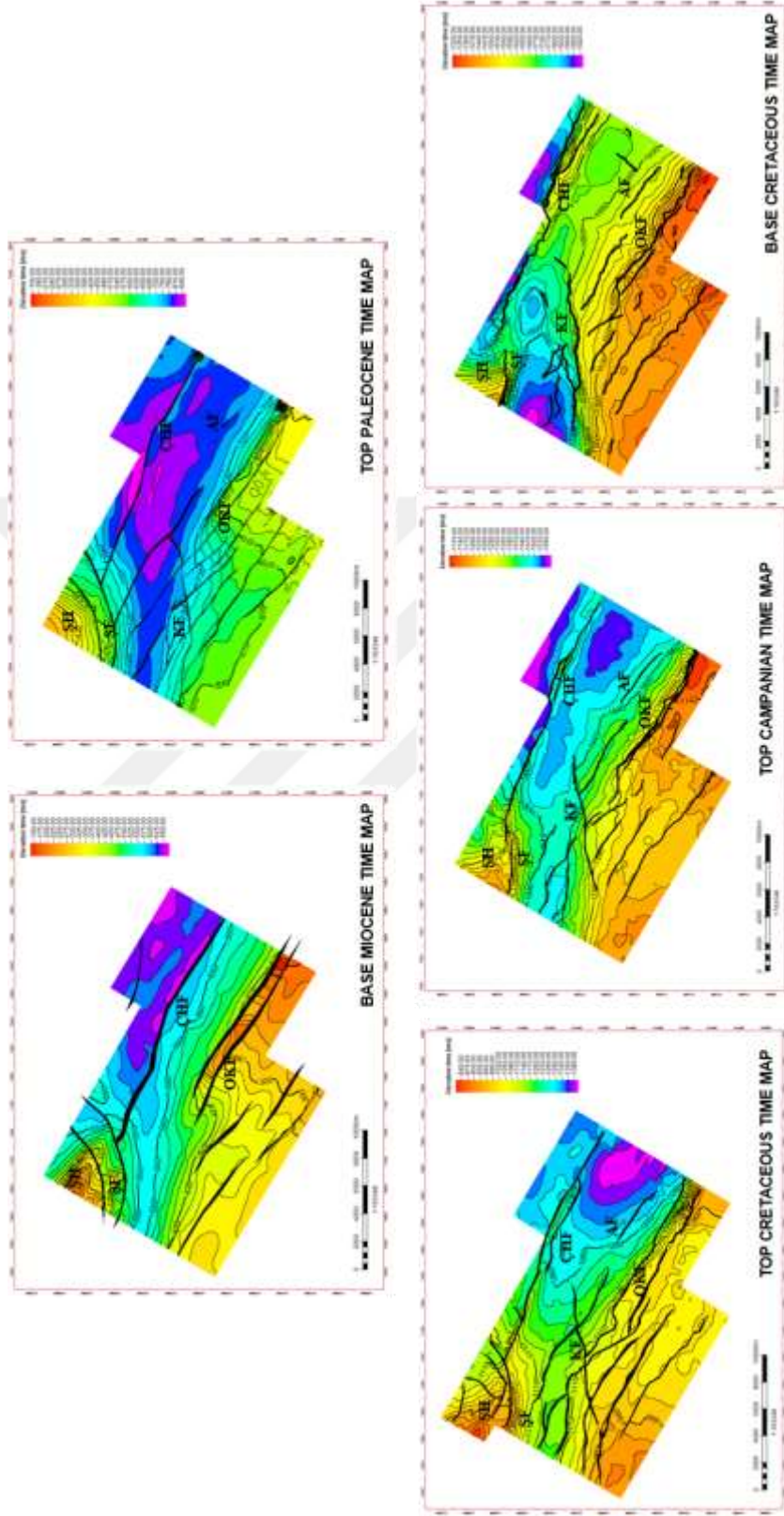


Figure 91. Base Miocene, Top Paleocene, Top Cretaceous, Top Campanian, Base Cretaceous horizons time maps generated in Petrel v. 2006 by using convergent interpolation algorithm with 25 m grid increment. Şelmo High (ŞH), Şelmo Fault (ŞF), Oyuaktaş Kurtalan Fault (OKF), Çelikli-Habandere Fault (ÇHF), Kumlupınar Fault (KF), Arıkaya Fault (AF).

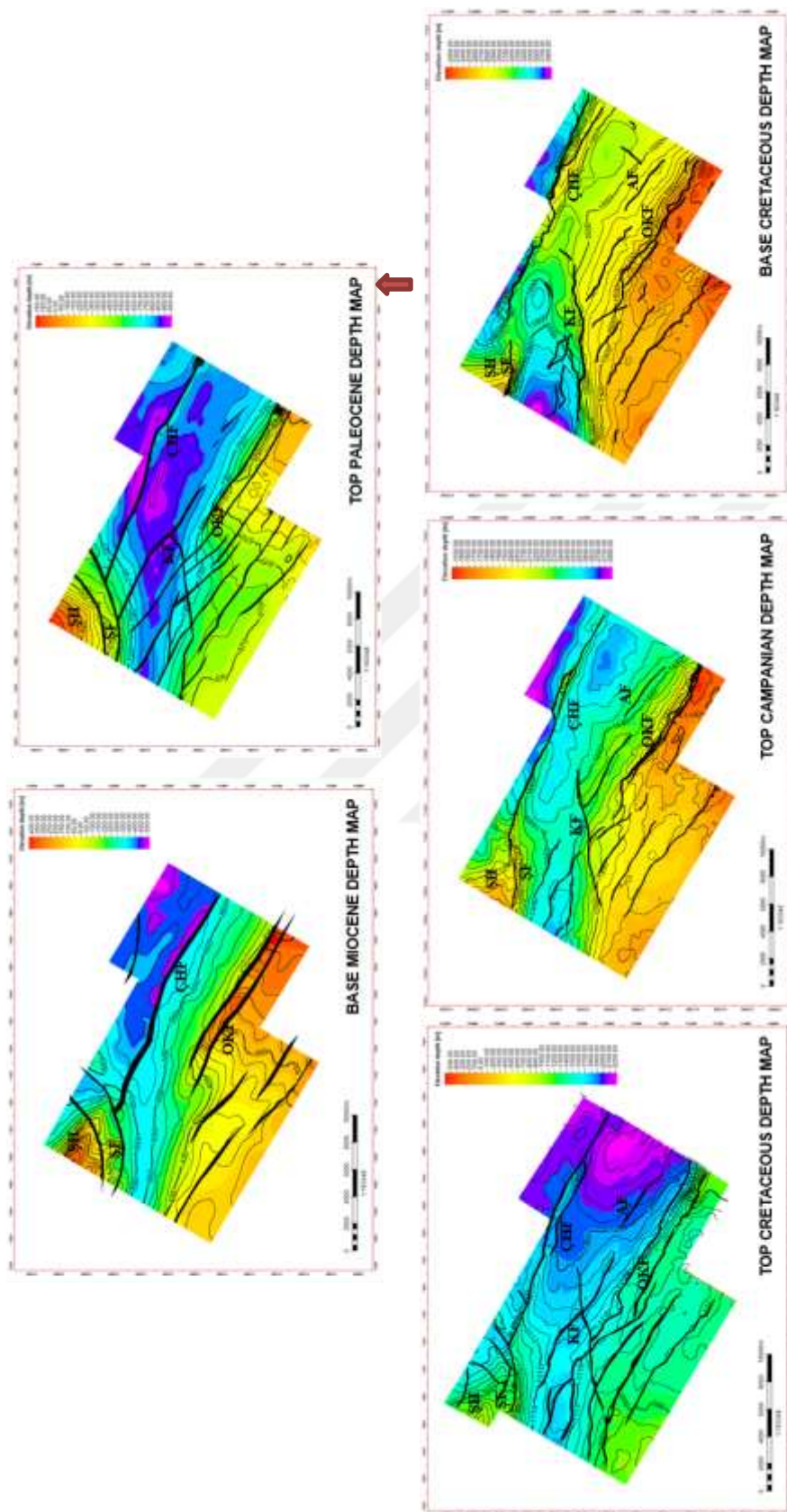


Figure 92. Base Miocene, Top Paleocene, Top Cretaceous, Top Campanian, Base Cretaceous horizons depth maps generated in Petrel v. 2006 by using convergent interpolation algorithm with 25 m grid increment. The depth maps have been generated from stacking velocity cube. Şelmo High (SH), Şelmo Fault (SF), Oyuktaş Kurtalan Fault (OKF), Çelikli-Habandere Fault (CHF), Kumlupınar Fault (KF), Arıkaya Fault (AF).

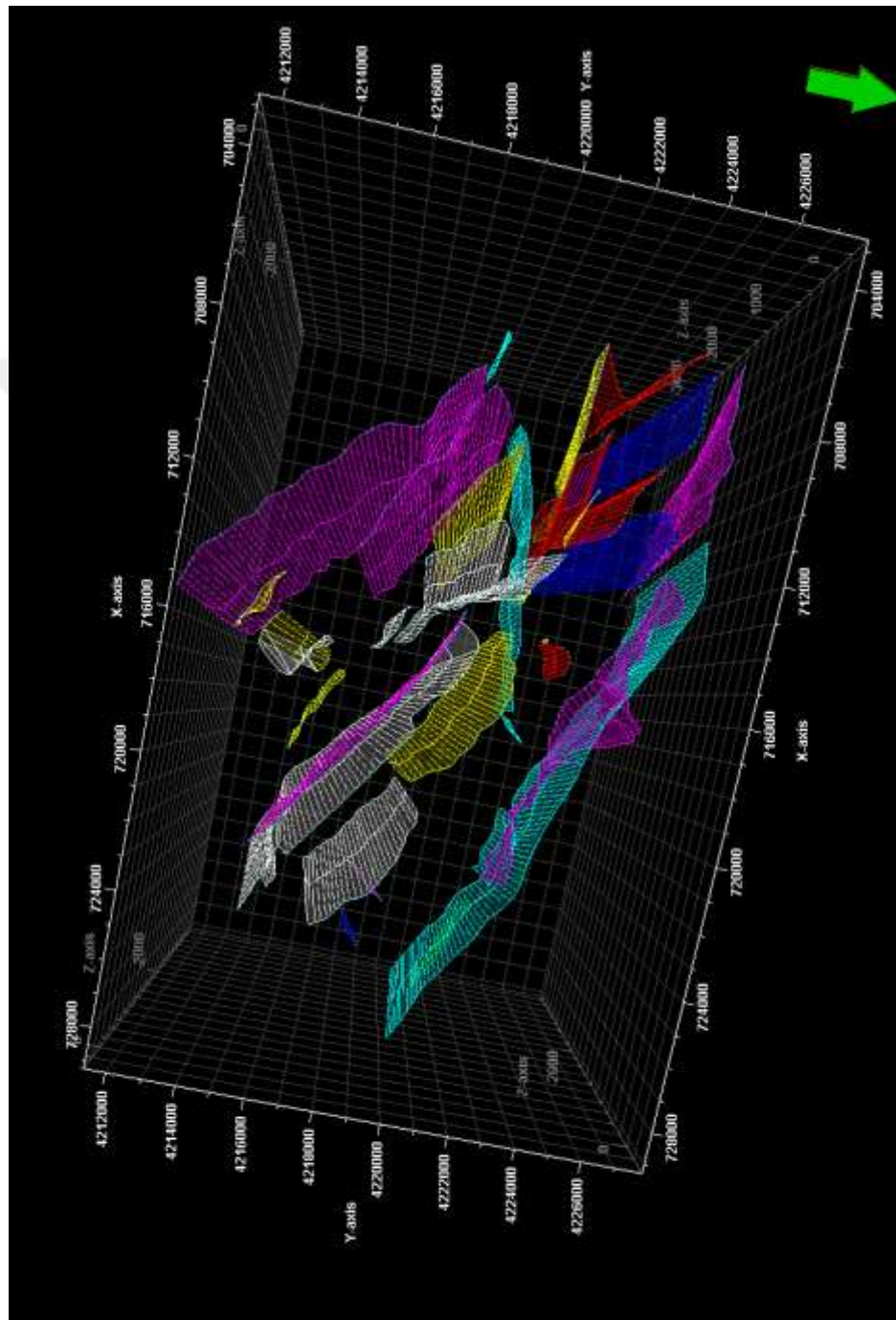


Figure 93. Depth converted fault interpretation used for structural modeling.

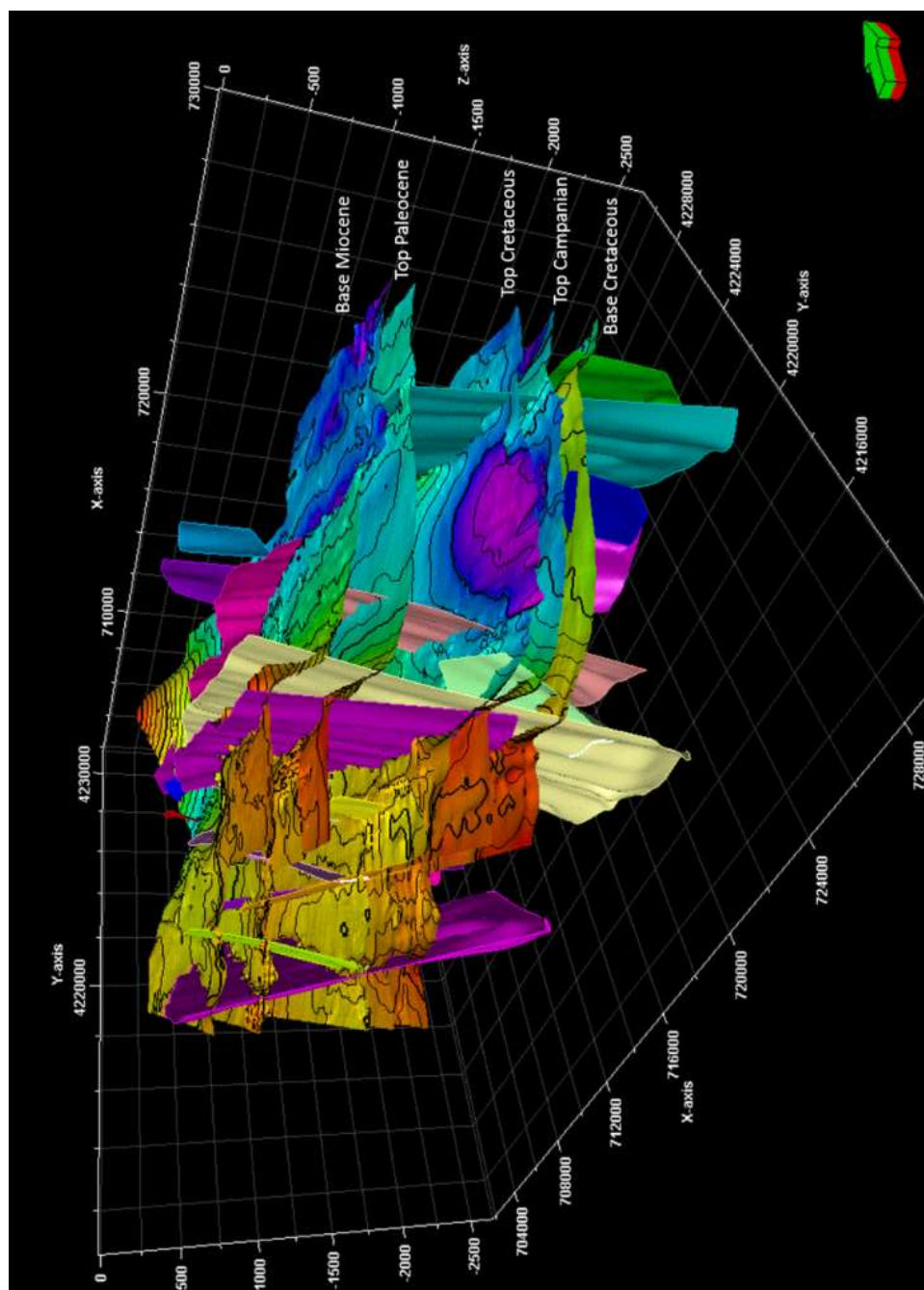


Figure 94. Horizon and fault interpretation used for modeling.

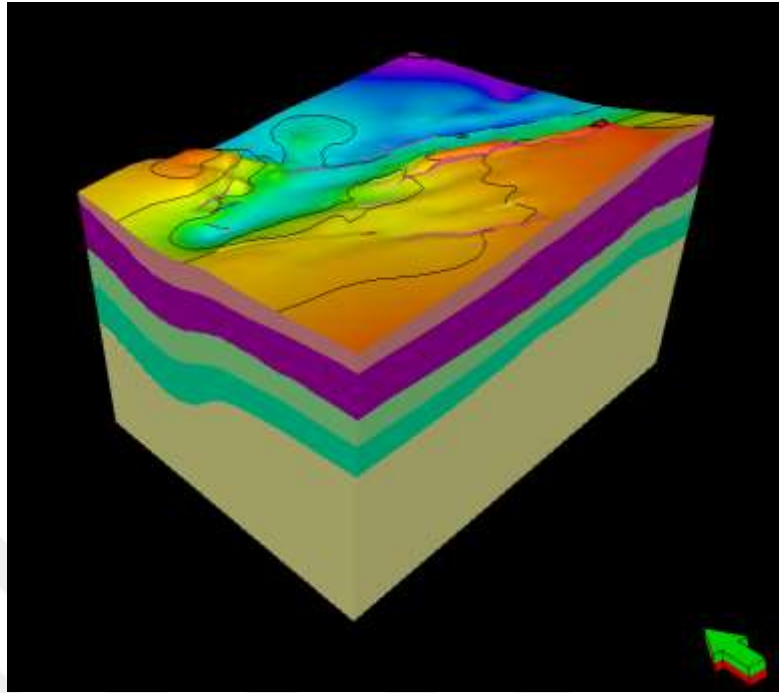


Figure 95. Geomodel of the study area developed from structural and stratigraphic interpretation of the Kozardere 3D seismic data. Pink Level, Eocene–Oligocene Succession; Purple Level, Paleocene Succession; Light Green Level, Upper Maastrichtian; Green Level, Lower Maastrichtian–Campanian; Yellow Level, Lower Cretaceous.

Once the model cube has been generated, it is possible to cut intersection lines from anywhere in the cube to analyze the model in cross sectional view. Four different north–south directed cross section intersections have been generated and shown in intersection windows (Figures 97 & 98).

Top to the bottom intersections demonstrate the change from west through east in the study area in the 5 km depth range (Figure 98). The layers represent Miocene, Eocene–Oligocene, Paleocene, Maastrichtian, Campanian–Lower Cretaceous and pre-Cretaceous successions. The fault displacements and formation thickness variations indicate that some of the faults have developed during the Cretaceous time, became reactivated over time, accompanied deformation and shaped the depositional environments.

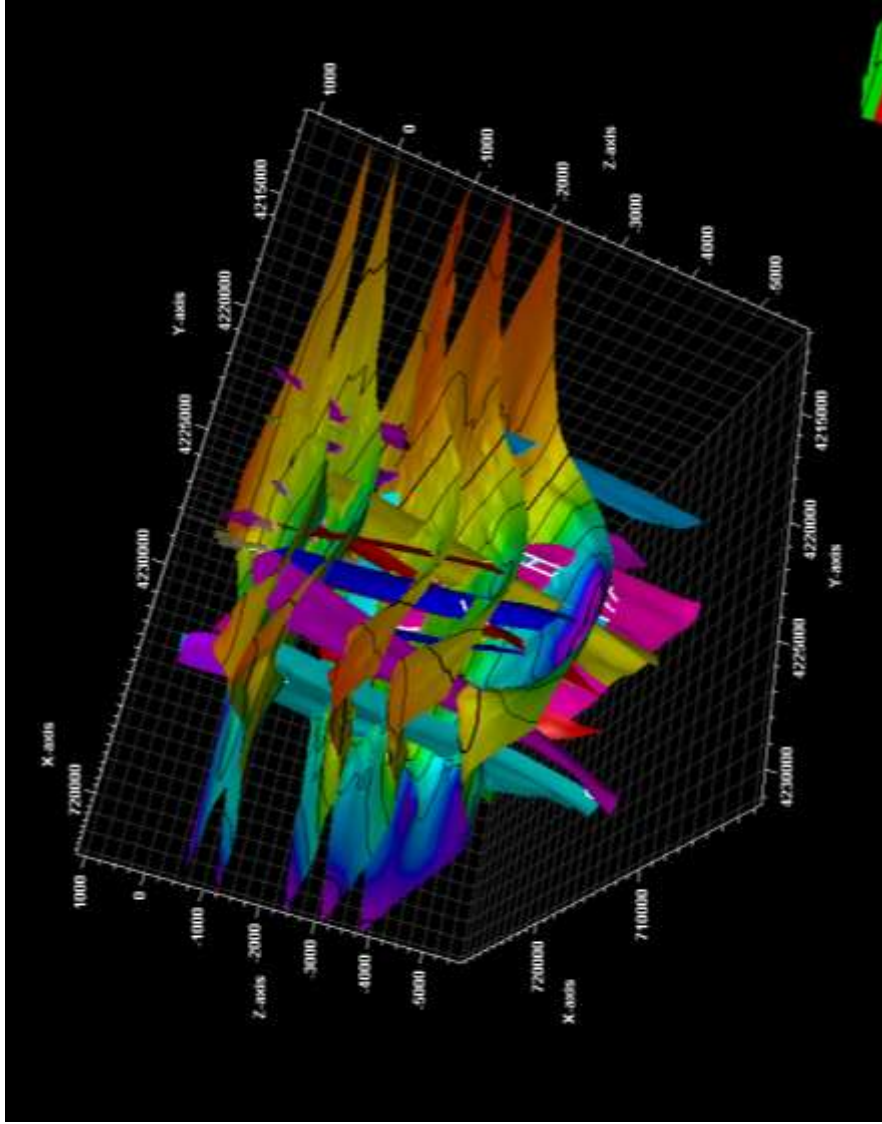


Figure 96. Geomodel for study area showing five key stratigraphic levels and all fault interpretations of the Kozardere 3D seismic data. Five horizons from top to bottom: Base Miocene, Top Paleocene, Top Cretaceous, Top Campanian, Base Cretaceous. Hot colors on surfaces represent shallower depths.

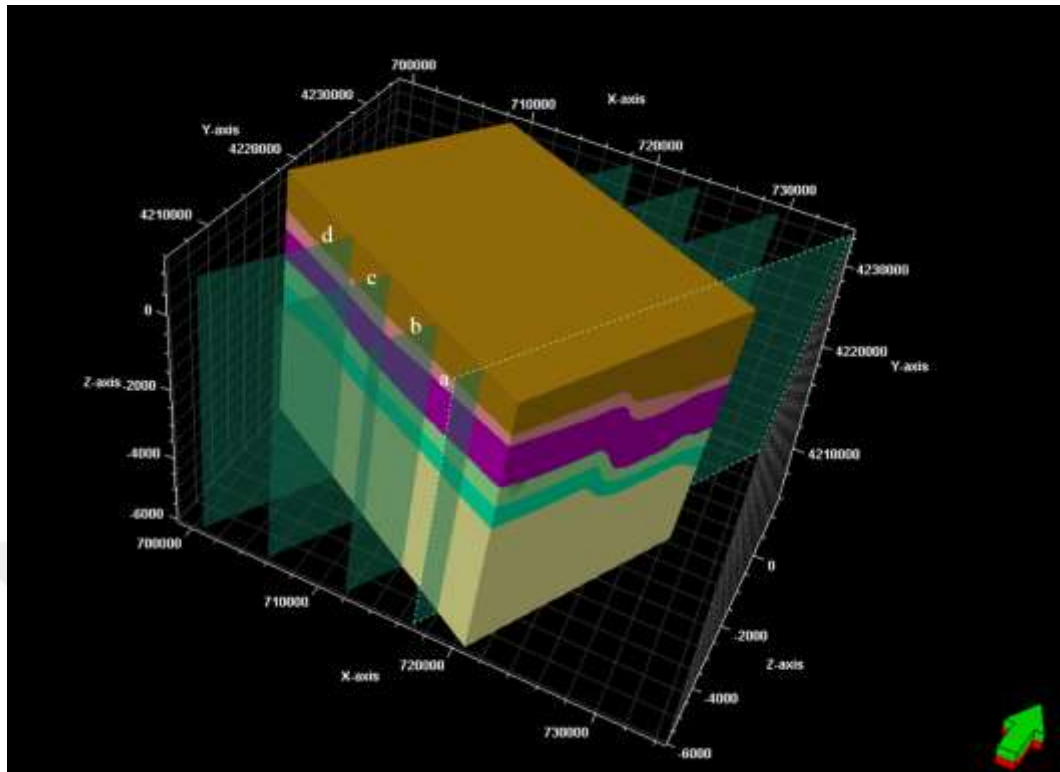


Figure 97. The location of N–S-directed model cross sections. Pink Level, Eocene-Oligocene Succession; Purple Level, Paleocene Succession; Light Green Level, Upper Maastrichtian, Green Level; Lower Maastrichtian–Campanian; Yellow Level, Lower Cretaceous. a through d shows location of cross sections in Figure 101.

Figure 99 shows model zone sections and the location of major faults in 3D window. Also more S–N directed modeled cross sections can be visualized using 3D window (Figures 100, 101). These cross sections effectively demonstrate the change in the NW-SE trending structural styles.

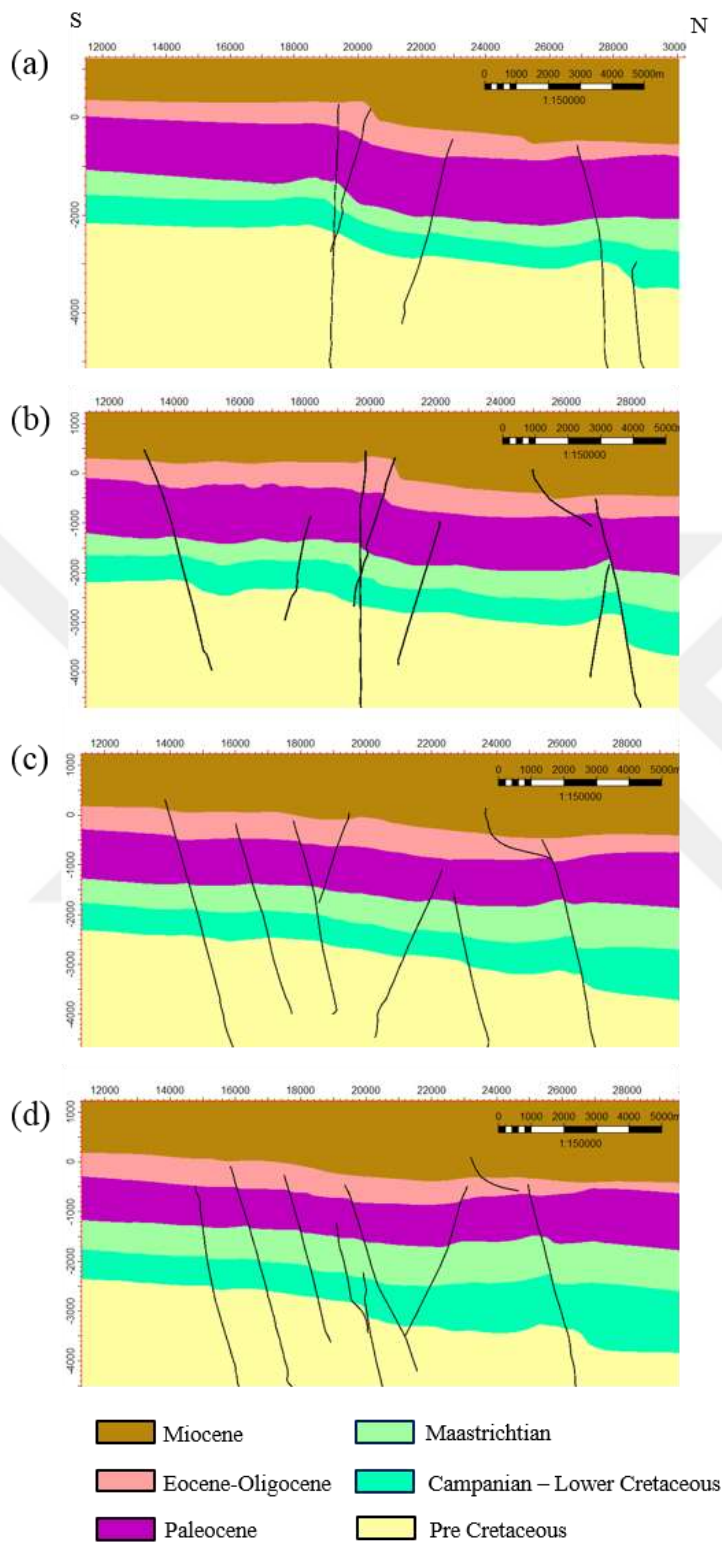


Figure 98. S–N-trending model cross sections demonstrated on intersection window from top to bottom shows the change from east to west. See Figure 98 for location of the sections and legend.

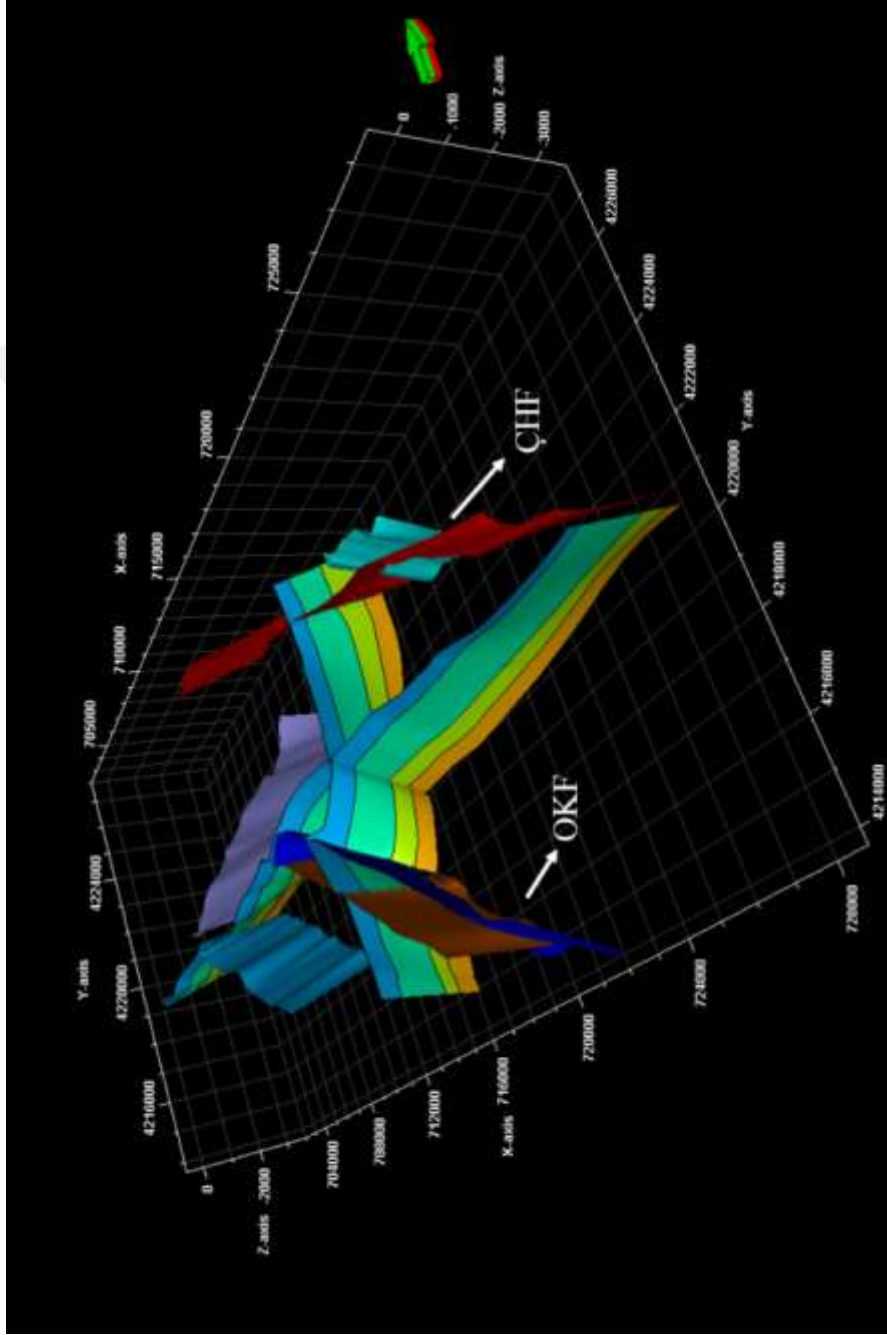


Figure 99. Model sections with major faults OKF: Oyuktaş-Kurtalan Fault, ÇHF: Çelikli-Habandere Fault. Blue zone: Eocene-Oligocene; green zone: Paleocene; light green: Maastrichtian; orange zone: Campanian-Aptian successions.

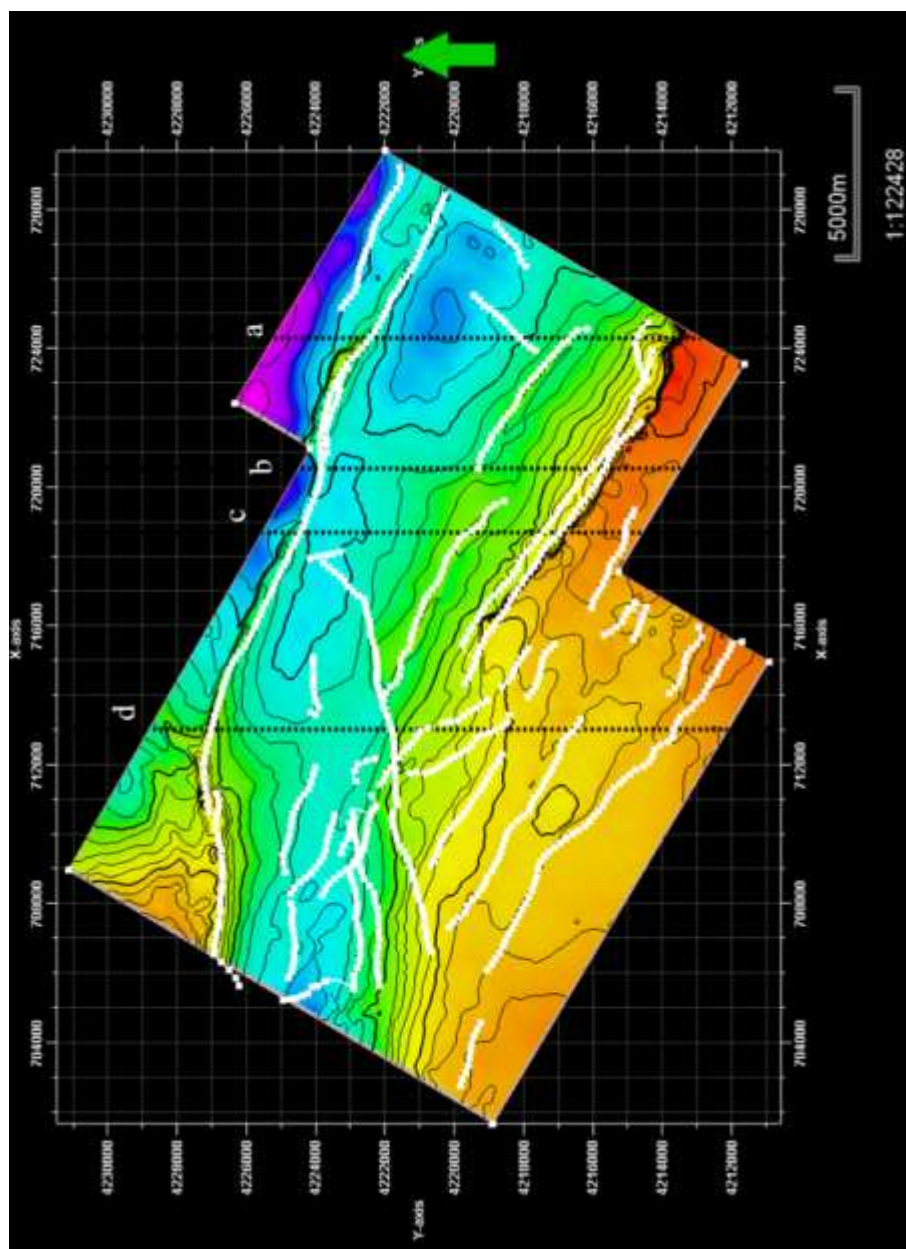


Figure 100. The location of S-N directed model cross sections on Top Campanian depth map. a thorough d shows location of cross sections in Figure 101.

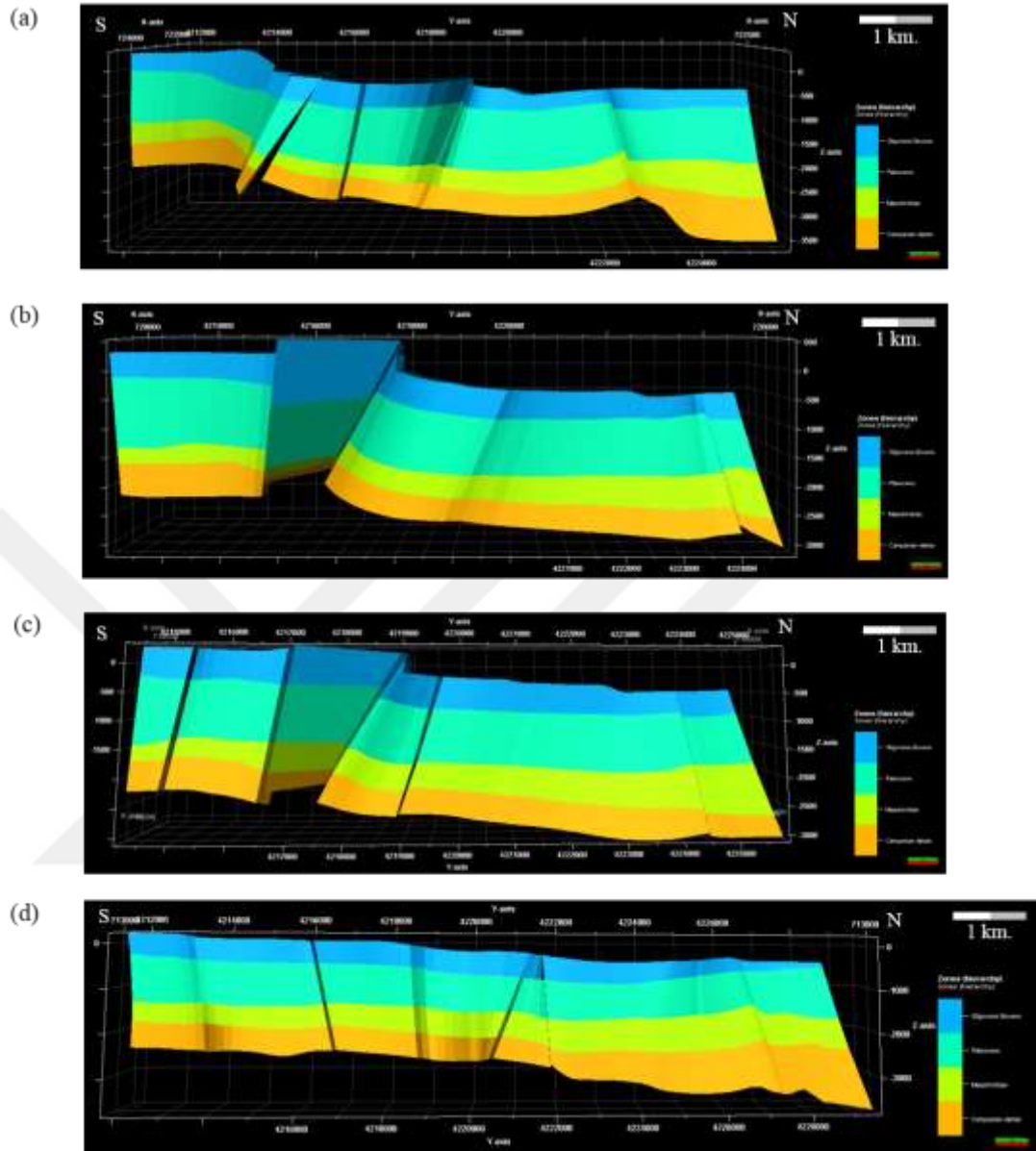


Figure 101. S–N-trending model cross sections from top to bottom show the change from east to west on 3D window. See Figure 100 for location of the sections and legend. Blue zone: Eocene-Oligocene; green zone: Paleocene; light green: Maastrichtian; orange zone: Campanian-Aptian successions.

4.2. Borehole Evaluation

4.2.1. Image Log Interpretation

From the wells drilled in the study area, the information about the orientation of the present day stress field can be determined by using either logging tools such as XRMI, FMI, and FED or borehole elongations. By oriented logging tools the borehole breakouts and/or drilling induced fractures are identified and then orientation of the maximum horizontal stress can be measured. The maximum horizontal stress (σ_{Hmax}) should be parallel to drilling induced fractures and perpendicular to the direction of borehole breakouts (Figure 102). As is seen on the examples illustrated in Figures 103 and 104, while the drilling induced fractures oriented almost in N–S direction, the strike of the borehole breakouts is in east–west direction. The image log data (XRMI) of the 9 wells drilled in the study area have been analyzed. The orientations of borehole breakouts and drilling induced fractures of the Upper Cretaceous intervals have been measured and the results have been plotted in a rose diagram (Figure 105). The rose diagram indicates that the present-day maximum horizontal stress (σ_{Hmax}) is oriented in N–S direction. And, this is consistent with fault plane solutions of recent earthquakes with focal mechanisms (see section 3.3 for more information).

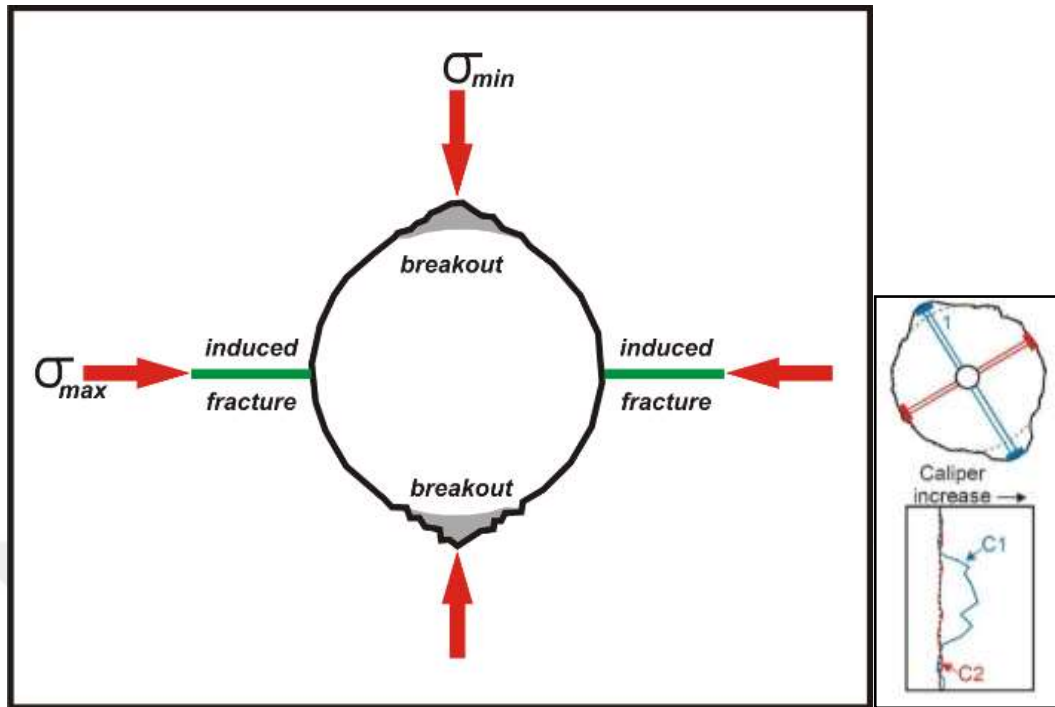


Figure 102. Representation of orientation of breakouts and drilling induced fractures with stress orientations in the borehole.

Figure 106 shows the processed borehole image data (XRMI) for well Arikaya-3 and illustrates the orientations of beddings, conductive (open), and resistive (healed) fractures. The existing data for other wells in the study area have been processed in TPAO well log evaluation department (Figure 107). The open (conductive) fractures are oriented almost N–S and it is consistent with the determined direction of maximum horizontal stress (Figure 107a). The heterogeneous fracture pattern is interpreted as resistive or closed (healed) fractures (Figure 107b).

The borehole breakout half widths from image logs of three wells in the study area have also been measured and the values of S_{Hmax} have been calculated by using the formula given in Chapter I (Table 6).

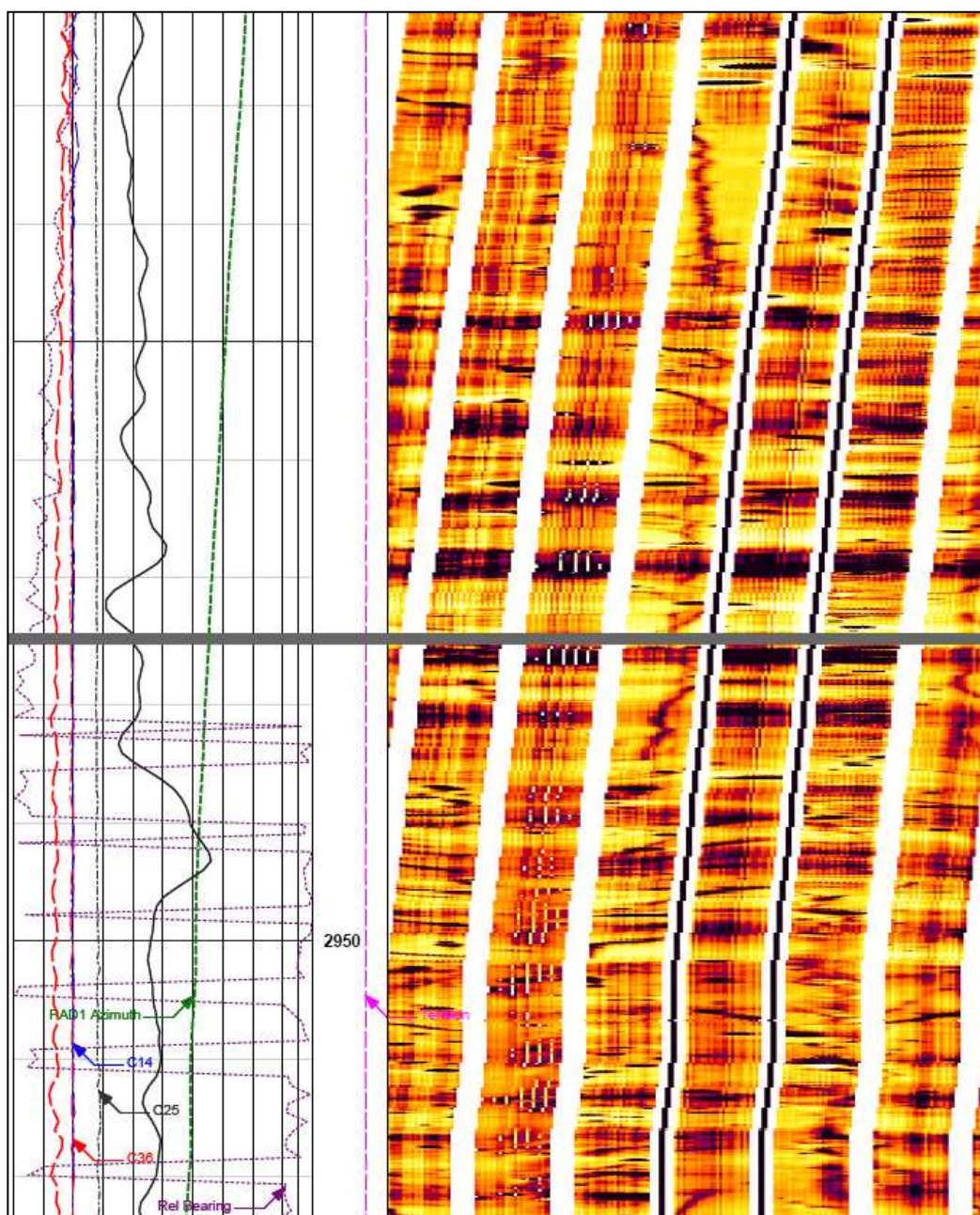


Figure 103. XRMI log of well A-1 in the study area. Drilling induced fractures indicate maximum horizontal stress oriented in N–S direction (180°).

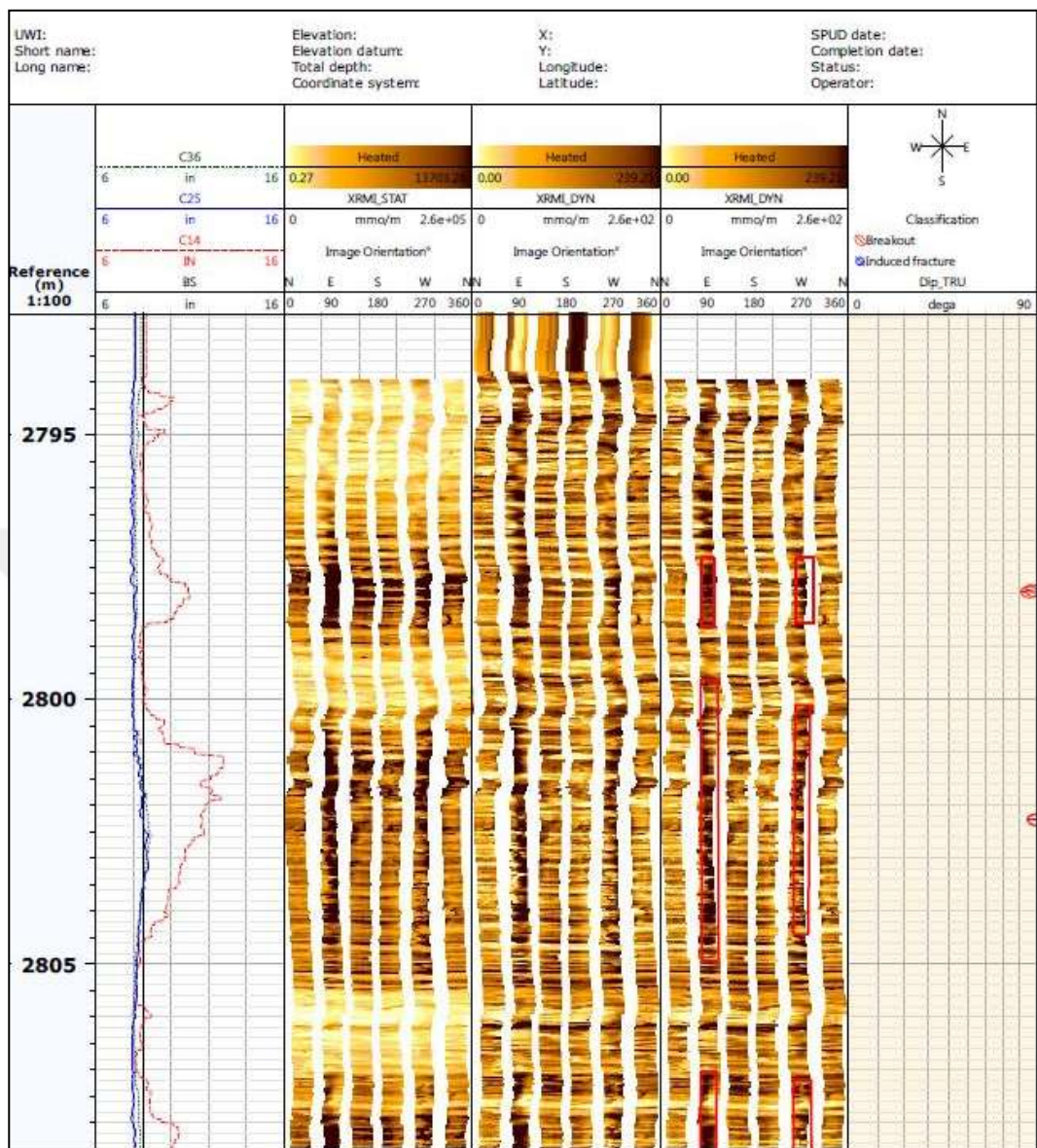


Figure 104. XRMI log of well Y-4 in the study area. Borehole breakouts are oriented in E–W direction and indicate a maximum horizontal stress in N–S direction. Caliper log data also confirms the borehole breakouts.

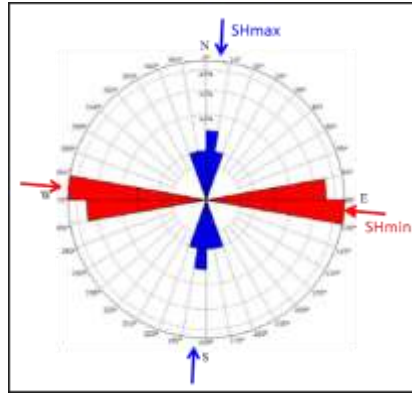


Figure 105. Rose diagram of borehole breakouts from the wells drilled in the study area. The direction of the maximum horizontal stress (S_{Hmax}) is nearly N-S and the strike of drilling induced fractures (blue colored) is parallel to it. The E-W strike of the borehole breakouts (red colored) is perpendicular to S_{Hmax} .

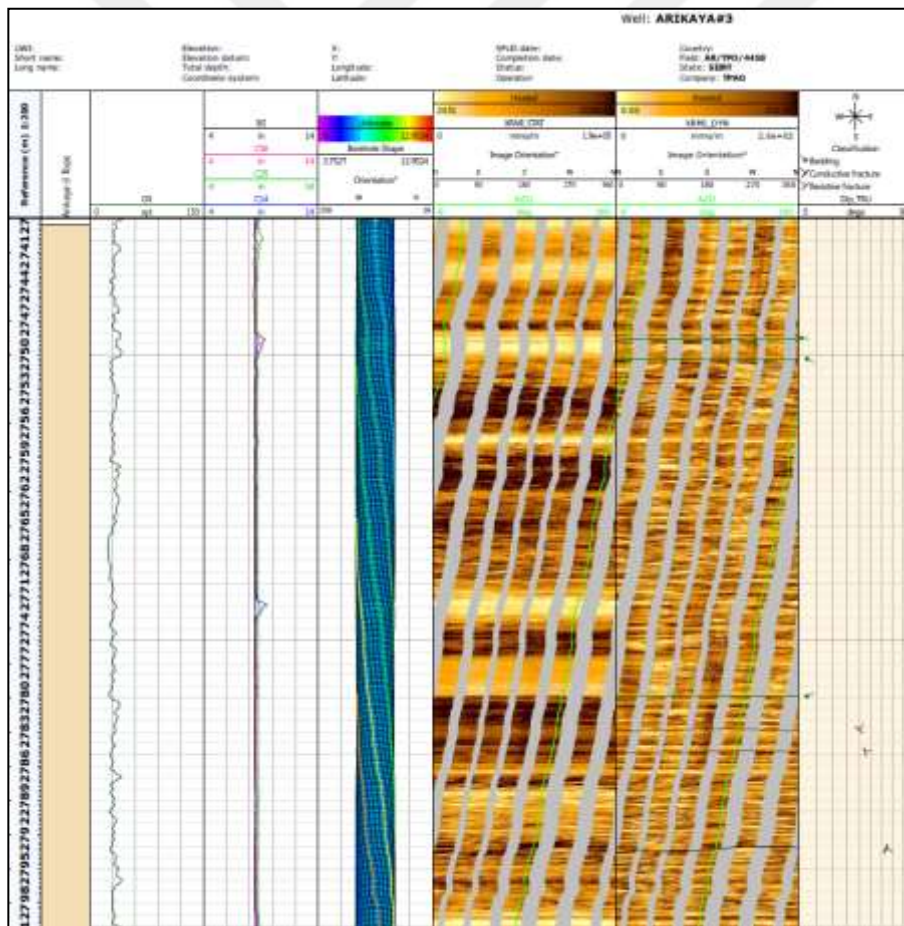


Figure 106. Example of a process of borehole XRFI data of well Arikaya-3 in the study area. The fractures are classified and interpreted as conductive (open) or resistive (closed) fractures (processed by TPAO Exploration Department).

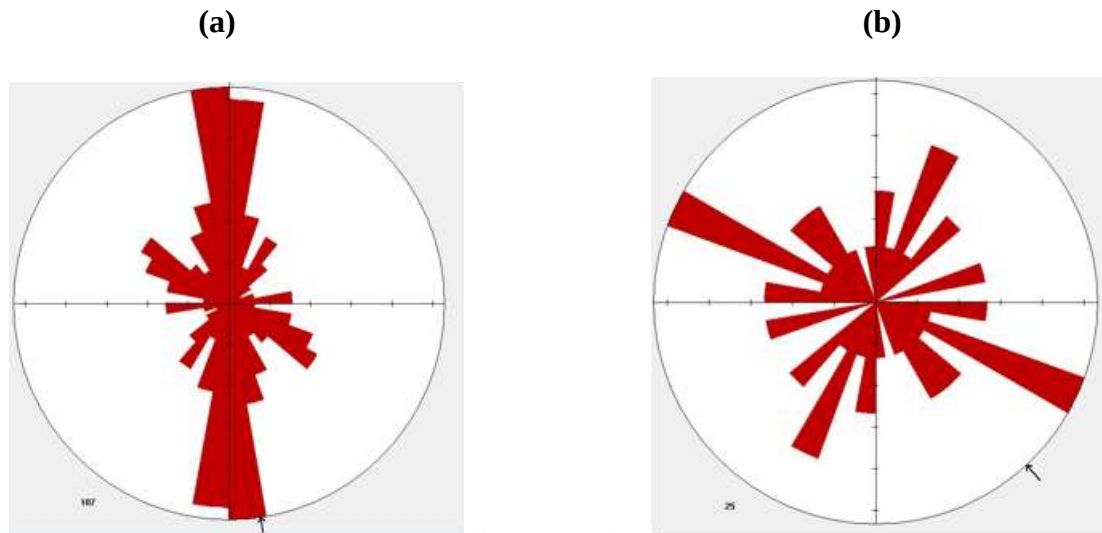


Figure 107. Rose diagram plots of fractures (azimuth data) gathered from XRFI data of the drilled wells in the study area. (a) 107 conductive fractures; (b) 25 resistive fractures.

Table 6. Parameters used to calculate S_{Hmax} by using wellbore width measurements of three different wells.

Wells	Well-1	Well-2	Well-3
Depth (m)	2128	2165	2832
S_{Hmax} (MPa)	75.2	65.8	96.3
S_{hmin} (MPa)	42	44	57
S_v (MPa)	53	55	74
P_p (Mpa)	21	22	26
del-P	3.4	4.2	3.3
Breakout halfwidth (°)	29	22.5	38
C_o	107	92.5	117

4.2.2. Leak-off Test (LOT) Data Evaluation

The extended leak-off test data and determined leak point pressure magnitudes from 24 wells in the study area and nearby region have been evaluated in order to calculate minimum horizontal stress (S_{hmin}) values to build the representative earth geomechanical model for study area (Zoback, 2007). The tests have been conducted right after the casings being set in the well during drilling operations at different depths. The calculated S_{hmin} data is given in Table 7 and plotted in Figure 108.

Table 7. Minimum horizontal stress (S_{hmin}) values calculated from extended leak-off test data and determined leak point pressure magnitudes of 24 wells.

Wells	Depth (m)	S_{hmin} (MPa)
1	1964	35.2
2	1363	32.6
3	821	20
4	1376	28.7
5	840	18.2
6	836	19.5
7	1456	23.8
8	1382	31.4
9	1530	36.2
10	1438	32.5
11	88	1.7
12	104	2.5
13	2014	34
14	757	18
15	1740	36.5
16	1255	30.6
17	2587	60.5
18	1501	27.4
19	2095	38.4
20	2503	48.3
21	1385	21.1
22	1603	23.4
23	2891	54.5
24	876	22.3

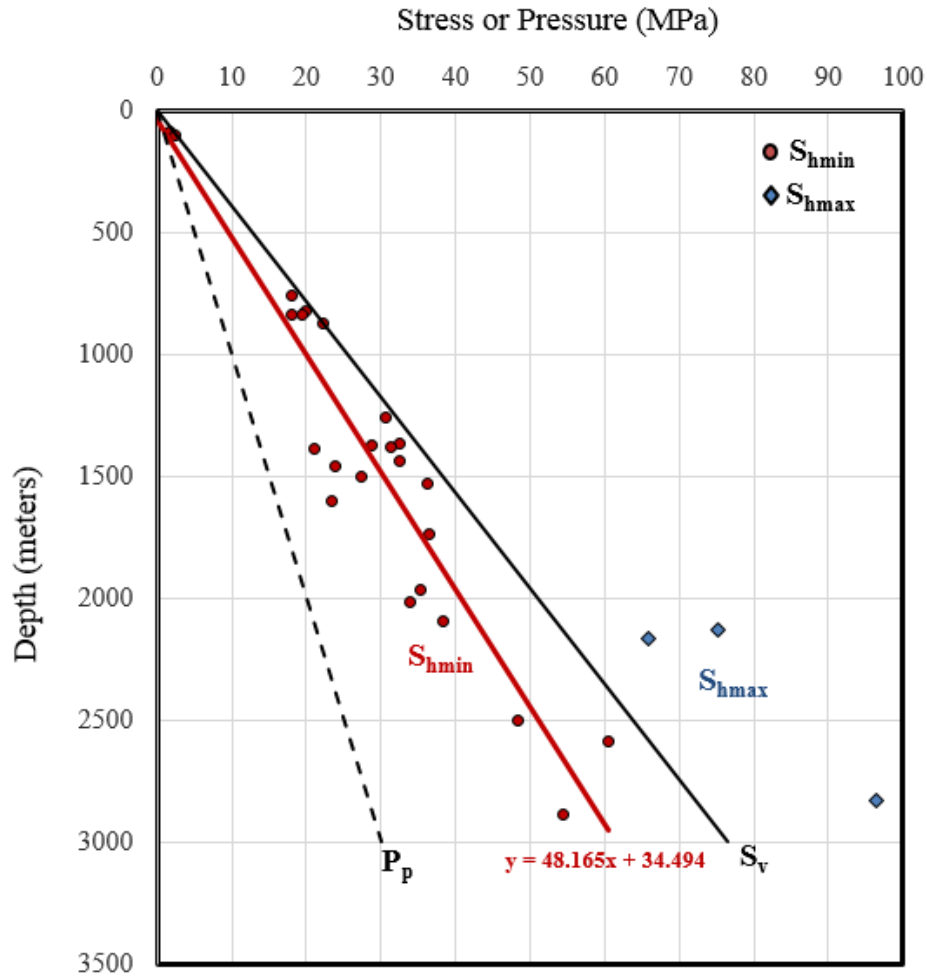


Figure 108. Stress measurements with depth in study area and nearby for hydrostatic conditions. S_{hmin} is determined from extended leak-off tests, S_{Hmax} is estimated from borehole breakout widths, P_p is used ~ 10 MPa/km (~ 0.44 psi/ft), and S_v is used ~ 23 MPa/km (~ 1 psi/ft).

4.2.3. Stress Prediction Profile with Depth

The vertical stress (S_v) and pore pressure (P_p) have been plotted as 23 MPa/km (~ 1 psi/ft) and 10 MPa/km (~ 0.44 psi/ft), respectively (Zoback *et al.*, 2003; Zoback, 2006). The S_{hmin} data gathered from extended leak-off tests of 24 wells and S_{Hmax} values obtained from borehole breakout widths from image logs of 3 wells have been plotted by depth (Figure 108). The stress magnitudes increase with depth

(as S_v increases with depth). Figure 108 also shows that the S_{Hmax} is fairly greater than S_{hmin} values and that the S_{hmin} values are smaller than theoretical S_v curve.

Thus, as discussed in Chapter I, the plot demonstrates $S_{hmin} < S_v < S_{Hmax}$, which indicates a strike-slip regime dominated tectonic setting in the study area and neighborhood. On the other hand, the magnitude of S_{hmin} is only slightly below the magnitude of S_v in the interval of 0–1500 meters; this further indicates that a strike-slip/reverse faulting regime in that interval (Zoback, 2007).

4.3. Faults, Hydrothermal Fluid Migration and Hydrocarbon Potential

The Çelikli-Habandere Fault (ÇHF) runs through the Oligocene Germik Formation near surface and ends in that ductile unit. On the other hand, the Miocene section has numerous strike-slip faults and associated fractures. The style of deformation changes due to mechanical layering such as while unconsolidated Miocene layers deforming severely, the ductile Oligocene section absorbs the stress distribution of the major fault. The occurrence of upward-diverging fault splays is thus not due essentially to convergence but to the upward propagation of faults through the sedimentary cover toward a free surface (cf. Allen, 1965; Sylvester and Smith, 1976). This claim is also confirmed in experimental studies with unconsolidated sand (Emmons, 1969), and with homogenous rock samples under confining pressure (Bartlett *et al.*, 1981).

Strike-slip faults may be characterized by convergence or divergence with distances (Namson *et al.*, 1985; Harding *et al.*, 1985) and also with respect to having restraining or releasing bends, fault junctions, and oversteps. The pre-existing structures and the depositional environments with stratigraphic features are crucial elements of the strike-slip deformation. While the wells drilled in the rest of the study area does not contain dolomites in Campanian and Maastrichtian carbonates,

the wells associated with the Çelikli-Habandere Fault have penetrated into special type of dolomitization called hydrothermal dolomites along with Campanian carbonate reservoirs (Figure 109). Especially these dolomites are associated with infill materials of fractures (Figure 110).

Hydrothermal is defined as fluid or mineral product emplaced into a host rock by a higher temperature than itself (Davies and Smith, 2006). The hydrothermal dolomitization is mostly related with extensional and/or strike-slip (wrench) faults with extensional fractures, tensional areas and hanging walls (e.g., Warren, 2000; Davies and Smith, 2006) (Figure 111). They are associated with sulfide mineralization, sulfate-bearing carbonates, hydrocarbon reservoirs (cf. Radke and Mathis, 1980).

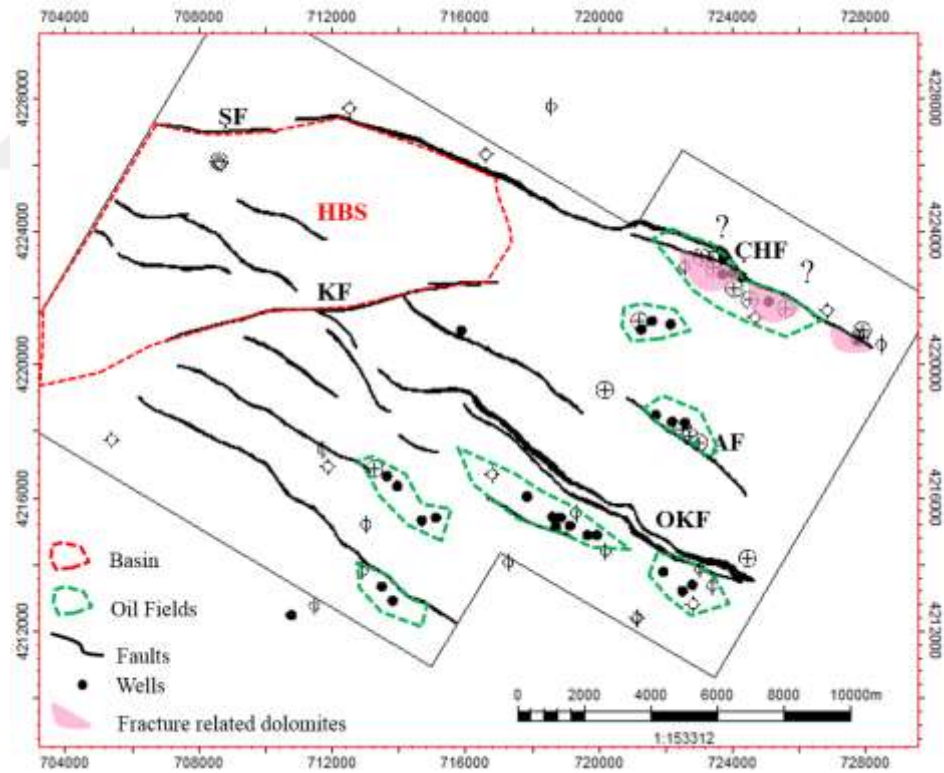


Figure 109. Map showing faults within the Campanian reservoirs in the study area. Pink polygons show the saddle dolomitization along the Çelikli-Habandere Fault (CHF). AF: Arıkaya Fault, KF: Kumlupınar Fault, ŞF: Şelmo Fault, OKF: Oyuktaş-Kurtalan Fault, HBS: Habandere Sub-basin.

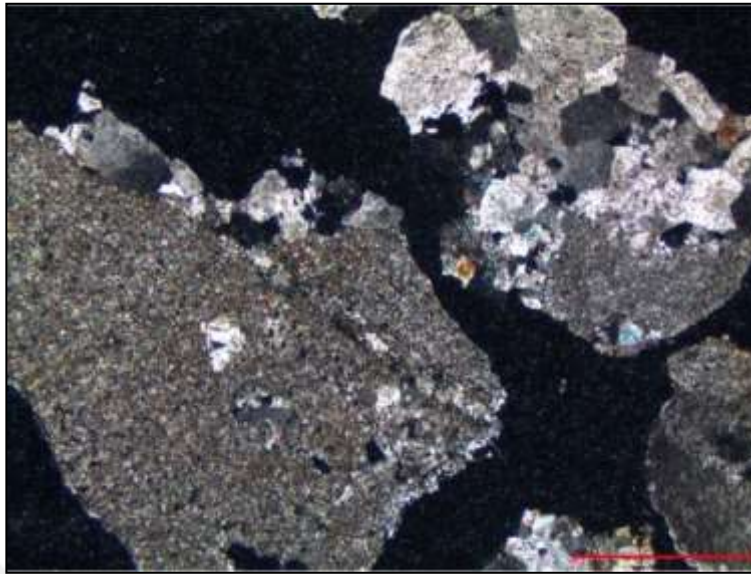


Figure 110. Mardin Group dolomitization pattern in well Y-3, located along the Çelikli-Habandere Fault. 2884 meter cutting sample, saddle dolomite as fracture and void infills in host rock dolomite, 2,5x cross polarized light, scale bar 500 μm .

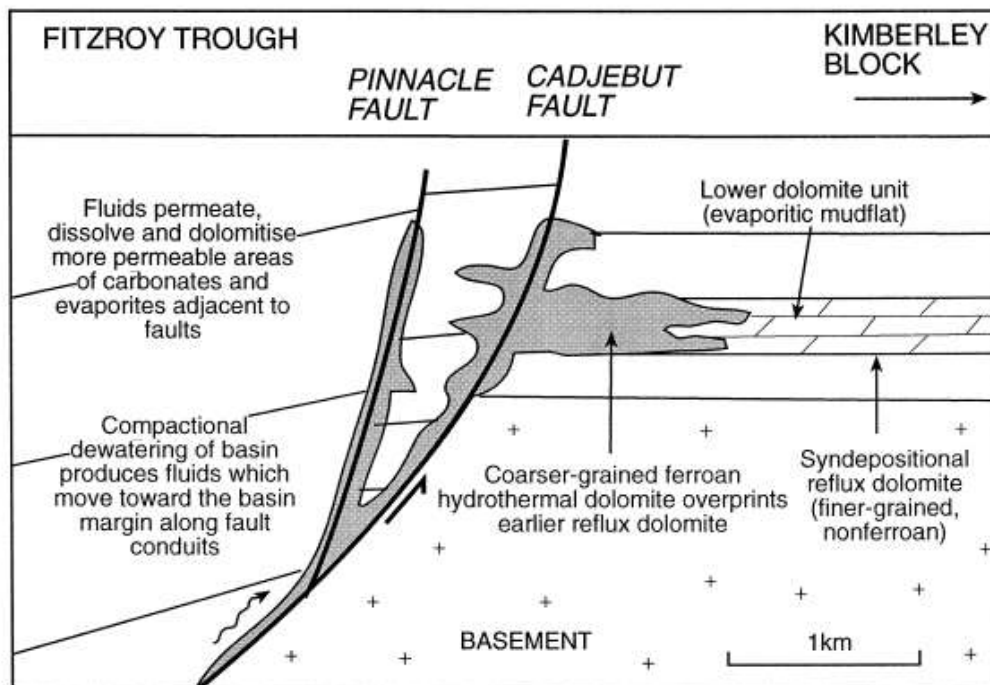


Figure 111. Schematic representation of fault-controlled burial dolomitization and distribution of hydrothermal dolomites. Example from Devonian carbonates of the northern Canning Basin Margin, Australia (Warren, 2000)

The occurrence of this late diagenetic event in wells near Çelikli-Habandere Fault can not be a coincidence and suggests a genetic link between faulting and hydrothermal dolomitization (saddle dolomitization); dolomites are therefore attributed to hydrothermal dolomitization associated with the Çelikli-Habandere Fault deformation zone and indicates temperature ranges between 60 to 150 °C. In production wells associated with Çelikli-Habandere Fault, the reservoirs are always characterized by higher H₂S ratios. There, better reservoir qualities due to their crack forming tendencies that helps to develop better porosity and permeability characters (Çelikli and Yemişlik oil fields).

Şelmo oil field is located northwestern part of the study area along the trend of Çelikli-Habandere Fault (Figures 109 & 112). Şelmo oil field produces from dolomitized Maastrichtian Lower Sinan carbonates which show evidence for dolomitization associated with hydrothermal fluids (personal communication with Joerg Mattner). Also, Taşlıdere thermal spa center, which is located 8 km to the study area, produces thermal water from well Şelmo-32 from the depths between 1700–2400 m in the Cretaceous reservoirs (Figure 112). The chemical analysis of the hot water is summarized in Table 8 (Dağıstan and Şimşek, 2005).

Table 8. Chemical analyses results of water sample from Taşlıdere hot water (Dağıstan & Şimşek, 2005).

Sample	pH	EC	TDS	T	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	SiO ₂
Taşlıdere hot water	7.72	3015	2090	83.0	287	34.3	256	26	325	839	245	56

The source of hydrothermal fluids needs to be addressed. There is no known Cretaceous volcanic activity in the study area and its surroundings. The hydrothermal fluid related dolomitization can therefore be related with younger volcanic phases. The age of volcanism in the region extends from the Mid-Late Miocene to the present day (Lustrino *et al.*, 2012; Koçbulut *et al.*, 2013). The nearest volcanic rocks are exposed approximately 16 km east of the study area. In addition,

the Kıradağ basalts trace the flow of volcanism along the river bed which is also located on 22 km south in Tigris River valley. In the wells opened by TPAO in Southeastern Anatolia dolerite dykes with thicknesses of 50–100 meters are cut in the autochthonous succession (personal communication with F.M. Türesin). Also in this area, there is some evidence that the origin of CO₂ gas in NW–SE-trending Dodan Anticline is the product of contact metamorphism of the carbonate rocks with emplaced deep magmatic intrusions (Çorbacioğlu, 2014).

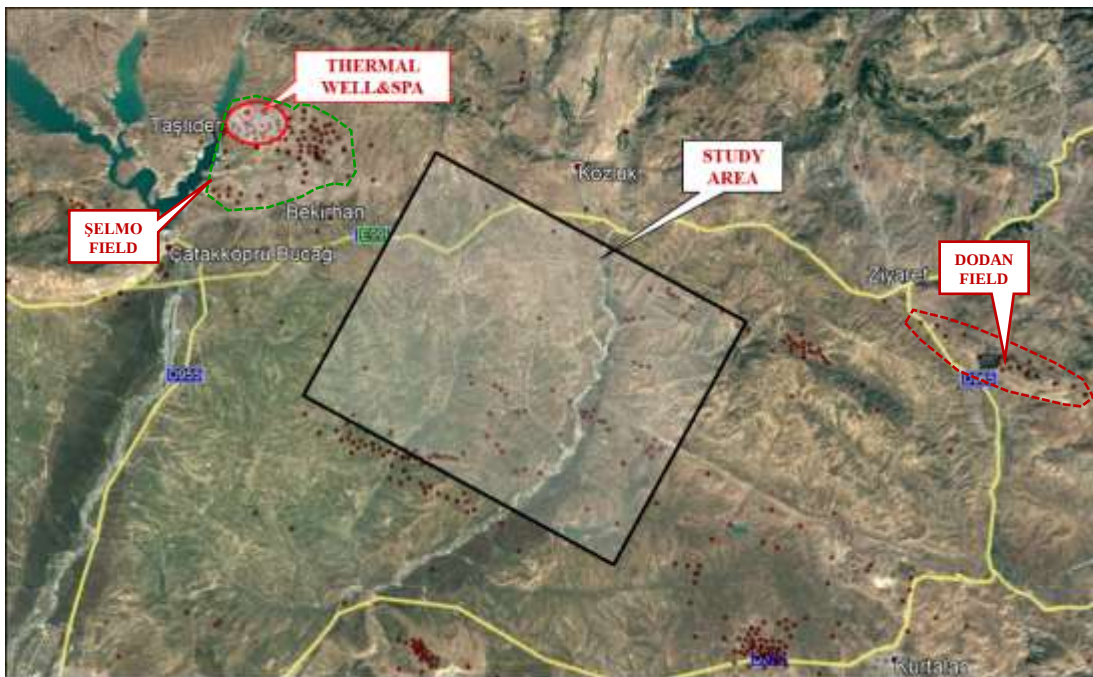


Figure 112. The Google Earth capture showing the location of study area (white rectangle) and thermal water well and spa center along with Şelmo oil field.

CHAPTER V

DISCUSSION & CONCLUSIONS

5.1. Discussion

The foreland of Bitlis-Zagros Suture Zone is formed by a thick pile of rocks consisting of Paleozoic, Mesozoic and Cenozoic strata. These strata have been deposited in extensional and passive margin settings during Paleozoic and Early–Middle Mesozoic periods. Then the compressional regime commenced by Late Cretaceous with the development of flexural basin (Beydoun *et al.*, 1992). Field observations, well sections, drilling data, well logs and interpreted 3-D seismic cubes are all combined to provide insights into the study area. The issues, which are approached in the Introduction Chapter, are discussed in the following subheadings.

5.1.1. The Kinematic History, Timing and Mechanism of Deformation

Recent studies emphasized that the main compressional stress is determined as N020–025° for the Iranian plateau of Bitlis-Zagros region (Lacombe *et al.*, 2006; Mouthereau *et al.* 2012). The evaluation of borehole data and measured fractures from image logs of the wells in and around the study area indicated the maximum principal stress is oriented in N–S direction. This is also conformable with: (i) the present-day stress map of the Arabian Plate published in GeoTech webpage (2010) and (ii) fault plane solutions of recent earthquakes with focal mechanisms (see section 3.3 for more information).

The evaluation of fracture distribution determined from the image logs of drilled wells indicated while the open (conductive) fractures are oriented almost N–S, the closed (resistive) fractures doesn't show any particular orientation. The

minimum horizontal stresses are calculated from extended leak-off tests that are conducted during well-drilling operations. Once the determined stress data plotted against depth, the earth mechanical model is established; the model shows the dominant present-day tectonic regime is represented by both strike-slip faulting with reverse component between the depths of 0–1500 meters, and strike-slip regime for the depths deeper than 1500 meters. The stress permutation from vertical σ_3 to σ_2 with depth is most probably be related with the burial loading.

The oldest prominent structures observed in 3D seismic data trend in NE–SW direction and the Kumlupınar Fault is the most remarkable structure in the study area. There is evidence in seismic sections that NE–SW-trending faults were developed during Late Permian–Triassic rifting event. And some of them might have been reactivated during mid–late Campanian as a response to obduction happening further in the north. The seismic shows that the Kumlupınar Fault had been active at least until the end of Early Miocene. This fault controlled the stratigraphic evolution especially during Late Cretaceous and the deposition of source, seal, and reservoir rocks.

The field observations reveal the presence of both reverse and normal faults in the study area and its vicinity, as well as the traces of inverted normal to reverse movement along fault planes. The normal faulting regime could explain the deposition of the Lower Miocene Kapıkaya and Fırat formations on top of the Eocene-Oligocene Germik evaporates. The Hazro, Garzan, Raman and Silvan faults, observed near the study area might have developed as normal faults and then re-activated as thrust faults during Miocene collision and then gain their final shapes with dextral strike-slip regime since Pliocene. Especially the existence of the Fırat Formation on the Hazro Anticline and its absence in the wells drilled on the southern downthrown block foreland can be considered as evidence for the inversion of NW–SE-trending Hazro Fault. The evidence for the Çelikli-Habandere Fault and Kumlupınar Fault is not clear both in the field and seismic lines. Rather there are

numerous (other) strike-slip faults deforming the Miocene units in this part of the seismic data. The mechanical characteristics of thicker, soft Şelmo clastics (up to 800 meters) might have affected the style of deformation in this part of the data.

The NE–SW-trending Oyuktaş-Kurtalan, Çelikli-Habandere, Arıkaya, Beyçayır faults, other parallel and related faults show dextral sense deformational patterns in the seismic data. End of Oligocene–Early Miocene time is most probably a good candidate for the timing of the development of NW–SE-trending major faults, which controlled the Lower–Middle Miocene Silvan Group deposition. This time interval also corresponds to re-activation of NW–SE-trending faults as extensional structures, which were then inverted later in the progressive phase of deformation after the deposition of the Lower-Middle Miocene Lice Formation. The new geomorphology controlled the geometry of the Upper Miocene Şelmo Formation deposition. The thickness of this unit dramatically changes along with NW–SE-trending Oyuktaş-Kurtalan Fault and all the faults observed in Kozardere-3D seismic data are parallel to each other; they are most probably attributed to the Miocene deformational events related with continent-continent collision of Arabian and Eurasian plates and consequent orogenesis. Then, rapid kinematic change through strike-slip regime or west-ward tectonic escape in the region is represented by a regional unconformity between the Miocene clastic rocks (Şelmo Formation) and overlying Pliocene conglomerates (Lahti Formation) (ca. 5 Ma) (Authemayou *et al.*, 2006). There should be a change in the paleo-drainage distribution due to folding-faulting and uplift of the northern section. Most faults were reactivated, deformed and gained new geometries since then.

As it is also observed in the field studies and seismic sections, there are numerous normal faults located in and around the study area. Some of the major ones are the NW–SE-trending Kanimiri Fault and the Beytil Fault. Figure 113 shows seismic sections where these structures are well expressed. Northern blocks form hanging walls of these faults, which have controlled subsidence before the

deposition of the Lower-Middle Miocene Silvan Group. The reverse faults in the study area are most probably developed along re-activation of some of these early formed normal faults during Mid–Late Miocene compressional events; they were later deformed by strike-slip faults. The Oyuktaş-Kurtalan Fault might have developed as a normal fault and, then reactivated after stress inversion during Mid–Late Miocene and regained its final geometry during Pliocene strike-slip deformational events. Oyuktaş-Kurtalan Fault has controlled the deposition of Upper Miocene units and also display characteristic features typical of strike-slip regime, such as sag pond, reidel shear fractures with lateral movements. Like Oyuktaş-Kurtalan Fault, some NW–SE-trending faults are still active and continue to create earthquakes as it is observed from the instrumental earthquake data.

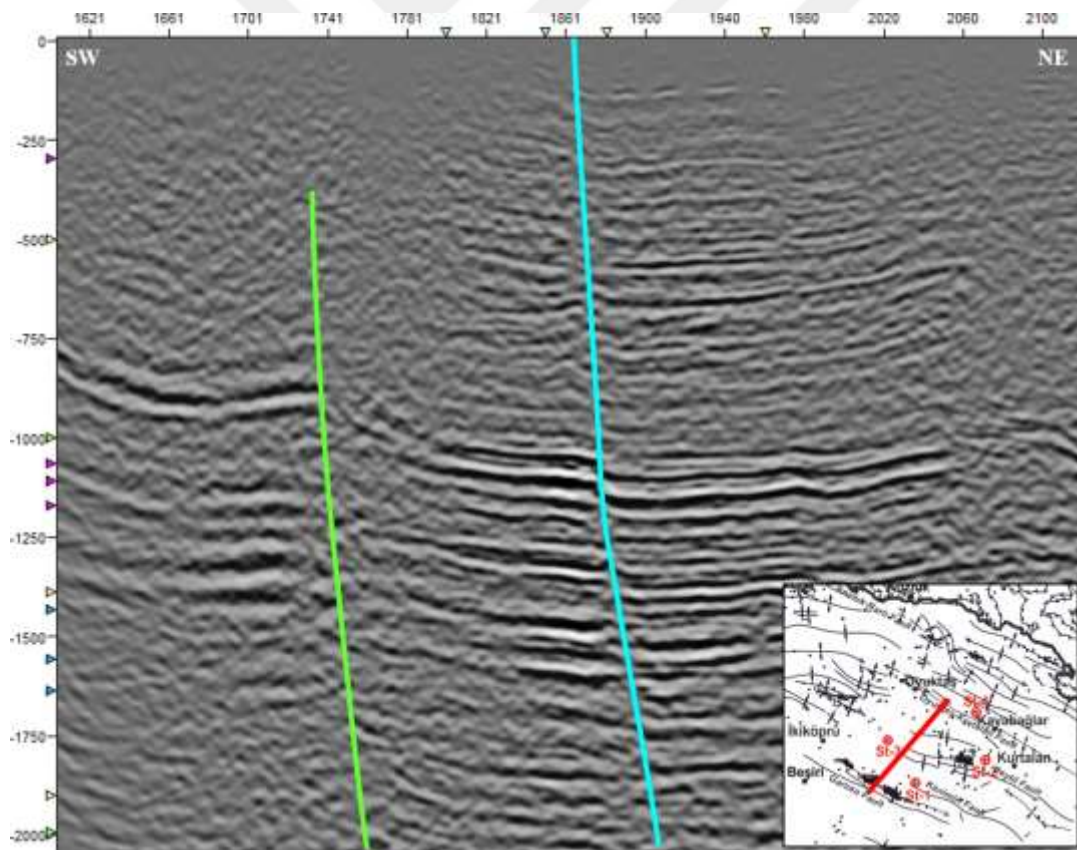


Figure 113. The seismic section shows the Kanimiri (green) and Beytil (blue) Faults in SW–NE trending seismic line.

Figure 114 demonstrates the interpretation of structural elements observed in the variance slices of 480 msec. (Figure 77) gathered in Miocene strata in the Kozardere 3D seismic data. Displaced ancient river course is interpreted as occurred along syntethic riedel shears that belong to a right-lateral strike-slip system of several NW–SE-trending faults (Figure 114). The deformation ellipsoid (Figure 114) also fits well with the interpreted system and indicates almost maximum stress directed N–S.

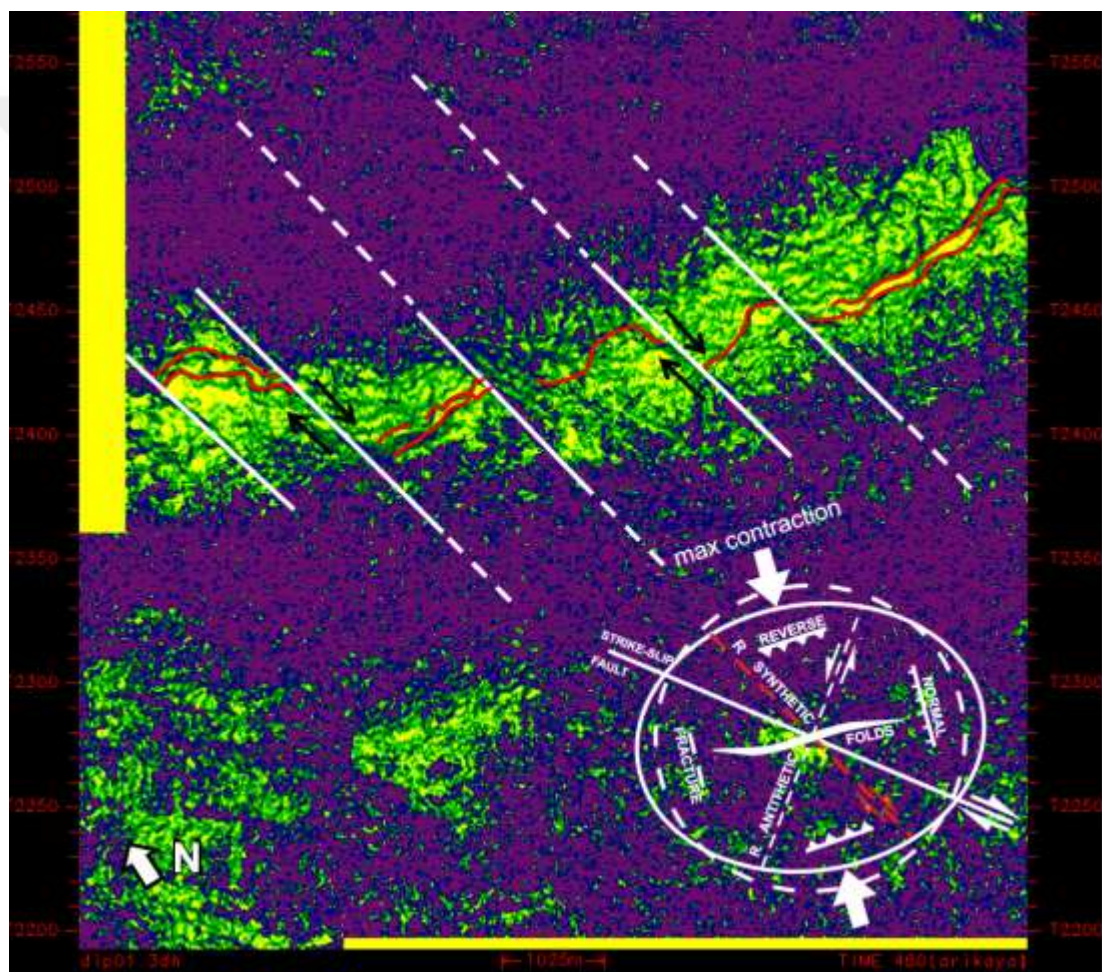


Figure 114. Variance slice of 480 msec from Arikaya 3D Data (some part of Kozardere merge data). Interpreted data shows an ancient river course (red line) deformed (cut and offset) by faults that are related to younger strike-slip regime. These synthetic faults displaced the river course in a right-lateral sense.

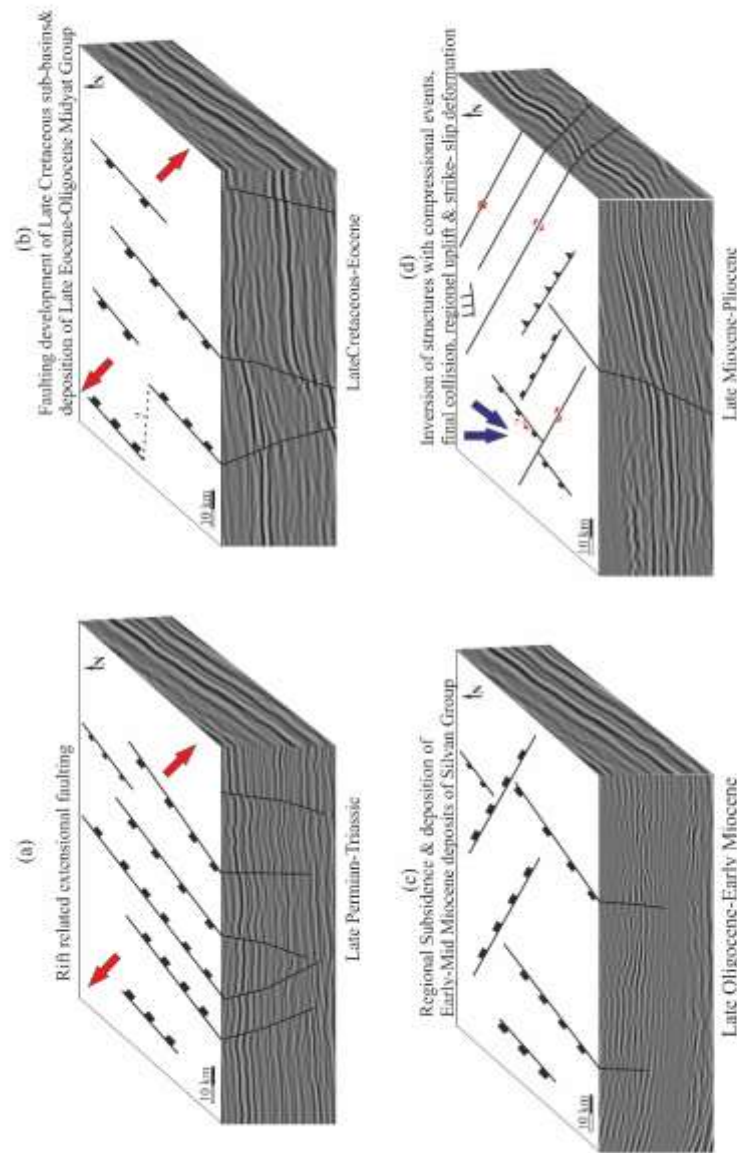


Figure 115. Tectonic evolutionary sketch for the southern Kozluk area, Batman. (a) Late Permian-Triassic (b) Late Cretaceous-Eocene (c) Late Oligocene-Early-Miocene (d) Late Miocene-Pliocene. The red arrows indicate direction of extension and the blue arrows for the shortening directions. The black arrow shows north.

Figure 115 summarizes the possible tectonic evolutionary sketch for the southern Kozluk area, Batman. There are five deformation phases described in this study: (1) D₁, rift-related extensional faulting (Late Permian–Triassic); (2) D₂, deformation along inherited and newly developed NE–SW-trending normal faults (Late Campanian–Eocene); (3) D₃, formation of NW–SE-trending faults and continuum of movement along NE–SW-oriented normal faults (Late Eocene to Early–Middle Miocene); (4) D₄, Reverse faulting along NW–SE-trending faults (Middle–Late Miocene); (5) D₅, commencement of strike-slip regime (Pliocene onwards).

5.1.2. Role and Control of Tectonic Development on the Stratigraphy

The sedimentary successions deposited on the Arabian continental margin near Kozluk (Batman) provide valuable insights into sedimentary, tectonic and climatic processes that affected the southern Neotethys and its continental margins since Middle Cretaceous. The Northern passive margin of the Arabian Plate experienced an extensional regime in the time interval between the Permo–Triassic opening of Neotethys and the Late Cretaceous onset of its closure in Campanian–Maastrichtian time (rifting started with NE–SW-trending normal faults and movement along these structures) (Kazmin, 2002). As a result of this extensional phase, the northern Arabian Platform was dissected by numerous horst and graben style structures both during Permo–Triassic and Cretaceous (Figure 115). The NE–SW-trending Kumlupınar and Şelmo faults have the same orientation with the normal faults developed during Triassic rifting in the study area and surrounding region. The orientation of the existing structures with respect to current stress regime and plate kinematics is the key aspect for the deformational patterns of these inverted structures. Therefore, faults that have worked in Late Permian–Triassic time period could have been reactivated in response to Middle–Late Campanian major compressional regime in the study area.

After the deposition of Aptian–Early Campanian shelf carbonates (Mardin Group), the region has been faulted under the influence of the onset of compressional regime during Late Cretaceous. While many NE–SW-oriented thrust faults have been developed on the northern parts near the Bitlis-Zagros Fold and Thrust Belt, the study area was represented by a transitional environment from shallow-marine platform through deep marine sediments where re-activated NE–SW-trending normal faults and opening of sub-basins have dominated the area during this time interval. The style of deformation strongly affected the stratigraphy, such that while the deep water sediments (Sayındere and Kastel formations) were deposited on the downthrown block of these NE–SW-trending normal faults in Habandere sub-basin, the shallow-water carbonates (Beloka Formation) were developed on the platform areas. The Habandere sub-basin was controlled by NE–SW-trending Kumlupınar Fault in the southeast and the Şelmo Fault in the northwest. The base of the Sayındere Formation is the main source rock of the oil produced in this area and it is represented by organic matter rich (TOC: % 1.09; T_{max} : 460° C) clayey carbonates, deposited under anoxic conditions (İztan, 1999; Akçay, 2009). Thus, Habandere sub-basin is the mature area for the oil production fields of southern Kozluk (Batman) (such as, Oyuktaş, Yemişlik, Silivanka, Güzeldere, Arıkaya, etc) (Figure 109). Both the source rock Sayındere and reservoir rock Beloka formations contain iron-rich glauconite mineral and also the Beloka Formation shallow-water facies has alg-rich bioclastic limestone, which indicates that ferrigenous sea water conditions might be due to further north volcanic activities and ophiolite obduction. Basal Sayındere organic matter-rich succession is referred as the Karaboğaz Formation, which is the main source rock of Adıyaman oil fields on the west of study area near Adıyaman (İztan, 1999).

Between the main orogenic belt and the undeformed continental platform lies a thick series of sediments mostly derived from uplifting source area in the neighboring mountains (Figures 3 & 4). These sediments were deposited in foredeep or foreland basins. In some foredeeps, the clasts in the conglomerates and sandstones

contain debris and materials from stratigraphically deeper levels in the mountains. This sequence reflects the progressive uplift and erosion or unroofing of the adjacent mountains and developed during the Cretaceous and Miocene with the deposition of Kastel and Lice formations, respectively.

In foreland basins, conglomerates grade into sandstones and shales, and then, in turn, may pass into carbonate marine shelf sediments. Similar to that, along with the onset of Late Cretaceous obduction and associated compression, the platform was uplifted and the continental deposits, which are erosional products of obducted units (Terbüzek and Kıradağ formations), were started to deposit both conformably and unconformably after erosion in the platformal regions of the study area. Then, there was a major relative sea level rise, which might have related to subducting Arabian Plate slab during Late Maastrichtian, and it has resulted in the deposition of the Garzan Formation (one of the major reservoir oil producing unit in the study area) on top of the Kıradağ Formation in the east and the Terbüzek Formation in the west. Second sea level rise is marked by the deposition of the Germav Formation marls and clay-rich limestone in shallow-marine bioclastic Garzan reservoirs as a top seal rock.

The Paleocene–Early Eocene depositional sequence was developed under the influence of flat slab subduction of Arabian Plate and ended with continental deposits of the Antak-Gercüş formations. Another tectonic activity has commenced right before the deposition of the Midyat Group carbonates in association with the development of numerous NE–SW-trending normal faults, which have the same orientation with the Cretaceous faults in the study area. This phenomenon is consistent with the subsidence that might have occurred at about 34 Ma during late Eocene. This subsidence could have initiated due to decrease in subduction velocity, denser Arabian Plate, and/or Arabian-Eurasian Plate coupling, thus transferring the stress to upper Eurasian Plate (Keskin, 2007; Mouthereau *et al.*, 2012). The Midyat Group carbonates were deposited during Late Eocene–Oligocene time period and

the thickness varies between 450 meters and 600 meters in the study area. The continental evaporitic sediments deposited as final products of Oligocene succession shows arid climate conditions persisted prior to Miocene. At the end of Oligocene and the beginning of Miocene, the unconformably overlying carbonates were deposited (Fırat Formation). Deposition of Lower Miocene carbonates corresponds to the timing of a change in the direction of stress distribution in the Arabian Plate most probably due to rifting of Red Sea and opening of Gulf of Aden (e.g., Mouthereau *et al.*, 2012; McQuarrie and van Hinsbergen, 2013). There are however ongoing debates about whether mantle convection of Afar Plume pushes Arabia northward (Becker and Facenna, 2010; Facenna *et al.*, 2011) or Arabian Plate movement trigger the upwelling plume.

Early–Mid Miocene deposition is also represented by the Lice evaporitic-playa sediments in the study area. The north to south and west to east migration of the depocenters and lithological diversity during the deposition of Lower–Middle Miocene successions of Fırat and Lice formations could be related with the southward propagation of thrust loading and related faulting. These indicate that Lower–Mid Miocene units are syn-orogenic and were deposited in a flexural basin. Similar observations have been documented for Lower–Middle Miocene Asmari carbonates in the previous studies in southeastern Zagros Fold and Thrust Belt (Mouthereau *et al.*, 2007b; van Buchem *et al.*, 2010). Then, after final collision, the Şelmo Formation continental fluvial clastics were deposited transitionally on top of the evaporitic Lice Formation in the study area. The thickness of the Şelmo Formation reaches up to 1500 meters near the Çelikli-Habandere Fault. This thick pile of the fluvial Şelmo deposition was controlled by the massive source located in the north and the basin controlling Oyuktaş-Kurtalan Fault on the south. The Lice Formation evaporate content increases northwards under the Miocene allochthonous units. In this area, the Çüngüş and Lice formations together served as major detachment surfaces for southward movement of thick piles of the Miocene allochthonous rocks. The allochtones placed further south in the north of the study

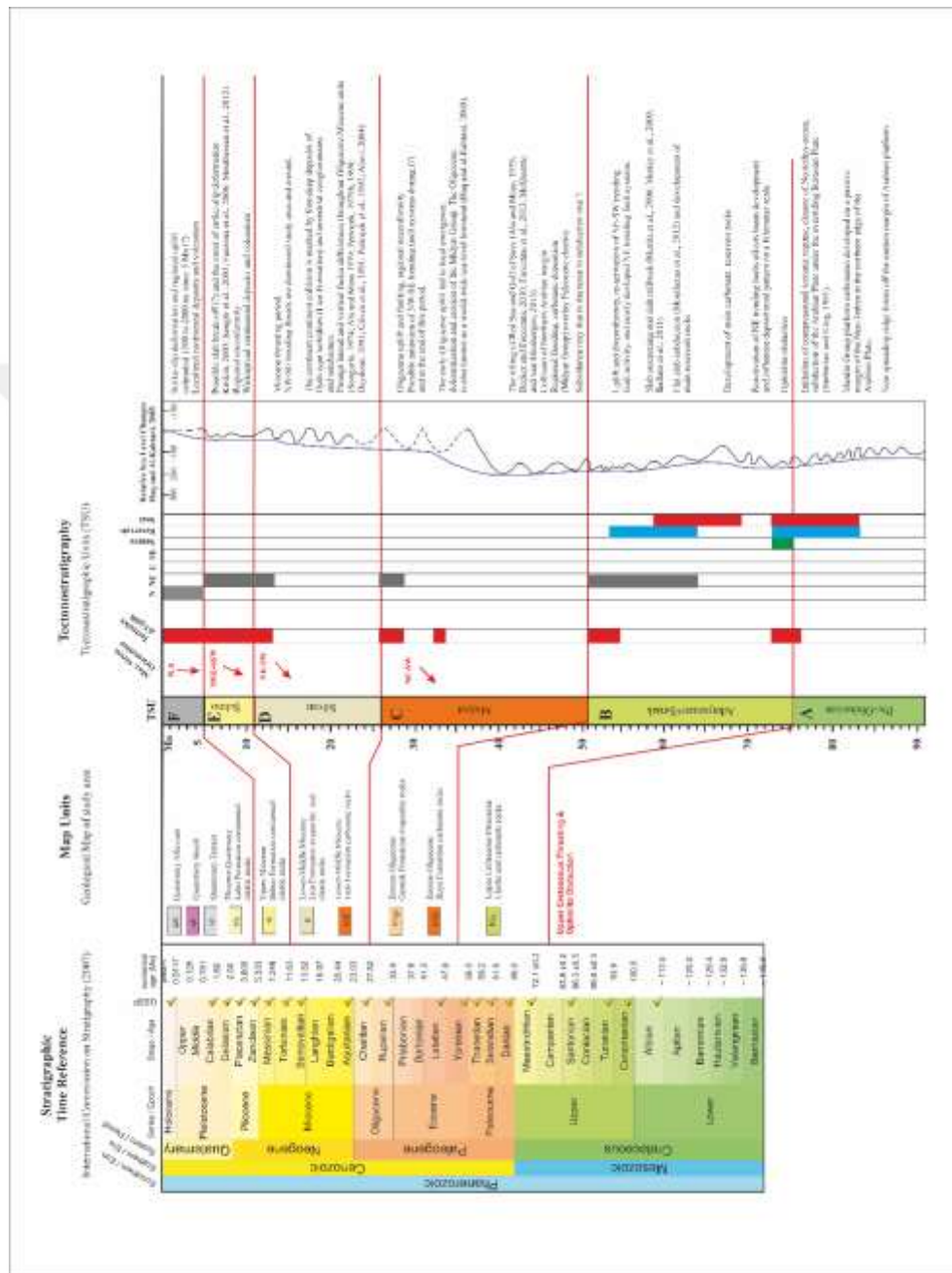
area (Kozluk, Batman) when compared with the mass located on the north of Hazro Anticline. The deeper deposition area for the foredeep Lice basin was located in the further northwest, north of Hazro Anticline (Figures 2, 3).

5.1.3. Investigate the Effect of Deformation on Hydrocarbon Potential

The basin bounding/controlling NE–SW-oriented Kumlupınar and Şelmo faults helped the development/uplift of source rocks for basal Sayındere Formation in the Habandere sub-basin during Late Campanian. Then, NW–SE-trending faults in the platform lead to the occurrence of structures having potential of trapping oils that have migrated from the Sayındere Formation.

The Oyuktaş oil field, located on the southern block of Oyuktaş-Kurtalan Fault is producing from Upper Campanian Beloka Formation and Maastrichtian Garzan Formation bioclastic limestones. The Yemişlik oil field, located south of Çelikli-Habandere Fault, is producing from the Mardin Group dolomites. The latest dolomitization along the Çelikli-Habandere Fault is most probably related with hydrothermal fluids and created better quality reservoirs in the area. Examples from other parts of the world indicates that the hydrothermal fluid circulation might have been occurred along faults, related with either extensional and/or wrench tectonics (cf. Warren, 2000; Davies and Smith, 2006). The Miocene (?) magmatic activity in the region can be considered as source for the hydrothermal fluids. The faults and fractures have used as conduits for hydrothermal fluids; the fluids invaded the Cretaceous carbonates (which also partly dolomitized during Campanian structural events), caused their dolomitization and helped the development of reservoir characteristics of these carbonates. The dolomitization thus affected the main Cretaceous reservoirs in a positive way by creating more brittle mechanical units and consequent development of better porosity and permeability rates by fractures.

The tectonostratigraphic construction of the study area is summarized in Figure 116. The rifting period was active throughout the region before the deposition of the Cenomanian–Turonian Mardin Group carbonates along the passive margin of the Neotethys Ocean at the northern edge of the Arabian Plate. After the initiation of ophiolite obduction during Late Cretaceous the deformation continued along NE–SW-trending normal faults. During Late Campanian, the depositional succession started to develop as five different sequences that represent deposition during late Campanian, late Campanian–late Maastrichtian, Paleocene, Eocene–Oligocene, and Miocene time intervals, respectively. Each sequence starts with transgression and develops into regression, and therefore form unconformably divided successions (Yeşilova and Helvacı, 2012). Once the compressional stress regime is activated, the study area is dominated with NE–SW-directed normal faults and the opening of new sub-basins during Late Cretaceous. The flat slab subduction yielded with the deposition of major reservoir rocks on the platform during Late Cretaceous (Verdel *et al.*, 2011). Then, the Paleocene succession was deposited under the influence of slab steepening and slab roll-back processes (e.g., Keskin, 2003, 2007; Şengör *et al.*, 2003, 2008). A major unconformity was developed before the deposition of the Midyat Group carbonates. End of Paleocene was represented by a major uplift, and then Eocene–Oligocene succession had started to form with subsidence, re-activation and development of NE–SW-trending faults. The subsidence might have been developed due to decrease in subduction velocity, opening of Red Sea and Gulf of Aden. The collision of Arabian and Eurasian plates also began during this time (e.g., Mouthereau *et al.*, 2012; McQuarrie and van Hinsbergen, 2013).





The Early Oligocene uplift led to local emergence, and erosion of the Midyat Group. The Oligocene is also known as a world wide sea-level lowstand (Haq and al-Kahtani, 2005). The NW–SE-trending normal faults have developed at the end of this period but before the deposition of the Silvan Group syn-orogenic deposits. The area was subjected to N–S-directed maximum principal stress since about 5 Ma. The strike-slip deformation and the regional uplift have been activated since then. The 1500–2000-meter uplift has been recorded. The possible slab break-off could be the most probable candidate for this regional unconformity between and the onset of neotectonic regime (e.g., Keskin, 2003; Şengör *et al.*, 2003; Facenna *et al.*, 2006).

5.2. Summary

The geology, tectonics and petroleum potential of the south of Bitlis-Zagros Suture Zone located in the southern Kozluk (Batman) region since Late Cretaceous have been investigated by integrating surface and subsurface data obtained from field studies, drilled wells, and 3D seismic data.

The tectonic and stratigraphic pattern of the study area have been developed under the influence of compressional tectonic regime during the closure of Neotethys ocean and subduction of the Arabian Plate under the overriding Eurasian Plate that started in Late Campanian (Berberian and King, 1981). Five different deformation phases have developed and controlled the stratigraphy during this period.

The main objectives of this study are to determine the deformation pattern of the sedimentary succession deposited since Late Cretaceous, and construct the Late Cretaceous-Pliocene tectonostratigraphic evolution of the southern Kozluk (Batman) in Southeast Turkey. And eventually, summarize how all these tectonic

and stratigraphic stages controlled and affected the hydrocarbon potential and future exploration activities in the region.

In this study the development of foreland basin since Early Campanian has been investigated in terms of the deposition center development, and migration; structural development of the foreland basin and deformational patterns have been studied in detail by field, well, seismic studies and construction of geological models. While the sedimentological field study has been conducted to understand the age and stratigraphic positions of the formations, the fault measurements and structural observations have been completed in and around the study area. In particular, the sedimentological studies have been focused on the key areas in which the units have direct relation with the faults. The well log data is also used to build the accurate stratigraphical model and also the orientation of fractures and the maximum stress orientation. The stress distribution and extended leak-off test data from boreholes helped to understand the geomechanical model of the area. The faults and horizons were interpreted in 3D seismic data and the geological model(s) has been evaluated. The kinematics, timing and the mechanisms of deformation, the effects of deformation on stratigraphy, and the petroleum system have been tried to be propounded.

The area has influenced by compressional regime in the Early Campanian period and it was represented by re-activation and newly developed NE–SW-oriented normal faults in the southern Kozluk area. The NE–SW-trending Kumlupınar Fault have controled the development of the Habandere sub-basin in the Early Campanian. Deep marine carbonates with organic-rich basal members (major source rock: Sayındere Formation, and flysch-type sediments: Kastel Formation) were deposited in the Habandere sub-basin, located on the downthrown blocks of these normal faults. While the Sayındere and Kastel deep water sediments were deposited in the basinal area in the western part of the study area, shallow marine-lagoonal carbonates of the Beloka Formation were deposited in the platform. The

basin had been quickly filled up with terrestrial materials derived from allochthonous units located further in the north. The Eocene deposition have started with major subsidence and manifested the deposition of the Gercüş and Midyat carbonates. Then, new transgressional period began and initiated the Early–Middle Miocene deposition of syn-orogenic Silvan Group sediments under the influence of extensional regime as marked by the development of the NE–SW- and NW–SE-trending faults. Later, Upper Miocene fluvial clastics of Şelmo Formation started its deposition after the final collision of Arabian-Eurasian plates and development of Bitlis-Zagros Fold and Thrust Belt. There is evidence for structural inversion from normal to reverse faulting of NW–SE-trending faults, which controlled the development of Late Miocene depositional centers as the model suggest. The implications of the results demonstrate that the deformational patterns of the study area have been represented by extensional structural elements until the Miocene time when the compressional structures was started to initiate. The well log and drilling data suggest that the present day maximum horizontal stress is oriented N–S and the ongoing deformation is manifested by both reverse faulting at shallow depths (0–1500 meters) while strike-slip faulting at deeper horizons (>1500 meters).

In petroleum exploration perspective view, the NW–SE- and NE–SW-trending faults generate very good oil potential structures in the study area. The deposition of thick pile of the Miocene succession in the source area of the Habandere sub-basin helped the generation of good quality oil. The oil producing better quality Upper Cretaceous reservoir rocks occur mostly in southeastern part of basin controlling Kumlupınar Fault. Also the dolomitisation of the Campanian reservoir rocks developed by circulation of hydrothermal fluids along faults and fractures contributed the development of better quality reservoirs in the study area. Further studies are recommended to understand the characteristics, mechanisms and development of the dolomitisation along the reservoirs in study area and neighbouring oil fields.

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APPENDICES

Appendix A.

Jkg-jkk: Jurassic-Lower Cretaceous Guleman Formation

Kk: Campanian Karaboğaz Formation

Kka: Early Cretaceous Karadut complex

Km-Kma: Aptian-Santonian Mardin Group

Tlh: Pliocene Lahti Formation

Kmka: Coniacian-Santonian Karababa Formation

Ks: Campanian Sayindere Formation

Ksg: Maastrichtian Lower Germav Formation

Ksga: Maastrichtian Garzan Formation

Kska: upper Campanian-Maastrichtian Kastel Formation

Ktsa: Paleocene Antak Formation

Ob: Ordovician Bedinan Formation

Plq-q-qal: Quaternary Alluvium

Pzmzb1-Pzmzb2: Devonian Bitlis metamorphics

Qb-tb: Upper Miocene-Quaternary basalts

Sdd: Silurian Dadaş Formation

Tc: Eocene-Miocene Çüngüş Formation

Tf: Lower Miocene Fırat Formation

Tk: Lower Miocene Kapıkaya Formation

Tma: middle Eocene Maden Group

Tmge: Eocene-Oligocene Germik Formation

Tmh: Eocene Hoya Formation

Tsg: Paleocene Upper Germav Formation

Ts: upper Miocene Şelmo Formation

Tl: Lower-Mid Miocene Lice Formation

Trc: Triassic-Jurassic-Lower Cretaceous Cudi Group

Ed: Cambrian Derik Group



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