



# 3D seismic model of faulting systems of a Jurassic - Cretaceous sedimentary packages in Merjan\_West Kifl Oil fields - Central Iraq



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## ABSTRACT

Study of three dimension seismic data of Merjan survey, central Iraq has showed that the Jurassic – Cretaceous succession is affected by faulting system. Seven major normal faults were identified and mapped. Synthetic traces calculated from sonic and density logs of the well Me-1. Two exploration wells were drilled in the area Me-1 and Wkf-1 wells. The area is characterized by extension phase led to graben system forms rift sub-basin. The structural components of rift sub-basin has identified and visualized in three dimensions. Discussion about the effect of this system on the sedimentary package has been presented. Faulting framework can be divided into two groups: the first affects the Jurassic and lower Cretaceous rocks and the second affects the upper Cretaceous and lower Tertiary rocks. The first group is associated with the post rift thermal sag, passive margin progradation and gravitational collapse (lower Jurassic – mid Turonian 190–92 ma); approximately during the Sargelu – NahrUmr depositional time. The second group is limited and is associated with the rifting creating the Euphrates graben as collision wanes (Late Turonian – Maastrichtian 90–70 Ma) approximately during the Tanuma shale/Sadi – Shiranish depositional time.

## 1. Introduction

Depositional environments of continental sedimentary basins are influenced by several parameters such as; the pattern of geometrical shape of the basin, sediments supply and subsidence rate. These parameters leads to impact on the process of sedimentary filling and hydrocarbon accumulation (Tim et al., 2010; De Batist, 2011). It is a more beneficial approach to geomorphology and seismic data analysis (Posamentier et al. (2007). Within the last decade, the most logical workflow of using seismic data follows the transition from seismic stratigraphy, to sequence stratigraphy, to seismic geomorphology (Li et al., 2016). Seismic geomorphology was defined by Posamentier et al. (2007) as “the application of analytical techniques pertaining to the study of landforms and to the analysis of ancient, buried geomorphic surfaces as imaged by three-dimensional (3D) seismic data”. Therefore, seismic geomorphology, when integrated with seismic and sequence stratigraphy, is a powerful and effective tool for analyzing the stratigraphy, understanding structural styles, processes and basin evolution, and predicting the spatial-temporal distribution of sedimentary facies under a sequence stratigraphic framework (Zhu et al., 2016; Li et al., 2016).

The local structural framework sets controls on the sedimentary

systems. An understanding of the relation between local deformation and deposition helps to infer the positions of subtle pinch-outs that may provide hydrocarbon traps and can yield a detailed history of structural development (Shaw et al., 2004). The accommodation space created by faulting and fault-related topography is the primary control on the large-scale sedimentary systems within rift basins (Martins-Neto and Catuneanu, 2010; Maravelis et al., 2018). This topic has been addressed in many papers (Leeder, 1995; Contreras et al., 1997; Gawthorpe and Leeder, 2008). Information from different seismic attributes is used to define fault geometry, and can be used to optimize well locations (Santosh et al., 2013). Some researchers have proposed that, during rifting, the basins were relatively long, narrow, isolated, and asymmetric, bounded on one side by major faults, much as they are today (Schlische, 2003). Others have proposed that the basins were originally broad sag basins that were later tilted and faulted (Rodger, 2003; Schlische and Withjack, 2005). The tectonic evolution of rift basins has been studied by many researchers in different locations in the world such the Fushan Depression in China (Li et al., 2016), Luanping basin in northeast China (Zhu et al., 2016) and the eastern Ionian Basin, southwestern Greece (Bourli et al., 2019).

The study area is the Merjan\_West-Kifl- Oil fields, which are located in

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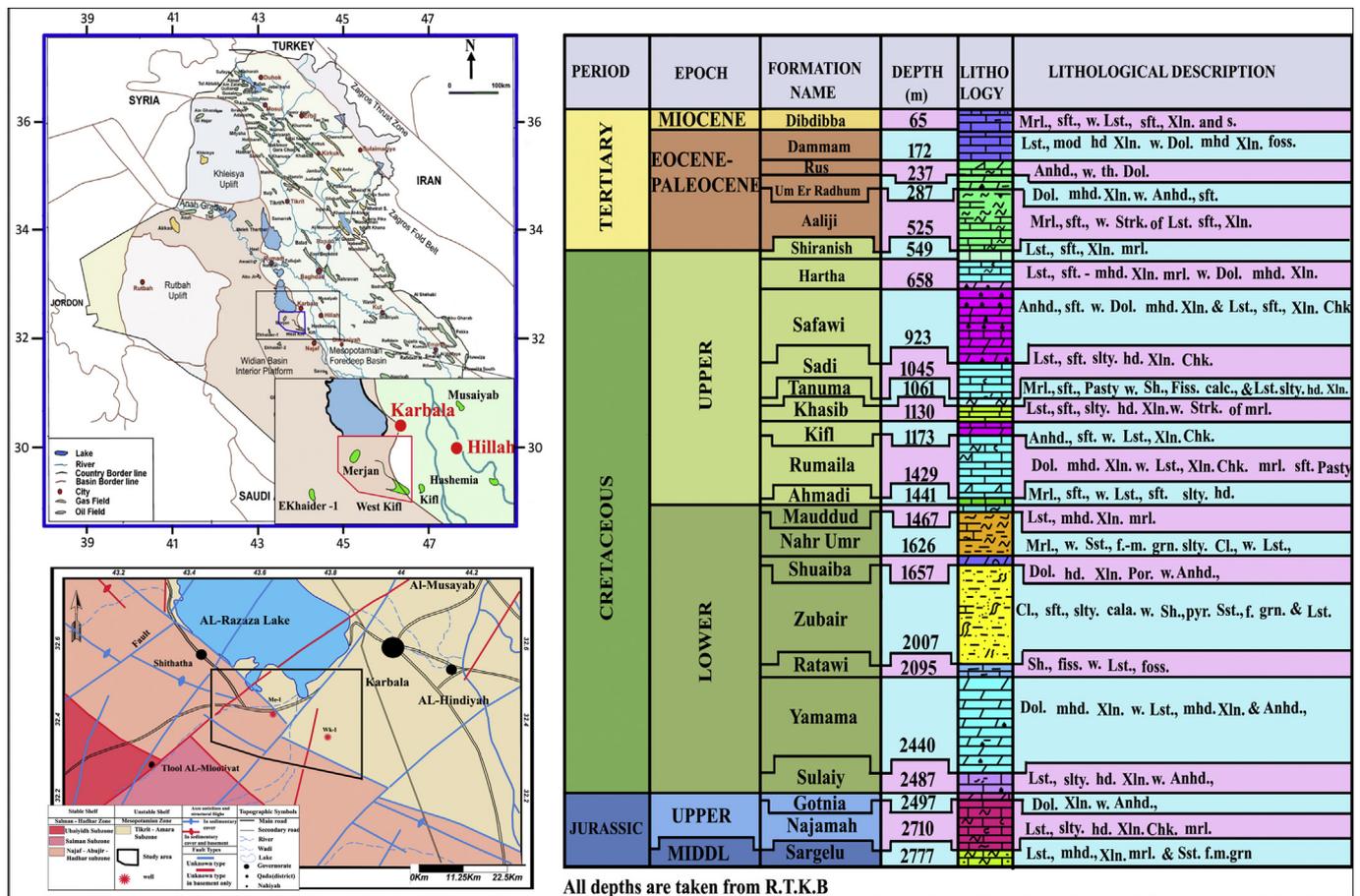


Fig. 1. a) Study area location map (after Al-Ameri et al., 2014). b) Location of the study area on the tectonic map of Iraq(after GEOSURV, 1996) and c) Stratigraphic secession of the study area from Me-1 well (after O.E.C., 2005).

the middle of Iraq. The Merjan area lies in a critical position (transition zone) between the Mesopotamian Basin (unstable shelf to the east) and the Stable Platform to the west according to the tectonic map of Iraq (Fouad, 2015). Pervious 2D seismic and subsurface (wells) investigations for oil fields have been mainly focused on the description of structures in the area (which is dominated by NW-SE trending 'high' plunges to the south east). However, they did not point to the faulting system because of the limitation of the 2D survey used in the interpretation (Exxon Mobil, 1982; O.E.C. 2000; O.E.C., 2005; O.E.C, 2007). Petrel Resources plc. (2007) deduced a study based on elevation data, satellite images and this study was later integrated with 2D seismic data to study the structures of the area. Only one main fault located close to the Merjan-1 well location has been delineated by the study. This has a NW-SE orientation which is similar with the dominant regional fault trend. On the other hand, satellite images were analyzed and showed the numerous trends of the lineaments.

With an increasing demand on petroleum resources in Iraq, the Hartha Formation has become a significant hydrocarbon bearing formation in the Merjan\_West Kifl Oil fields. There has been some documentation of the tectonics, stratigraphy, sedimentology, and petroleum exploration and development of the area that helps for further sedimentary research and hydrocarbon exploration (O.E.C., 2007). However, traditional geological research based on logging data and old 2D seismic data (that have low coverage and low resolution) limits the identification of the faults system in the area and the understanding of the complex characters and distributions of the Merjan\_West Kifl Oil field's structure.

In 2013, a 3D seismic survey was conducted for the study area. The collected data was interpreted by the Iraqi Oil Exploration Team. They

showed that the general dip of the sedimentary layers in the area is towards the east and structurally it cannot be considered as dependent because it can be interpreted only by the Hartha Formation which was not depended in delineation the geomorphology of subsurface structure, but they infer that the Hartha Formation is affected by a normal faulting with a N-S strike which is well known as the Tar fault (O.E.C., 2015).

Given this, the main objectives of this paper are to determine the detailed geomorphological picture of the subsurface faulting framework by examining the 3D seismic data of the Merjan area, and also, to provide a new case using seismic geomorphology to characterize structural styles over the sub-basin including the slopes area.

## 2. Study area

The Merjan area lie in the Karbala governorate, middle of Iraq (Fig. 1a). The area is located within the transition zone between the stable and unstable shelf of the Arabian plate (Fig. 1b). It is near to the stable shelf, and far from the center of the high structural activity zone of the last Albian movement that accrued in the Cenozoic time, so it has characterized by simple structural nose and NW-SE faults trend. The area is considering a part of the north and the northeastern edge of the Arabian plate (Beydoun et al., 1992). The stratigraphic column of the Merjan area is illustrated in Fig. 1c.

## 3. Materials & Methods

The used data in this paper are 3D seismic volume covering an area 1026.17 km<sup>2</sup> (Merjan area), log and velocity survey data of two wells

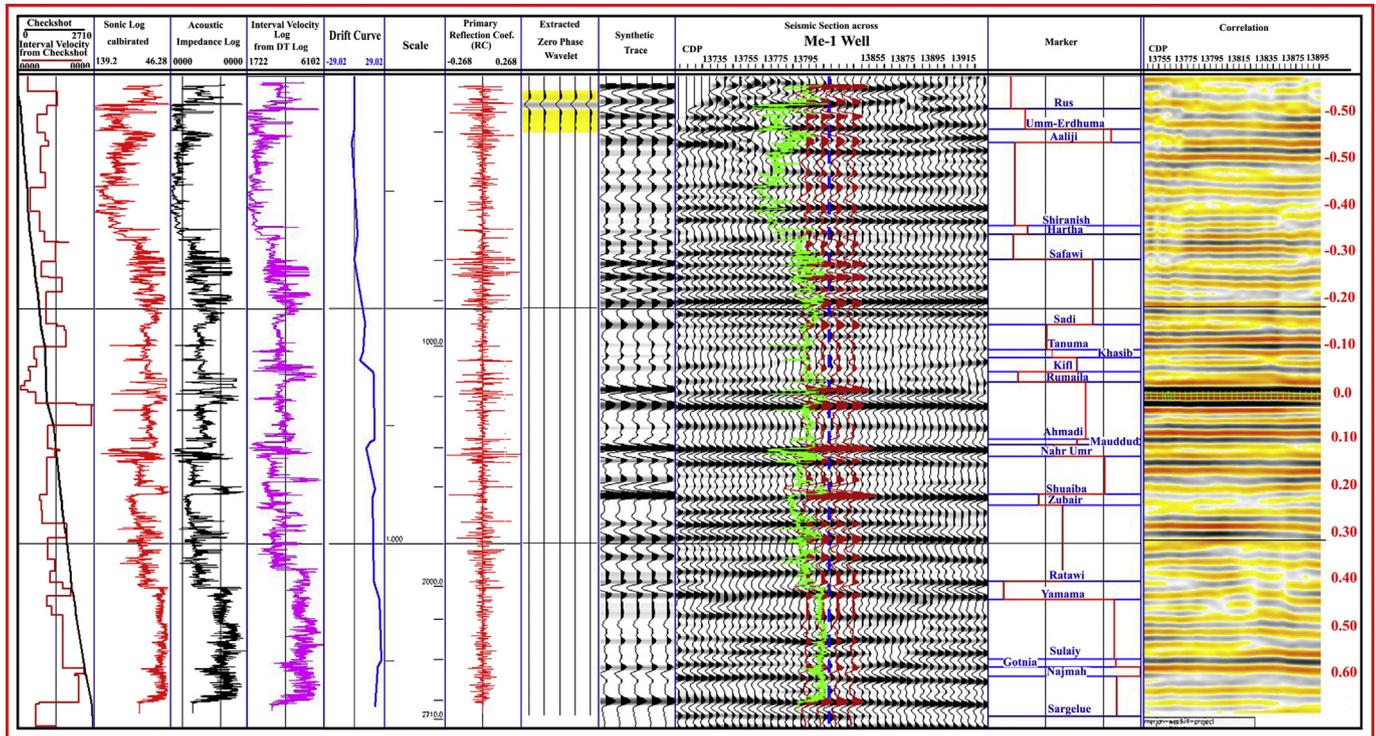


Fig. 2. Synthetic seismogram of Me-1 which shows a good tie with seismic data.

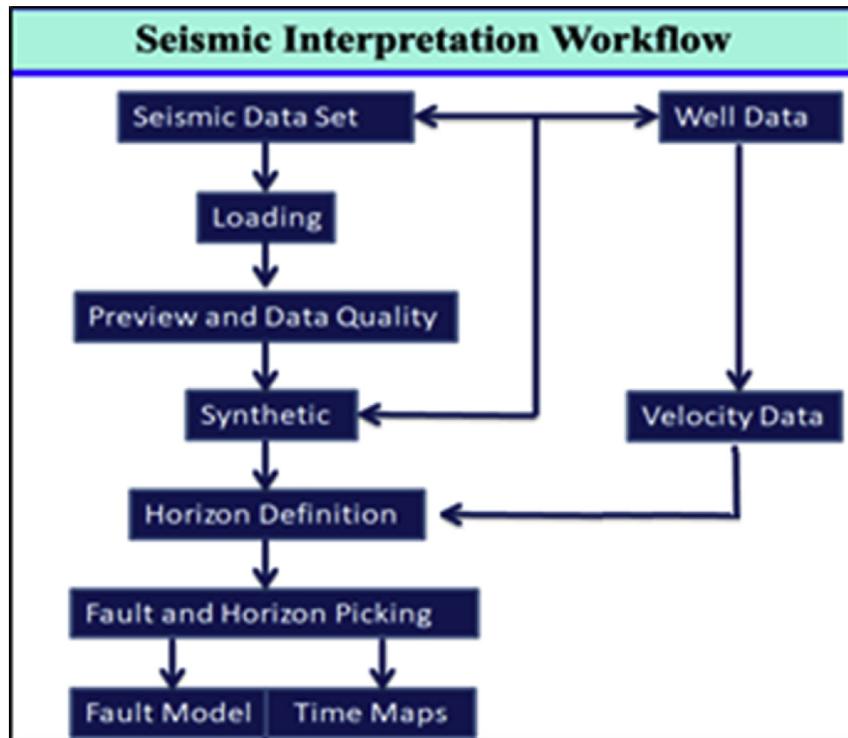


Fig. 3. Generalized workflow chart for structural seismic data interpretation.

(Me-1 and Wkf-1).

### 3.1. Synthetic seismogram and methodology

The synthetic seismogram was generated using the Seismic to

Well Tie module in GeoFrame Software. The sonic data was first edited for any spiky noise and was calibrated to check shot and any gap in the sonic data was filled by interpolating the nearby data. The correlation of the synthetic seismogram and 3D seismic data is very good and it has been easy to identify well markers on the

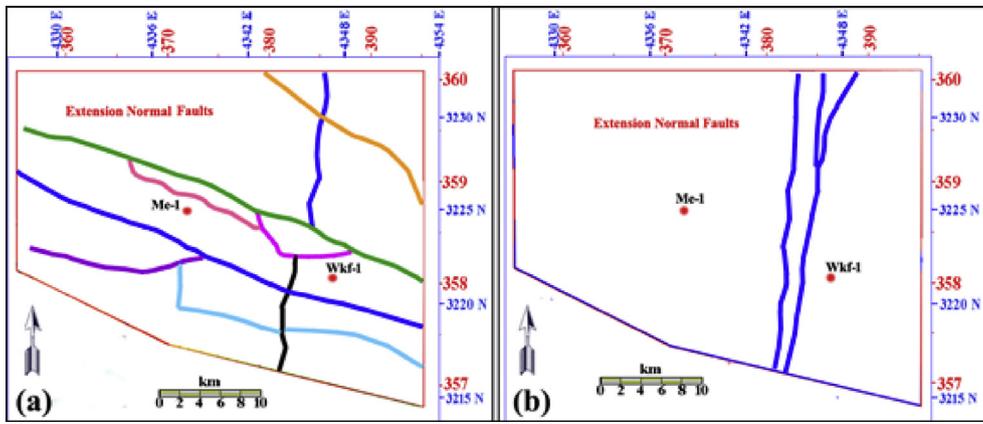


Fig. 4. Illustrates fault distributions maps affecting the study area (a) faults system effect on Jurassic – lower Cretaceous rocks and (b) faults system effect on U.Cretaceous and Tertiary rocks.

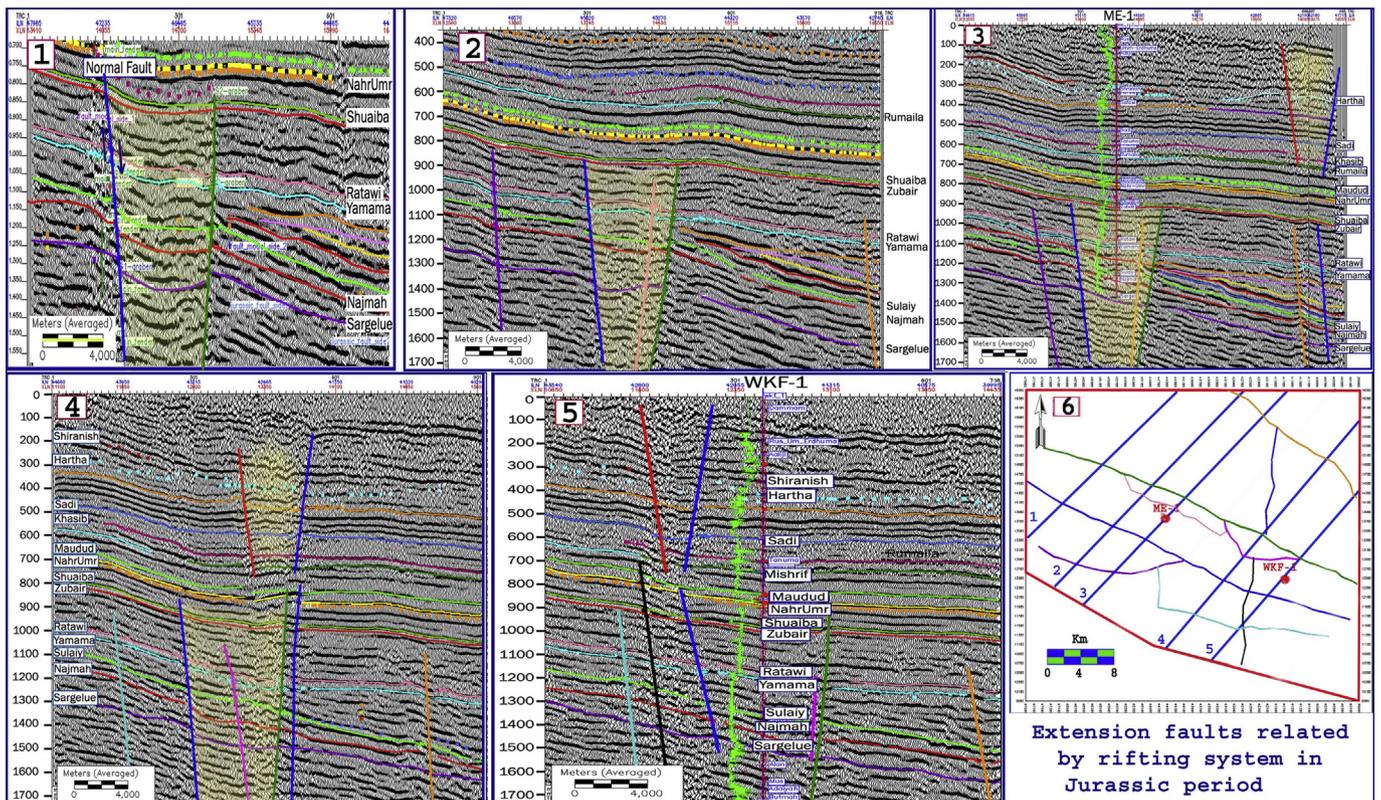


Fig. 5. NE-SW seismic profiles across the picked fault system that affect Merjan field, all them illustrate NW-SE graben structure as in image (1) and also illustrate (2) three normal faults (NF) affect Jurassic to lower Cretaceous succession, (3) two NW-SE NF with N-S NF, also it shows N-S flower structure affects the upper Cretaceous – Tertiary succession, (4) four NW-SE NF with N-S NF, also it shows N-S flower structure affects the upper Cretaceous – Tertiary succession, (5) two NW-SE NF with N-S NF, also it shows N-S flower structure affects the upper Cretaceous – Tertiary succession, (6) fault trace map on the Jurassic –lower Cretaceous horizons, also represents the track line map showing the location of seismic reflection profiles used in this study.

seismic data (Fig. 2). Methodology is summarized by the following workflow (Fig. 3).

#### 4. Results and discussion

##### 4.1. Fault interpretation

Examinations of the seismic sections show that the area is affected by an extensional normal faults system which has picked and followed from line to line to track their strike and to determine the affected geological column. Both the Jurassic and Cretaceous packages have been faulted. The Jurassic succession is characterized by more dense extensional faults

than Cretaceous rocks. They were picked in all the study area along each inline and also along many cross lines and arbitrary lines. The fault appears as a zigzag line on the base map due to a change of the strike trends. Also, differences in the dip of the fault plane indicate an influence of horizontal stress on the structures which led to lateral displacement. The seismic geomorphology of the observed faults can be divided into two groups: the first affects the Jurassic and lower Cretaceous rocks and the second one affects the upper Cretaceous and lower Tertiary rocks (Figs. 4a, b and 5).

The first group of faults is the most intensive and visible from the second group in the study area, especially those that formed the NW striking extensional graben structures in the area.

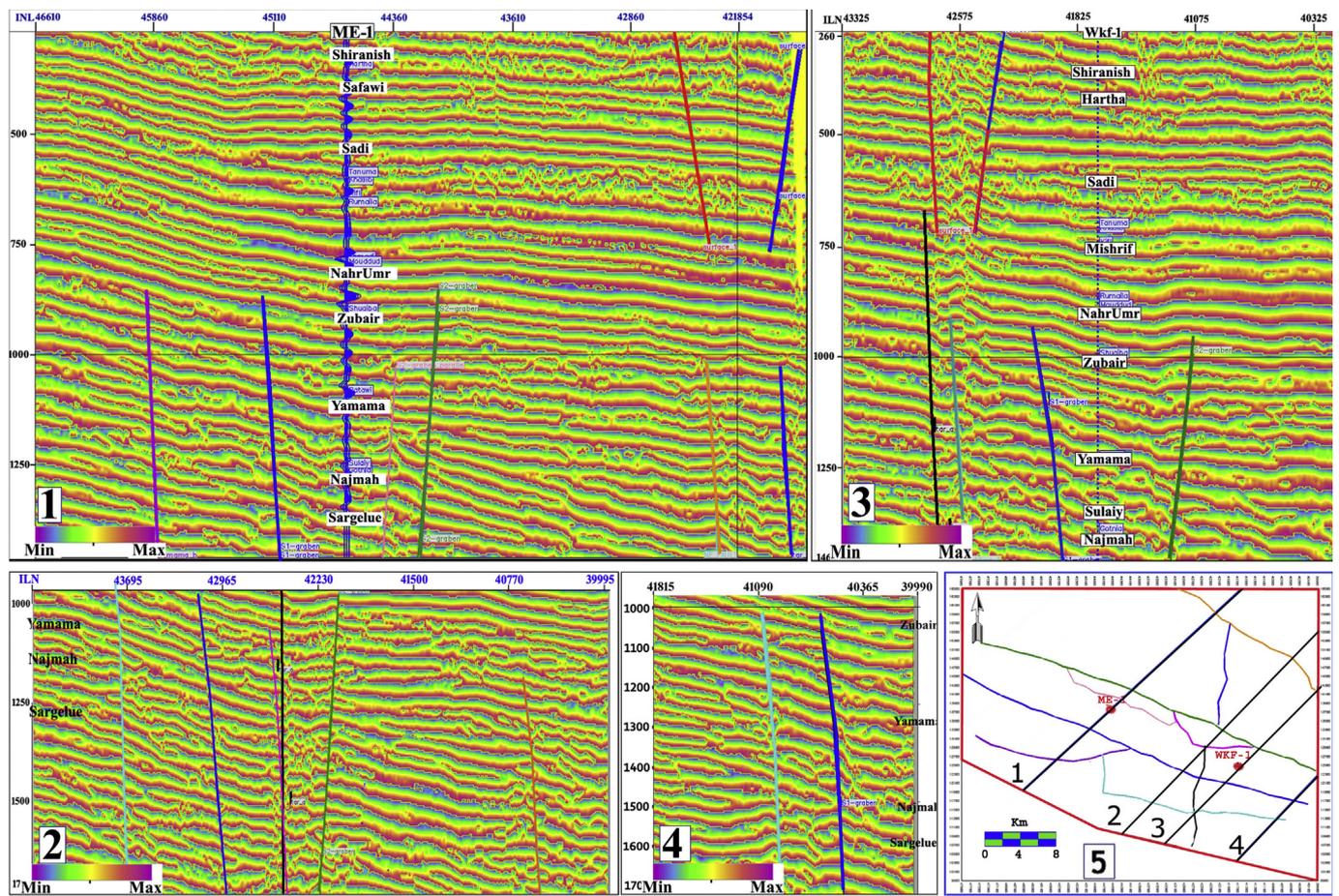


Fig. 6. Shows NE-SW instantaneous phase profiles across the picked fault system that affect Merjan field, all them illustrate NW-SE graben structure and illustrate (1) two NW-SE NF with N-S NF, also it shows N-S flower structure affects the upper Cretaceous – Tertiary succession, (2) three NW-SE NF with N-S NF (black fault) affects the upper Cretaceous – Tertiary succession, (3) NW-SE NF with N-S NF (black fault) also it shows N-S flower structure affects the upper Cretaceous – Tertiary succession (4) NW-SE NF, (5) fault trace map on the Jurassic –lower Cretaceous horizons, also represents the track line map showing the location of seismic reflection profiles used in this study.

It is appropriate to consider that, these faults in their regional context (in terms of structural style) have a gross structural position through time which is consistently demonstrated by interpretations from wells and seismic sections. The first group is associated with the post rift thermal sag, the passive margin progradation and the gravitational collapse (lower Jurassic – mid Turonian 190–92 ma); it is approximately related to the depositional time of Sargelue – Nahr Umr Formations.

The second group is limited and is associated with the rifting that has been creating the Euphrates graben as collision wanes (Late Turonian – Maastrichtian 90–70 Ma); it is approximately related to the depositional time of the Tanuma shale/Sadi – Shiranish Formations.

4.2. Using instantaneous phase attribute for fault recognition

Taner et al. (1979) have indicated that seismic attribute sections, especially the instantaneous phase sections, are very important for the distinction of reflector surfaces continuity termination because it does not depend on the reflection strength. For this reason, an instantaneous section (Fig. 6) is used for distinguishing the reflector surface terminations and sharp discontinuities in the amplitude such as that caused by faults. Fig. 7 illustrates the instantaneous phase slices which were selected at different levels as shown in Table 1.

4.3. Description of the observed faults

A total of 7 major normal faults were identified which are

summarized in Table 2. The following provides a general description for the observed faults in the study area:

- a Trend: All faults striking NW- SE trend along the basin margin except these faults striking NE-SW trend. The principal, northwest trending zone coincides with faults controlling the southwest margin of the Mesopotamian Basin. The WNW trending fault zone forms a graben system. It is an important structure at the basin margin that has controlled sedimentation and thickness of stratigraphic units, particularly during the Late Jurassic and Early Cretaceous.
- b Type of fault: These faults are extensional faults.
- c Throw and heave: are vertical separation and horizontal separation as illustrated in (Fig. 8). The seismic data and respective cross-sections are vital for the verification of fault/fold geometries and style, dip of faults and throw on faults. The throw has been calculated from depth map, and heave is calculated according to Eq. (1) (Table 2).

$$\tan \theta = \frac{\text{vertical throw}}{\text{heave}} \tag{1}$$

There is linear relation between the throw and heave (Table 3), displays their values of the picked normal faults that have the same dip angles (80 and 84°) respectively.

The relation indicates that proportionality relationship between the heave and throw as shown in (Fig. 9). Now if we propose that dip angle equal 90°, the resultant is unknown quantity, thus, it will not be there heave.

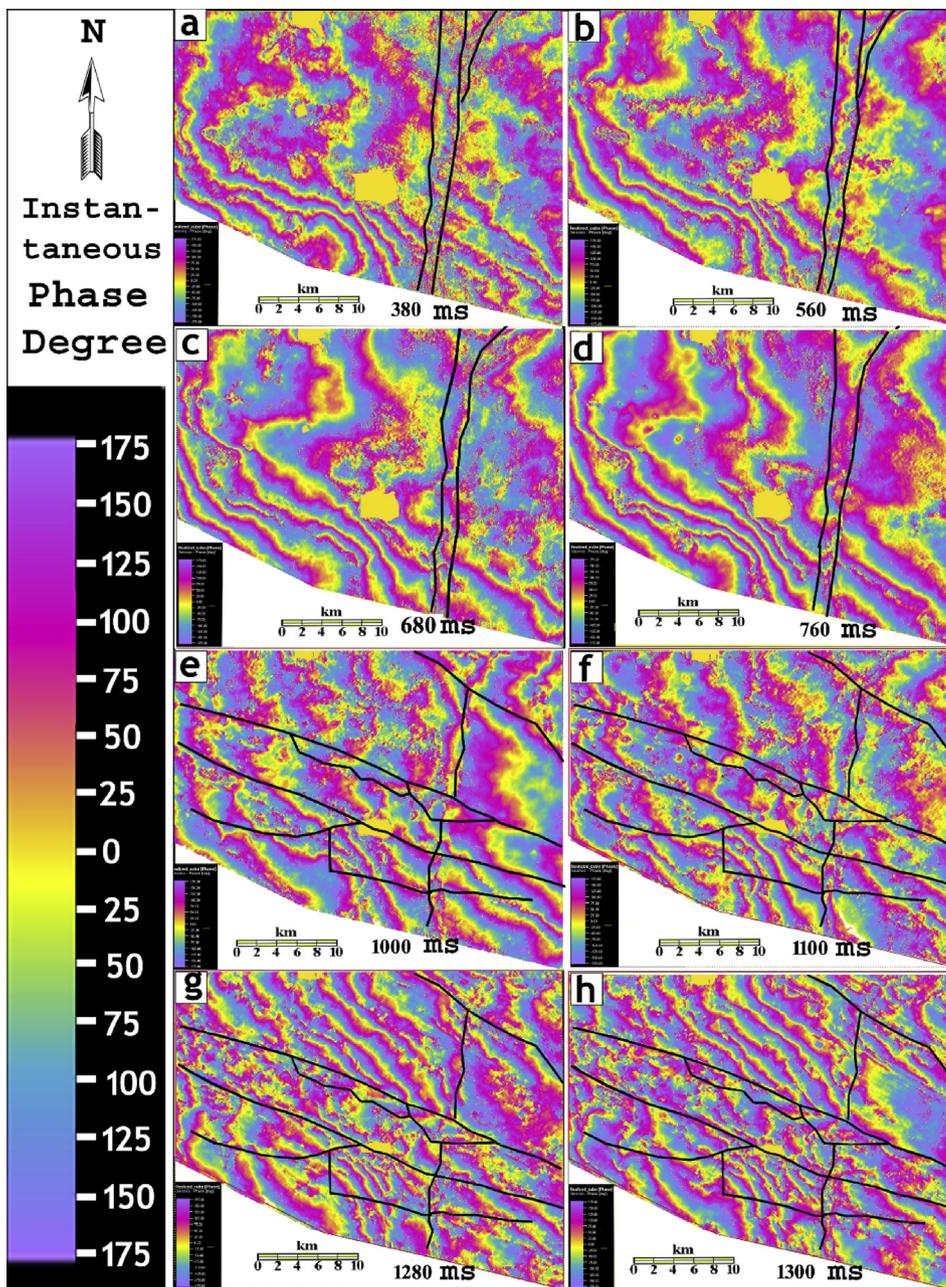


Fig. 7. Horizontal sections along Cretaceous –Jurassic formations through seismic instantaneous phase. It is noted that the phase displays two main behavior; random in the fault locations and coherent in the non-faulted areas, also a abrupt change is noted between the two behaviors, the black lines indicate normal faults (a, b, c, d), instantaneous phase slices illustrates that the area is affected by N-S normal faults affect upper Cretaceous – Tertiary succession, and (e, f, g, h) illustrates the picked fault system which affects the Jurassic – lower Cretaceous succession.

4.4. 3D creating a basin model according to time of fault occurrence

Depending on seismic geomorphological interpretation of the 3D seismic data, a 3D morphological-structural model according to time of fault occurrence has been constructed to determine the faulting framework of the study area (Figs. 10 and 11). The morphology of the faults

Table 1  
Illustrating the time slices levels relative to their equivalent formations.

Time Slice	Me-1 (Formation)	Wkf-1 (Formation)
380	Hartha	
560	Sadi	Hartha
680	Rumaila	Sadi
760	≅ Bottom Rumaila	≅ Top Mishrif
1000	Zubair	Within Shuaiba
1100	Ratawi	Zubair
1280	Najmah	Within Yamama
1300	Najmah	Within Yamama

boundaries with their sticks were mapped using the GeoFrame software (Fig. 12). This model shows a rift system which influences the Jurassic - Cretaceous sedimentary packages. The three dimensional model gives an idea about the seismic geomorphological geometry of faults and the topography of the sedimentary sub-basin of the Cretaceous rocks in the Merjan area. The graben faults system was reactivated during the tectonic inversion in the Tertiary. The relation between the Jurassic and Cretaceous is determined from this model, where Jurassic faults' movements and horizontal stresses caused folding of the lower Cretaceous succession as it will be noted in the next section.

4.5. Stratigraphic units of rift basins

The most basic stratigraphic units associated with rifting are the pre-rift, syn-rift, and post-rift packages. Depending on the faulting system from seismic geomorphological data, the tectono- stratigraphic framework in the area can be summarized as follows:

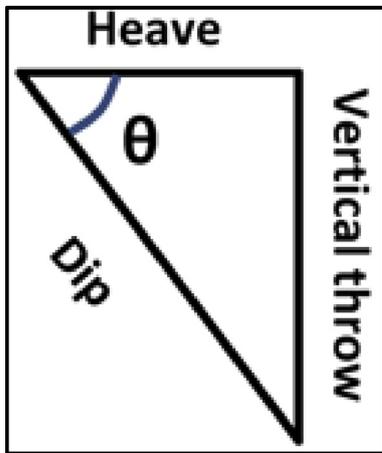


Fig. 8. Simplified diagram showing vertical and horizontal separation.

Table 2  
Interpreted faults system parameters calculated from seismic data.

Fault no./color on a map	Trend	Throw (m)	Heave (m)	Dip angle (θ)
1 (Turquoise)	WNW-ESE	10	1.4	82
2 (Purple)	WNW-ESE	10	1.76	80
3 (Blue)	NW-SE	20	3.5	80
4 (Green)	NW-SE	10	1.76	80
5 (Black)	NE-SW	10	0.87	85
6 (Blue also called Tar fault)	NE-SW	12	1.26	84
7 (Orange)	NW-SE	10	1.4	82
8 (Red)	SURFACE 1	8	0.84	84
9 (Blue)	SURFACE 2	8	1.26	81

- Sargelu Formation is a pre-rift phase sequence.
- Najmah to Yamama Formations are syn-rift phase sequences.
- Ratawi, Zubair and Shuaiba Formations were deposited during the post-rift phase.

Table 3  
Throw and heave values for the picked normal faults that have the same dip angles (80 and 84°) respectively.

Throw at dip 80	Heave at dip 80	Throw at dip 84	Heave at dip 84
10 m	1.76 m	12 m	1.26 m
20 m	3.5 m	8 m	0.84 m
10 m	1.76 m	10 m	0.87 m

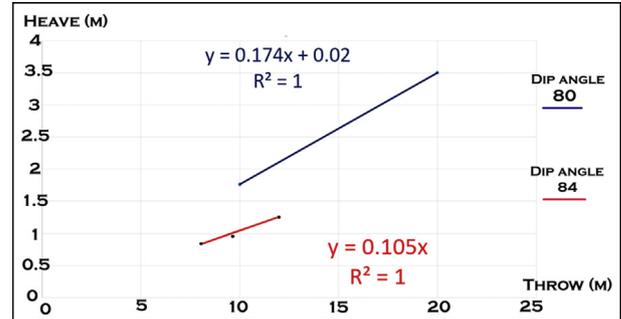


Fig. 9. Relationship between the Heave and throw in the picked normal faults have the same dip angle for the picked faults, Correlation coefficient ( $R^2$ ) is very strong.

d Angle: It is calculated from the seismic section.

e Vertical effects of faults: The faults affect mainly the Jurassic to early Cretaceous formations and secondarily act on the upper Cretaceous formations.

4.6. The geomorphological structural components of rift sub basin

Rifting in the study area forms elongated sub basins bounded on both sides by normal faults. The structural components of the rift sub-basin include faulted margins, the border faults (BF) of the faulted margins, the uplifted flanks of the faulted margins, hinged margins, deep troughs and intra-basin faults. A fold has been formed in the sedimentary cover above the border faults.

In the seismic geomorphological model, the border faults are a fundamental part of every faulted margin, nearly have a stepping morphological geometry and convergent dip directions, causing the faulted and hinged margins to shift from side to side of the rift basin. The secondary

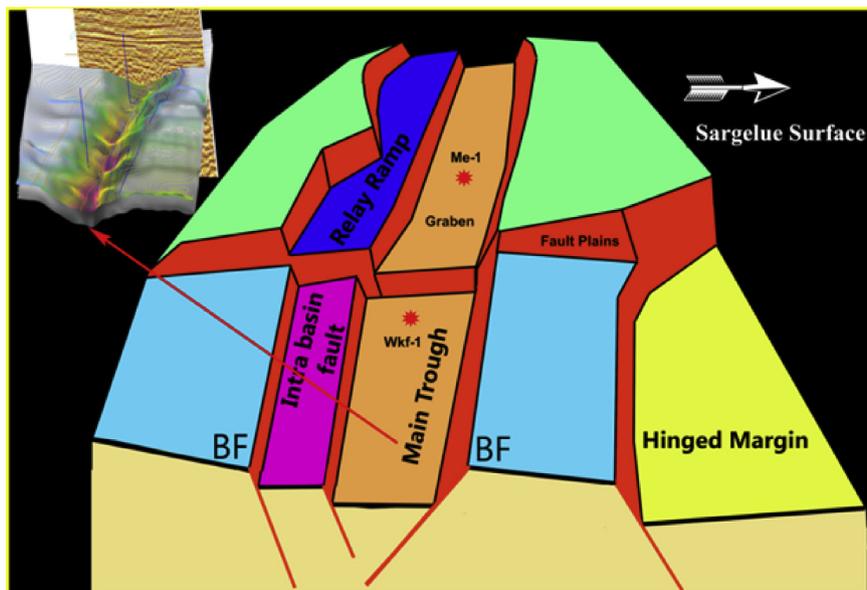


Fig. 10. Top view of a 3D geomorphological structural model captured depending on seismic data of the Sargelu surface which illustrates the basin topography of the Jurassic that affects the geometry and geomorphology of Cretaceous rocks in the study area.

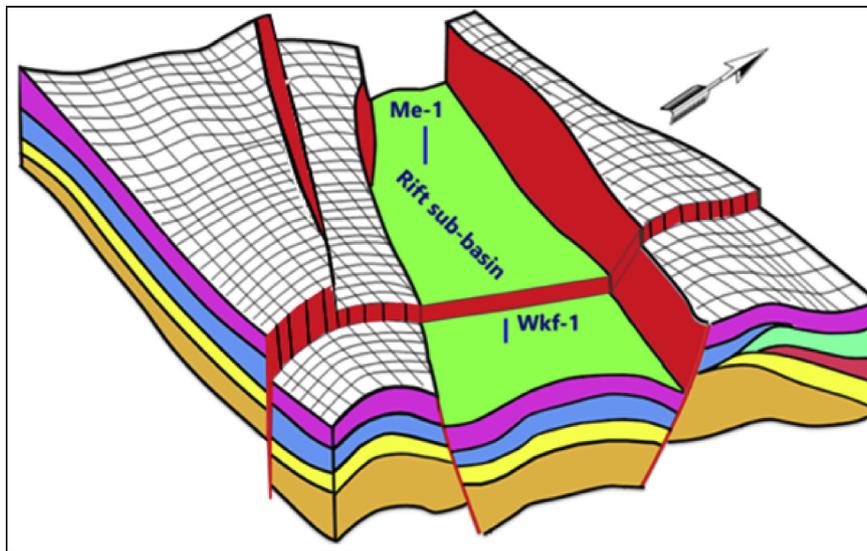


Fig. 11. 3D reconstruction illustrates the seismic geomorphology of the graben system in the study area.

deformation which has been associated with border faults is a fold which was formed in the sedimentary cover (Najmah to Rumaila formations) above the border faults as response to flexures that occur above the border faults (Figs. 13a and b). Another deformation includes secondary normal faults that strike obliquely to the trend of the border faults.

4.6.1. Flanks and troughs

One of the structural manifestations that form when a rifting occurs are flank and trough. These features have been clearly distinguished in

the seismic sections. The shape and depth of the trough are governed by the angle of two border faults and their displacements. Trough be deeper at the edges of rifting and decreases towards the center of the trough. With regarding to the flank, it is a distinctive structural uplift at the tip of border faults and gradually decline away from border fault.

4.6.2. Intra basin fault blocks

When the extension stress which caused by a tectonic and sedimentary loading increases, the rifting can be developed by intra basin faults

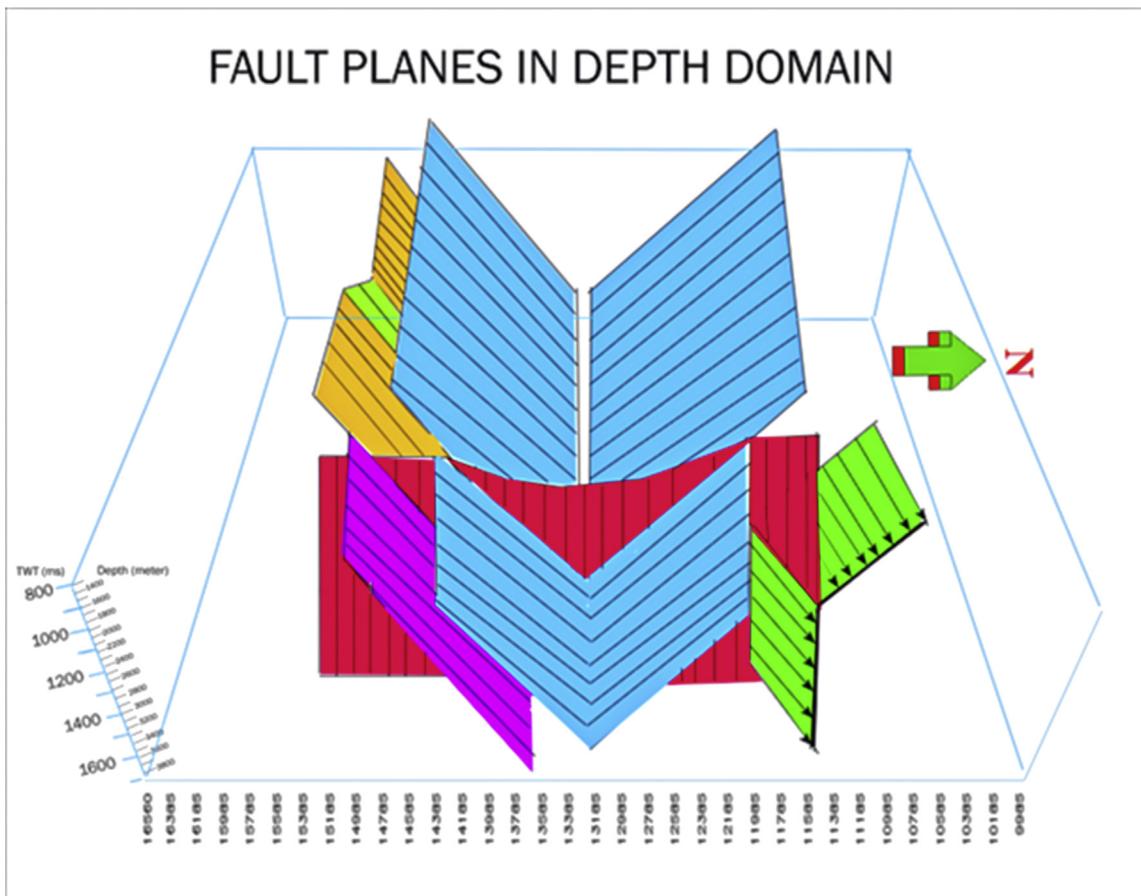


Fig. 12. 3D view of the morphology of faults planes model depending on the boundary and sticks of faults in the time domain.

which take parallel direction to the line of border fault.

The Jurassic-Cretaceous sedimentary package have been deposited in the rift sub basin, and the intra-basin fault is an orthogonal extension which strikes parallel to the rift trend and perpendicular to the maximum extension direction (Figs. 13a and b), which have been folded as response to the vertical loading causing the by the border fault movement.

4.6.3. Fold

After rifting process, which accrued during the Jurassic time, the sediments fill the sub basin rift, producing the post-rift package, which later folded when the border faults reactivated by the compression stresses during the tectonic inversion phase during tertiary time. The crest of fold approximately seated above the edges of border faults The

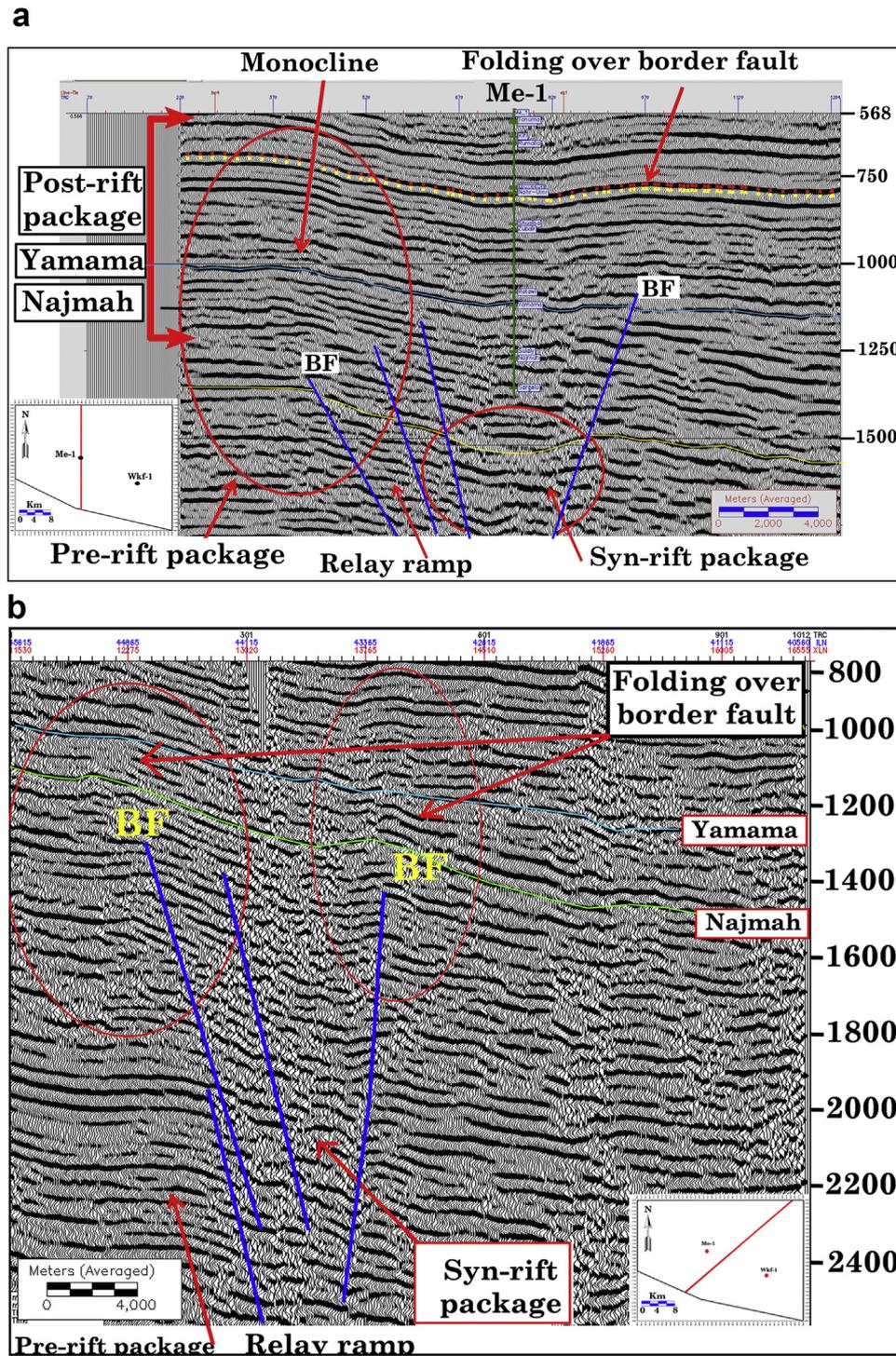


Fig. 13. a. Seismic inline section illustrating the rift sub basin and folded reflectors. b. Seismic arbitrary line section illustrates the rift sub basin and the folded reflectors.

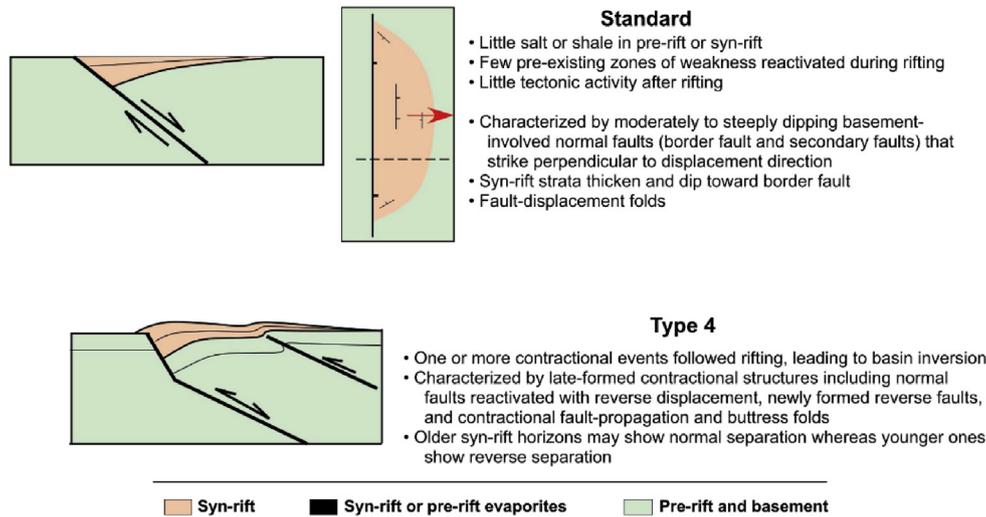


Fig. 14. Rift basin structural styles (modified from Withjack and Callaway, 2000).

Cretaceous succession is the most affected package by folding in the area (Figs. 13a and b).

4.7. Type of rift sub basin

Type of basin depend on the geomorphology shape of basin which driven by a series of agents including:

- Intensity of tectonic movement.
- Rigidity of basin – fill sediments (syn - rift and pre - rift packages).
- Thickness of the sediments.
- Type and direction of stress.

Based on these factors, there are a standard rift basin and four end member variations of geomorphological structural styles in rift basins. In our case, the type of rift sub-basin is a standard rift basin that later converts into factor type (4) as a response to tectonic inversion from an extensional tectonic phase during the Jurassic and Cretaceous into a compressional tectonic phase during the Tertiary Period. The characteristics of these types were determined according to Withjack and Callaway (2000) (Fig. 14).

4.8. Sub basin accommodation space

The tectonic episodes are responsible on the creation of accommodation space. The rift sub basin can give us a good accommodation to accumulate the Cretaceous succession in the area. The size of space is controlled by the magnitude of a border fault throw and subsidence rate. Seismic section depicts that the rift sub basin were suffered to several extension tectonic shocks which led to increase of accommodation space, it illustrates some evidences such

- Deposition of thick syn-rift packages which separated by a regional unconformity (Jurassic – Cretaceous unconformity).
- Presence of intra basin faults

The rift sub-basin is a symmetric one, troughs form on both sides of the rift basin like the case presented by Withjack and Callaway (2000) (Fig. 15).

The sediment supply effects on the subsiding rate of rift sub basin, thus, this factor also contributes in increasing of accommodation space. It is noted in seismic data the sediment – fill are thick in center of trough while it thin towards the border faults.

Given these parameters about the basin geometry in the study area it

is very important where; it could help with following the vertical migration of the fluid from the source rock and the enhancement of the permeability system of a stratigraphic column.

This delineated faults system is the main controller on the:

- Shelf margin development (Najmah platform).
- Accommodation space.
- Creation of a trapping mechanism by forming the secondary structures that can trap oil.

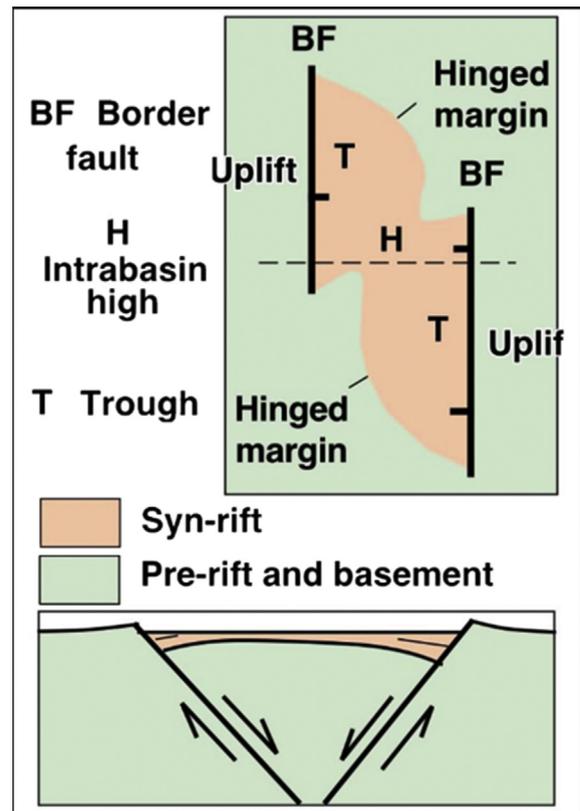


Fig. 15. Illustrate border faults that have a stepping geometry and convergent dip directions. These geometry leads to faulted and hinged margins to shift from side to side of the rift basin (modified from Withjack and Callaway, 2000).

- Fault controls sedimentation and facies variation.

The results of seismic geomorphology faults from sub-seismic resolution data beside the compressional reactivation of graben faults are related to regional inversion and may have all played an important part in the structural entrapment and the development of permeability facilitating vertical hydrocarbon migration. The combination of extension and later inversion would have reduced the apparent displacement on the faults.

## 5. Conclusion

3D seismic data provide a fantastic performance to make geomorphological faulting analysis in the Merjan West-kifl oil fields. The study area has been affected by extensional normal faults which have been divided into two groups: the first affects the Jurassic and lower Cretaceous rocks and the second one affects the upper Cretaceous and lower Tertiary rocks. The first group is associated with the post-rift thermal sag, the passive margin progradation and gravitational collapse (lower Jurassic – mid Turonian 190–92 ma), approximately during the Sargelu – Nahr Umr Formations depositional period. The second group is limited and is associated with the rifting creating the Euphrates graben as collision wanes (Late Turonian – Maastrichtian 90–70 Ma) approximately during the Tanuma shale/Sadi – Shiranish Formations depositional period.

Seismic geomorphological and structural interpretation of the 3D seismic data allowed us to construct a 3D structural model in time domain, to determine the stratigraphic units associated with rifting and subtle fault delineation. This model shows a morphology of rift system which influences the Jurassic Cretaceous sedimentary packages and gives an idea about geomorphological geometry of faults and the topography of the sedimentary sub basin of the Cretaceous rocks in the Merjan area. The graben faults system were reactivated during the tectonic inversion during the Tertiary.

The seismic geomorphology of the structural components of a rift sub basin is a very important element to be recognized and thus to understand the relation between the basin and sedimentary basin fill. The secondary deformation which has been associated with border faults is a fold which forms the sedimentary cover above the border faults as a response to flexures that occur above the border faults. The type of rift sub basin is a standard rift basin which later converts into type 4 as a response to tectonic inversion from an extensional tectonic phase during the Jurassic and Cretaceous into a compressional tectonic phase during the Tertiary Period.

Overall, the analysis of the faulting framework and tectonic evolution provide deep understanding of the oil fields of interest and a rigid theoretical background to support future prospecting whether it is in the study area and other similar rifted basins of the Mesopotamia.

## Declarations

### Author contribution statement

M. S. Fadhil: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

A. M. Al-Rahim: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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### Competing interest statement

The authors declare no conflict of interest.

## Additional information

No additional information is available for this paper.

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