Paleo and Neo-Tectonics of the Mosul Fault and its Impact on the Tectonics of the Foreland Area of Iraq

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ABSTRACT

Interpretation of Paleofacies maps was used as a tool to prove that Mosul fault was active since Middle Jurassic or even earlier. This fault extends from the Turkish border to the Lower Zab tributary of the Tigris River dividing the region into Mosul and Sinjar blocks. The sedimentary facies were used as indicators for the fault extension and its vertical displacements. They showed that Sinjar block was uplifted until Cretaceous when the two blocks were at almost a same elevation. Such a situation was remained until Middle Eocene.

During this epoch, the collision between Arabian and Eurassian plates resulted in a relative uplift of the Mosul block and the deposition of the continental Gercus Fm. In the mean time, a thick deposition of the basinal Jaddala Fm. was dominating the subsided Sinjar block. The Mosul block persisted the extremely uplifting until end of the Oligocene. The Early Miocene was characterized by the up- and downward movements of Sinjar block. This was also manifested by the facies alternations of both basinal and lagoonal types although in general the Sinjar block was relatively uplifted. During the Middle Miocene, the deposition of the Jeribe Fm. on the Sinjar block side may indicate that the Mosul block was in a higher position. In Late Miocene the Injana Fm. covered both blocks revealing that their elevation might be on the same level. However, later and according to the presence of the Bakhtiari Fm. the Sinjar Block seemed to be slightly in a higher position.

The paleostress analysis showed that the Mosul fault might be sinistral strike-slip at the extension phase of the Alpine orogeny (Triassic- Upper Cretaceous) then later it was becoming dextral strike-slip during the compression phase from Upper Cretaceous till now. As a result the present day may expose the risk of the fault displacement. Some fractures of such displacement were recorded on the Al-Shohada' Bridge (the 3rd bridge over the Tigris River) of the Mosul city, which are indicating the existence of the dextral strike-slip neotectonics within the city of Mosul. So it is highly recommended to take such a risk into consideration, particularly when constructing large projects in future.

Keywords: Tectonics, Mosul Fault, Foreland.

التكتونية القديمة والحديثة لفالق الموصل وتأثيره على تكتونية الفورلاند في العراق

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الملخص

استعمل تفسير خرائط السحنات القديمة كطريقة لإثبات نشاط فالق الموصل منذ الجوراسي المتوسط وربما قبل ذلك. لقد امتد هذا الفالق من الحدود التركية إلى التقاء الزاب الأسفل مع نهر دجلة. لقد قسم الفالق المنطقة إلى بلوك الموصل وبلوك سنجار. وقد استعملت السحنات الرسوبية لإثبات امتداد الفالق واثبات إزاحته العمودية التي أظهرت أن بلوك سنجار كان مرتفعا إلى عصر الكريتاسي حيث أصبح البلوكان في مستوى واحد تقريبا. هذه الوضعية للبلوكات استمرت إلى عصر الايوسين الأوسط، الفترة التي حدث التصادم القاري بين الصفيحة العربية واليوراسية ونتج عنها ارتفاع بلوك الموصل نسبيا وترسيب تكوين الجركس القاري. في نفس الوقت ترسبت ترسبات سميكة من تكوين جدالة فوق بلوك سنجار المنخفض. وبقى بلوك الموصل مرتفعا إلى نهاية الاوليكوسين. أتصف المايوسين المبكر بصعود وهبوط بلوك سنجار الذي نتج عنه تعاقب السحنات اللاكونية والسحنات العميقة لكن على العموم يعد بلوك سنجار مرتفعا نسبة إلى بلوك الموصل. ويعد ترسيب تكوين جريبي في بلوك سنجار خلال المايوسين الأوسط دلالة على ارتفاع بلوك الموصل نسبيا. أما في المايوسين المتأخر، فان ترسيب تكوين انجانا على البلوكين يدل على إن البلوكين كانا في نفس المستوى. وان عدم وجود تكوين البختياري في بلوك سنجار يدل على انه كان مرتفعا قليلا.

يُظهر تحليل الاجهادات القديمة أن فالق الموصل هو فالق مضربي يساري الإزاحة في طور الاستطالة العائدة للاوروجيني الالبي (الترياسي–الكريتاسي الاعلى)، ثم لاحقا اصبح فالق مضربي يميني الإزاحة خلال طور الانضغاط (الكريتاسي الأعلى –الآن). وكنتيجة لهذه الحركة، أظهرت هذه الأيام خطورة هذه الإزاحة. فقد ظهرت بعض التكسرات في جسم جسر الشهداء (الجسر الثالث على نهر دجلة) في مدينة الموصل والتي تدل على التكتونية الحديثة المتمثلة بالحركة اليمينية للفالق. لذا يوصي الباحث بتوخي الحذر حين القيام بإنشاء مشاريع كبير في مدينة الموصل.

الكلمات الدالة: التكتونية، فالق الموصل، الفورلاند.

INTRODUCTION

The Zagros-Taurus foreland basin was filled by a 7-14 km thick succession of sediments deposited widely along the north and northeastern margin of the Arabian Plate. Since the end of Precambrian, the foreland area evolved through a number of different tectonic settings. It was a part of the stable supercontinent of Gowndwana during most of the Paleozoic Era, then a passive margin was formed due to opening of the Neo-Tythes in the Mesozoic Era and became a foreland basin separated from the Tythean basin in the Cenozoic Era (Numan, 1997; Sharland *et al.,* 2001; Bahroudi and Koyi, 2004; Jassim and Goff, 2006).

Fig. 1: Location Map of the Studied Area.

Many Major faults, which are considered as transcurrent faults, have influenced the deformation of the foreland area, and Mosul Fault is one of them (Fig. 1). (Henson,1950) and (Dunnington, 1958) reported the Mosul High using the stratigraphic evidence, which means that the Mosul area, had been surrounded by basement faults. (Ameen, 1979) and (Numan, 1984) suggested that the basement of northern Iraq was fragmented into the Mosul and Kirkuk blocks and was separated by the Greater Zab river fault. (Jackson and Mc Kanzie, 1984) differentiated the Kirkuk and Mosul Blocks from the Sinjar trough (which he called) without mentioning to any faults that have parted them. (Bahroudi and Koyi, 2004) through their model located many faults in the Zagros foreland basin. They considered the northeastern trending ones as dextral strike-slip faults and the southeastern as sinistral faults. Such faults have divided the foreland basin into a number of subbasins.. They did not mention the Mosul fault and referred to the whole areas of Mosul and Sinjar under the title of Sinjar sub-basin.

Mosul Fault was firstly deduced geophysically by (Al-Shaikh and Baker, 1973). They described it as a vertical fault extending along the Tigris River with an uplifted western side. (Adeeb, 1988) calculated the throw of this fault to be about 20m displacement using a key bed within the Fat'ha Fm. Mohderbashi (personal communication) confirmed that the western bank of the Mishraq mine was uplifted relatively compared to the eastern bank of Tigris River with approximately the same throw. (Al-Naqib, 2006) denoted the Mosul fault in a location along the course of the Tigris River. Also, (Al-Saigh, 2010) has concluded two faults extending north-south along the Tigris River near the Badoosh Dam using geophysical (electrical) tools. However, it is believed that they may be related to the Mosul Fault too. (Ameen, 1992) pointed out that the Mosul Fault had sinistral displacement at a pre-folding phase and dextral displacement during syn-folding phase, and he had uncertainly located such a fault from the Iraqi-Turkish border towards the confluence of the Tigris and Greater Zab rivers (Fig. 1).

Previously, the Mosul Fault was studied and undoubtedly located by (Al-Shaikh and Baker, 1973) using geophysical gravity method. They suggested its location along Tigris River from the Mosul City towards Hammam Al-Aleel town. The present study investigates the location of the Mosul Fault using sedimentary facies types across the Tigris River specially during time span of the Jurassic, Cretaceous and Tertiary. In addition, satellite images were used to confirm the fault location. The above information may lead to the conclusion that this fault was extended about 150 Km from Syrian-Turkish-Iraqi triangle border point to the Greater Zab river and it could even be extended to Kirkuk (Fig. 1).

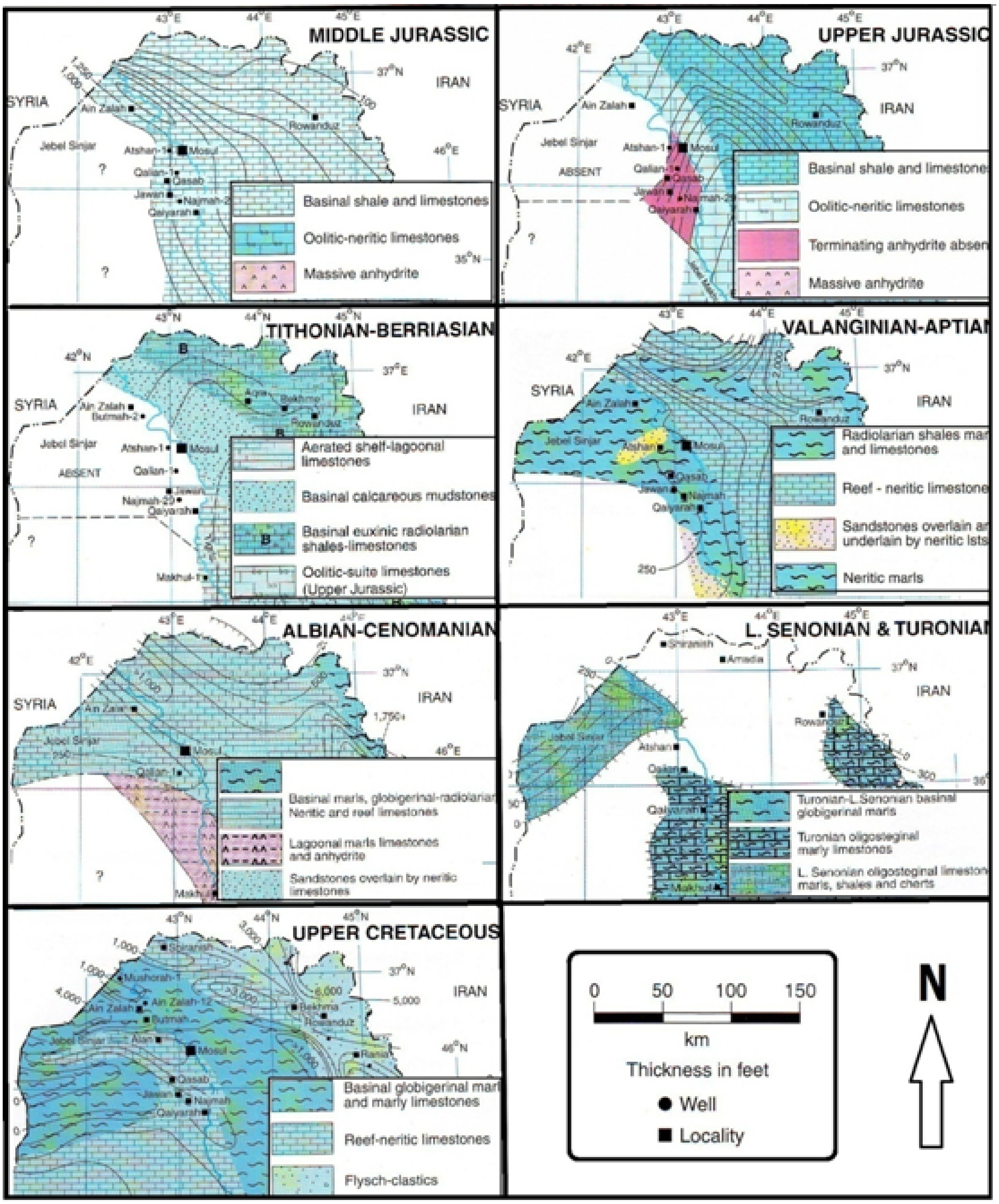

Fig. 2: Isopach-Facies Maps of (Dunnington, 2005).

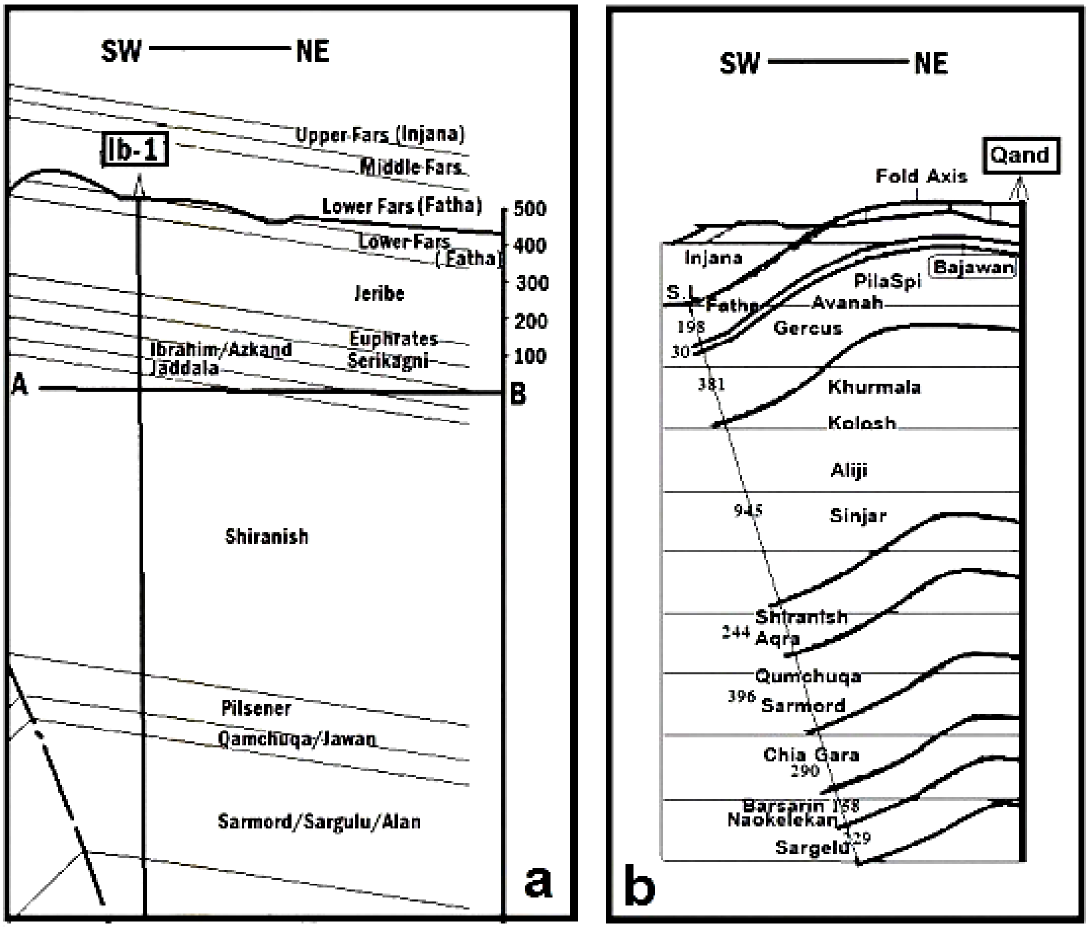

Fig. 3: Stratigraphic Successions of:
a- Ibrahim well after (Nadir, 1983).
b- Qand Well after (Gosling and Bolton, 1959).

PALEOTECTONICS

Tectonostratigraphic evidence:

Tectonostratigraphic evidence was used to prove the vertical displacement of the Mosul Fault. Accordingly, the paleotectonics of this fault can be detected since Upper Jurassic, because earlier the fault movement was not evident although it could had been occurred.

The main tool for identifying the Mosul Fault lineament is the facies changes on the both sides. Such changes are extending along a line from the Iraqi-Syrian-Turkish triangle border point towards the confluence of the Tigris-Zab rivers or even farther towards Kirkuk region (Fig. 1). Information about the facies changes in the deposited sedimentary rocks from Late Jurassic to Late Cretaceous is extracted from (Dunnington, 2005) (Fig. 2) and also from wells; Ibrahim-1 and Qand-1 (Nadir,1983; Gosling and Bolton, 1959). Such data were used to analyze the Late Cretaceous and Cenozoic facies characters (Fig. 3).

Table 1: The Stratigraphic Successions above Mosul and Sinjar Blocks.

Geologic time	Sinjar block	Mosul Fault Sense of Movement	Mosul block
Pliocene	Bakhtiari Fn. *(Continental)*		Bakhtiari Fn. *(Continental)*
Late Miocene	Injana Fn. *(Continental)*	Approximately became same level	Injana Fn. *(Continental)*
Middle Miocene	Fat'ha Fn. *(Lagoon)* Jeribi Fn. *(inner shelf-Shaols)*		Fat'ha Fn. *(Lagoon)*
Early Miocene	Dhiban Fn. *(Lagoon Carb. Evap.)* Euphrates Fn. *(Lagoon Carbonate)* Serikagni Fn. *(Basinal)*	Positive area	=== Eroded or no deposion ===
	Hamren Fn. *(Lagoon)* Ibrahim Fn. *(Basinal)*	Positive area	
Oligocene	Tar jil Fn. *(Basinal)* Palani Fn. *(Basinal)*	Positive area	===Eroded or no deposion===
Middle - Late Eocene	Jaddala Fn. *(Outer Shelf-Basinal)* Avanah Fn. *Locally*		Pila Spi Fn. *(Lagoon)* Gercus Fn. *(Continental-Fluvial)*
Paleocene- Early Eocene	Sinjar Fn. *Locally* Aliji Fn. *(Outer Shelf- Basinal)*	Area of Sinjar block was slightly deeper due to the basin shape	Kolosh Fn. *(Outer Shelf-Basinal)*
Late Cretaceous	Shiranish Fn. *(Basinal)*	Probably same level	Shiranish Fn. *(Basinal)*

The western side of Mosul Fault is represented by the Sinjar Block whereas the eastern side comprises the Mosul Block (Fig. 4). The additional information about the stratigraphy and sedimentary facies are derived from some key references on the geology of Iraq (e.g. Van Bellen *et al.,*1959; Jassim and Goff, 2006; Al-Banna, 2010).

The isopach-facies maps (Fig. 2) show that there was a sharp cut or change in sedimentary facies along the Tigris River course which is believed to be caused by the Mosul Fault. These maps indicate that during Upper Jurassic to Berriasian, the Sinjar block was uplifted relative to the Mosul block. Although there is no evidence of deposition on the Sinjar block region at that time, the sediments deposited might be eroded. From Valanginian to Aptian, there are abnormal depositions of radiolarian shales, marl and limestone, reef-neritic limestone and neritic marls that need detail and precise study. Unknown reason made these depositions that are not well-matched with fault movements (Fig. 2). Progressively, the subsidence started on both blocks during late Albian-Cenomanian but they were not creating the same depth to deposit similar facies and similar thicknesses on both blocks. The Late Senonian- Turonian time is not included in this investigation due to missing information in the eastern side of the fault. At Late Cretaceous, both blocks became at approximately the same depth level and the basinal globigerinal marl and marly limestone facies (Shiranish Fn.) were dominated the deposition (Fig. 2).

During Cenozoic Both Sinjar and Mosul Blocks showed some dramatic tectonic movements reflecting the effect of the well known tectonic event; the Zagros Alpine Orogeny, which was led eventually to the collision of the Arabian Plate with the Eurassian Plate. The correlation of the stratigraphic successions in both Sinjar and Mosul blocks (Table. 1) revealed the domination of the Aliji Fm. (of outer shelf to basinal sediments) on the Sinjar block area and the supremacy of the Kolosh Fm. (also of outer shelf to basinal sediments) on the Mosul block region demonstrating that both blocks might have approximately at the same depth or drowning level during this transgression.

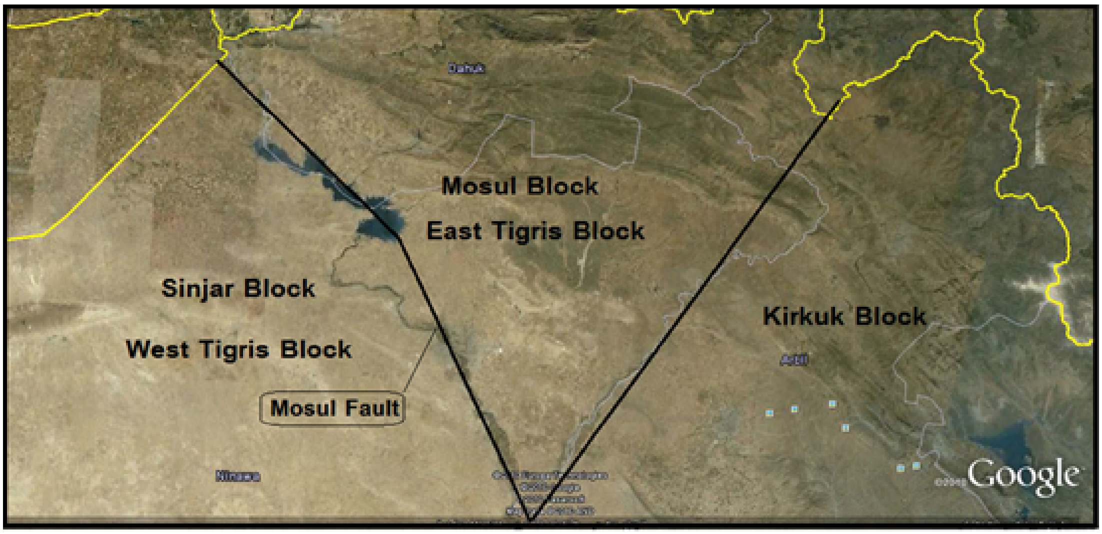

Fig. 4: Location of Mosul Fault and the Blocks Sinjar and Mosul.

The essential phenomenon happened during the Middle Eocene was the sudden and high uplifting of the Mosul block, which is marked by the sedimentary facies difference of the two block areas. The Sinjar block showed a continuation of outer shelf to basinal facies deposition, which was represented by the Jaddala Fm. (Middle to Late Eocene), whereas the Gercus Fm. (Middle Eocene) and the Pila Spi Fm. (Middle to Late Eocene) of the continental and lagoon facies respectively, were dominating the Mosul and Kirkuk block areas. This facies change indicates that the Sinjar block was remained stable during the Paleocene to Eocene Epochs relative to the Mosul Block.

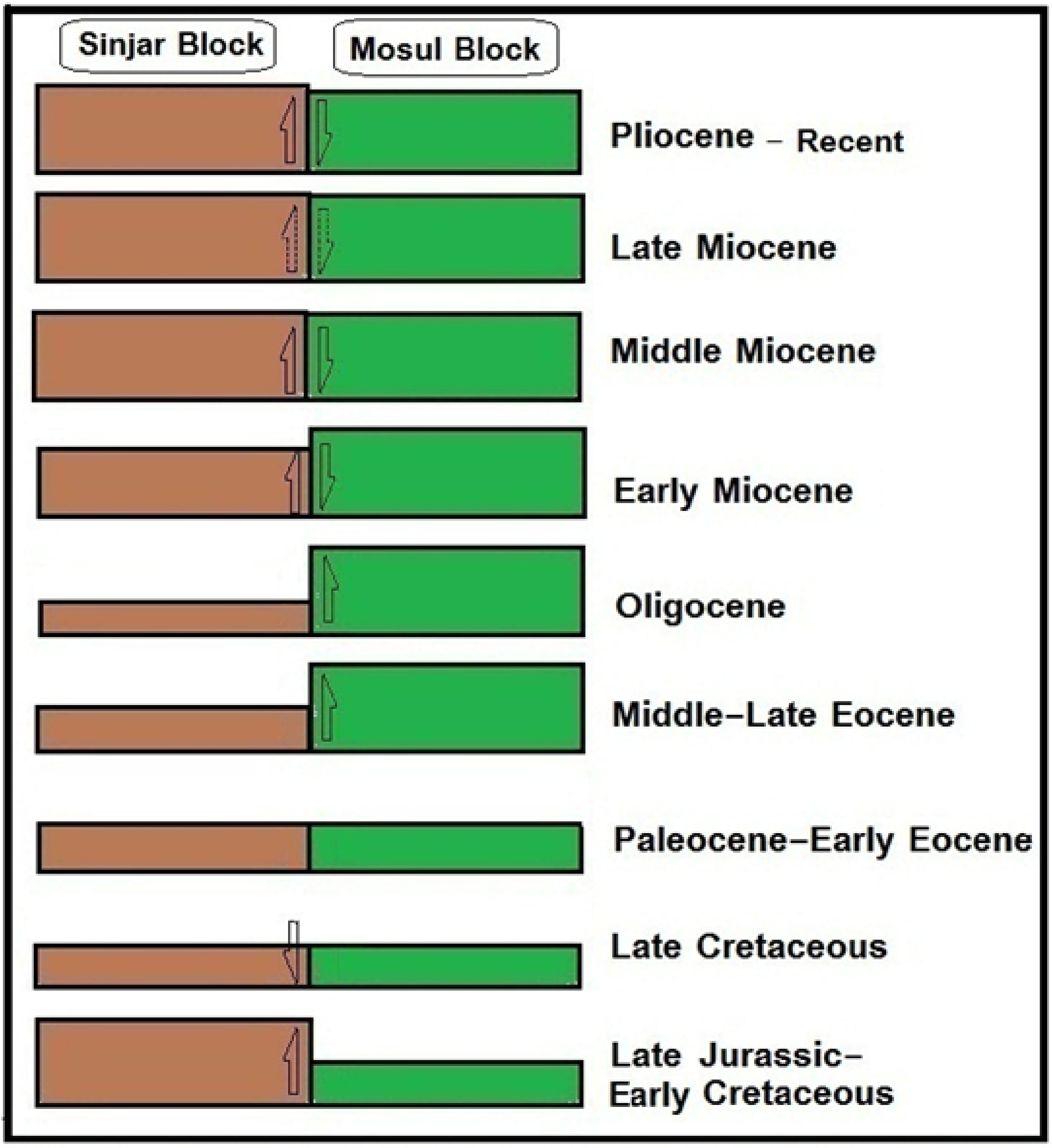

Fig. 5: Relative Movements of Mosul and Sinjar Blocks from Late Jurassic to Recent.

Table (1) shows that the Sinjar block have covered by Oligocene basinal stratigraphic sequences of the Palani and Tarjil Fms, whereas almost no sediments of such an age present within the Mosul block region, that could be either eroded or not deposited. This also may mean that the Sinjar block was continued to be relatively stable during the oligocene. on the other hand, the Mosul block persisted the uplift situation. Two cycles of uplift and subsidence where took place in the Sinjar block area during Early Miocene. (Table 1) illustrates the deposition of the Ibrahim. and Hamrin Fms. characterized by basinal and lagoon facies respectively, indicating to the deposition first Lower Miocene cycle. Furthermore, the presence of the Serikagni Fm. (basinal carbonates) and the Euphrates Fm (platform carbonates) and Dhiban Fm. (Lowstand evaporates (Aqrawi *et al.* 2010)) pointing out to the deposition of second Lower Miocene cycle. In the mean time, the Mosul block region stayed as a positive uplifted area. The Middle Miocene represented by the Jeribe Fm (of inner shelf– and shoal carbonates) followed by the Fat'ha Fm. (of carbonates and evaporites) within Sinjar block area, whereas only the Fat'ha Fm. exists within the Mosul block region. This may be interpreted that the Sinjar block area was slightly in a deeper position. Then after the deposition of the Jeribe Fm. the two blocks reached approximately the same level. They also maintained this situation during the Late Miocene, because the Injana Fm. (of continental deposits) was deposited on both block regions. Finally, the domination of the Bakhtiari Fm. on the Mosul block area compared with the Sinjar block (Jassim and Goff, 2006) may indicate that the latter was slightly uplifted by time (Fig. 5). It must be mentioned that this investigation is, in general, indicates the fault displacements, thickness determinations of these formations will led to more details.

Paleostress evidence:

A general analysis of the paleostress directions is used to detect the sense of the horizontal displacement of the Mosul Fault. Such displacement depends mainly upon the trend of the fault plane in addition to the azimuth of the regional field stress, which was inclined to the fault plane direction. The present velocity vector of Arabian Plate in the area which is directed N17E (Kadir, 2008), has been analyzed into normal and shear stress components, and the latter was tangential to the fault strike that caused the strike-slip displacement, whereas the normal component caused the uplift of either Mosul or Sinjar blocks (Fig. 6).

Three essential tectonic events have controlled the geology of Iraq since Triassic (e.g. Numan, 1997; Aswad, 1999; Sharland, 2004; Jassim and Goff, 2006; Boulton, 2009). It was started with the extension phase due to the rifting of the Arabian Plate from Eurassia and the opening of the Neo-Teyths ocean during Triassic period. This phase was spanned to the Late Cretaceous (and Turonian in particular). Then the compression phase started either at Turonian (Sharland *et al.,* 2001) or Albian-Cenomanian (Aswad, 1999). Finally, during the analysis of tensile stress, which was prevailing the extension phase, revealed that the shear stress caused a sinistral strike-slip along the Mosul Fault. And this type of movement was dominant since the Late Jurassic or earlier as it was shown in current study (Fig. 6a). The compression environment caused a shear stress tangential to the fault acting as a dextral strike-slip displacement and it was leading since Late Cretaceous until Recent time (Fig. 6b). This conclusion was compatible with that reported by (Ameen, 1992).

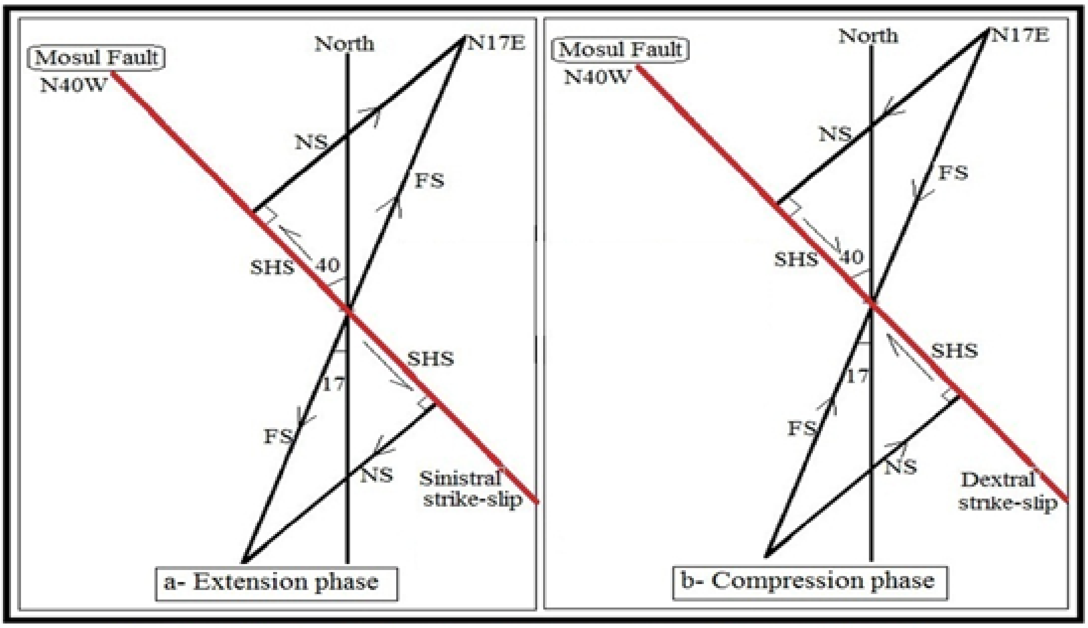

Fig. 6: Horizontal Paleostress Vectors of Mosul Fault.

NEOTECTONICS

The previous studies have showed that the Arabian Plate is still moving towards the northeast and the orogeny has not ceased yet (Sharland *et. al.,* 2001; Al-Azzawi, 2003; Jassim and Goff, 2006; Kadir, 2008). It means that the compression phase of the Arabian Plate is still active. Accordingly, faults in the foreland area are also continuously active and displacement must be taking place too. Consequently, the Mosul Fault which is approximately coincides the course of Tigris river is ongoing dextrally strike-slip displacement along its trend.

Kadir (2008) calculated the amount of recent movement of the Arabian Plate, it is about 29.99 $mm.a^{-1}$ toward N17E. This value was determined from IZQW of the Iraqi CORS (Table 2). A trigonometric calculation was carried out in the present study in order to find the direction of the shear stress which is found as a dextral strike-slip displacement along the Mosul Fault (Fig. 6). The latter will risk the future engineering projects of the Ninavah governorate**.** A recent example was in year 2010 when Al-Shohada' Bridge structure (i.e. the 3rd largest Bridge of the Mosul City over the Tigris River) was affected by some serious fractures. This can be related to the neotectonics activities of the Mosul Fault based on the orientations and openings of these fractures. An earthquake of magnitude 2.9, date: 21.05.2012, time: 00:25:19.8 UTC, location: 36.71N; 42.76E and 18 Km depth which was located on the course of the Tigris river may proved this interpretation.

Table 2: The Calculated Values of the Stationary GPS IZQW after (Kadir, 2009).

Stationary GPS	Latitude	Longitude	VX north mm/year	VY east mm/year	Velocity mm/year	Azimoth
IZQW	35.7608	43.1161	28.62	8.98	29.99	17

ORIGIN OF THE MOSUL FAULT

The analysis of the tectonostratigraphic data of (Dunnington, 2005 and Ziegler, 2001) indicated that the Mosul fault was originated before Late Jurassic. Therefore, it was not formed due to the Arabian- Eurassian plates collision. Moreover, according to (Table 2) and (Fig. 6) the Mosul fault attitude was not compatible with the field stress system at the rifting stage (Triassic-Late Cretaceous) as well as at collision (Middle Eocene). Consequently, the fault should be of older age from a pre-Triassic period. The Fault also corresponds to the NW-SE Najd Fault systems. This conclusion is in agreement with that stated by (Jassim and Goff , 2006).

SUMMARY AND DISCUSION

The sedimentary facies changes have proven that the Mosul Fault was extended from the Iraqi-Syrian-Turkish border towards the confluence of the Tigris River and the Greater Zab tributary. The sedimentary facies analysis confirmed that this fault was present before the Late Jurassic. Also it showed that the western part of this fault (i.e. the Sinjar block) was in a higher position compared to the Mosul block, until the Valanginian-Aptian, when the foreland basin started to develop (Fig. 2). This figure illustrates the domination of the radiolarian marls at the west, southwest, east and northeast surrounding the neritic limestone. Such a configuration has outlined the foreland basin shape of the northern Iraq. During Albian-Cenomanian both Sinjar and Mosul blocks had almost same level. Consequently, the Sinjar block was started subsidence with sinistral strike-slip displacement of the Mosul Fault during the extension phase until the ophiolite obduction, which is considered as the first sign of compression phase.The onset time of ophiolite obduction was assigned to the Albian-Cenomanian (Aswad, 1999) although (Sharland *et al.*, 2001) suggested the middle Turonian age. The current study coincides with (Aswad's, 1999) conclusion.

The Late Cretaceous Epoch manifested a compression pulse but the two blocks kept same level of depth reflecting that this pulse was not strong enough for rising any of the blocks. This situation was continued until Middle Eocene, when basinal to outer shelf facies deposited on both Sinjar and Mosul blocks or subbasins (Table 1). At Middle Eocene the remarkable continental collision phase started and a quite reasonable uplifting of the Mosul block took place, which prepared the sedimentary environments of Gercus Fm. of continental environments to deposit over the Mosul block. In the meantime, the basinal-outer shelf facies remained depositing on the Sinjar block sub-basin forming the Jaddala Fm. Simultaneously, a dextral strike-slip displacement of the Mosul Fault was accompanied with this uplift during this compression phase. The last event may be considered as another evidence for the continental collision between Arabia and Eurasia. However, there is no evidence for the onset time of the dextral strike-slip displacement, whether it is of Late Cretaceous or Middle Eocene. The Mosul block has continued uplifting during the Oligocene time, consequently a positive area without deposition or eroded sediments was prevailing most of the Mosul block sub-basin. After that, the Sinjar block was slightly uplifted during the successive geological epochs until reaching the same level of the Mosul block during Late Miocene.

It is important to mention that there were two cycles of uplifting and subsidence during the Early Miocene, but at same time the area of Mosul block remained positive. The restricted occurrences of Bakhtiari Fm. within the area of the Sinjar block may indicate a slightly uplifting during the Pliocene. Unfortunately, most of the information about Quaternary deposits was missing. Nevertheless, this uplift was continued to Recent, which was clearly confirmed by the measurements of (Al-Adeeb, 1988).

Comparing with (Ameen, 1979) and (Numan, 1984), there are three blocks dominating the foreland basin of Iraq (i.e. in both Zagros and Taurus regions) (Fig. 4). They are namely; Sinjar, Mosul and Kirkuk separated by Mosul fault and Greater Zab fault. Correlation between movements of the Sinjar and Mosul blocks (Fig. 5) on one hand and the Mosul and Kirkuk blocks (Fig. 7) on the other, revealed some important conclusions. The time span of Mesozoic until Late Cretaceous revealed that the three blocks were of gradual heights where Sinjar was the highest and Kirkuk was the lowest. Such a model took place within the extension phase. Then by the end of Early Eocene the three blocks had mostly the same level. After that both the Mosul and Kirkuk blocks were simultaneously uplifted until the end of Early Miocene when the Sinjar Block started to be uplifted too . This means that the continental collision (during that time) has influenced the uplift of both Mosul and Kirkuk blocks while the Sinjar block remained in its position, until almost Late Miocene reaching the level of the Mosul block. In the Middle Miocene the Kirkuk block subsided relatively compared to the Mosul block (Fig. 7). This could be due to the relaxation of field stress pulse at that time, (Hardenberg, 2003) proved that during Middle Miocene there was almost no tectonics between the African and Arabian plates and the movement of the Dead Sea fault system was also stopped. Hereafter, it may be predicted that the situation of these blocks has become like terraces as the Sinjar Block stayed at highest level whereas the Kirkuk was at the lowest, similar to their locations during the Mesozoic Era.

Neotectonics of the Mosul Fault may cause some risk on the large civil projects within the Mosul City. Therefore, future detailed studies are recommended on the Mosul Bridges, the Badoosh Dam and even the Mosul Dam. In addition, caution must be taken in planning for any future establishments around the zone of Mosul Fault.

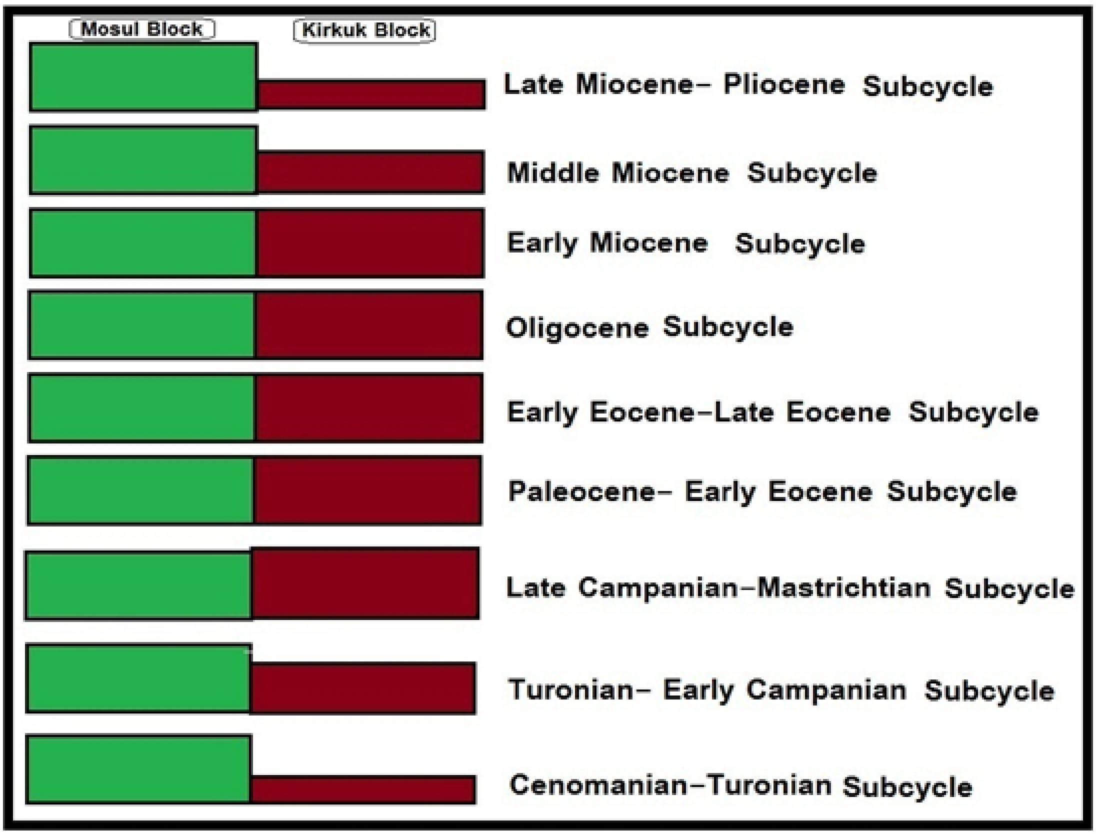

Fig. 7: Movements of Mosul and Kirkuk Blocks after (Ibrahim, 1985).

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