GEODYNAMICS & TECTONOPHYSICS
Published by the Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences

PALEOGEODYNAMICS

2021 VOLUME 12 ISSUE 3 PAGES 608–627

ISSN 2078-502X

DOI: 10.5800/GT-2021-12-3-0541

TECTONIC AND EROSION FEATURES, AND THEIR INFLUENCE ON ZONAL DISTRIBUTION OF THE UPPER TRIASSIC AND THE LOWER CRETACEOUS SEDIMENTS IN THE EUPHRATES GRABEN AREA, SYRIA

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ABSTRACT. We have investigated the tectonic and erosion features of the Upper Triassic (Mulussa F Formation) and Lower Cretaceous (Rutbah Formation) sediments in the Euphrates graben area and analysed their influence on changes in the thickness and zonal distribution patterns of these sediments. In this study, the geological modeling software of Petrel Schlumberger is used to model the regional geological structure and stratigraphy from the available geological and geophysical data.

The Upper Triassic and Lower Cretaceous sediments (in total, almost 800 m thick) are the major hydrocarbon reservoirs in the Euphrates graben, which contain approximately 80 to 90 % of the total hydrocarbon reserve in this area. These sedimentary zones experienced variable changes in thickness and zonal distribution due to erosion processes caused by the two major regional unconformities, the Base Upper Cretaceous (BKU) and Base Lower Cretaceous (BKL) unconformities. The maximum thickness of the Upper Triassic sediments amounts to 480 m in the central parts of the Euphrates graben and along the NW-SE trend, i.e. in the dip direction of the Upper Triassic Mulussa F Formation. Towards the NE flank of the graben near the Khleissia uplift and the SW flank near to the Rutbah uplift, the thickness of the Upper Triassic sediments is gradually decreased due to their partial or total erosion caused by the BKL unconformity, and also due to a less space for sediment accumulation near the uplifts. The thickness of the Lower Cretaceous sediments increases in the northern, NW and NE flanks of the graben. Their maximum thickness is about 320 m. The BKL unconformity is the major cause of erosion of the Lower Cretaceous sediments along the southern, SE and SW flanks of the graben. In the Jora and Palmyra areas towards the NW flank of the Euphrates graben, the Upper Triassic and Lower Cretaceous sediments show no changes in thickness. In these areas, there was more space for sediment accumulation, and the sediments were less influenced by the BKL and BKU unconformities and thus less eroded.

KEYWORDS: tectonic and erosion features; Upper Triassic; Lower Cretaceous; Euphrates graben; Syria

FUNDING: This study was supported by the Ministry of Sciences and Higher Education of the Russian Federation (Agreement 075-15-2020-931) within the framework of the development program for a world-class research center – Efficient Development of the Global Liquid Hydrocarbon Reserves.

RESEARCH ARTICLE

Received: April 2, 2020
Revised: January 28, 2021
Accepted: February 12, 2021

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FOR CITATION: Yousef I., Morozov V.P., El Kadi Mohammad, Alaa Abdullah, 2021. Tectonic and erosion features, and their influence on zonal distribution of the Upper Triassic and the Lower Cretaceous sediments in the Euphrates graben area, Syria. Geodynamics & Tectonophysics 12 (3), 608–627. doi:10.5800/GT-2021-12-3-0541

ТЕКТОНИЧЕСКИЕ И ЭРОЗИОННЫЕ ОСОБЕННОСТИ И ИХ ВЛИЯНИЕ НА ЗОНАЛЬНОЕ РАСПРЕДЕЛЕНИЕ ВЕРХНЕТРИАСОВЫХ И НИЖНЕМЕЛОВЫХ ОТЛОЖЕНИЙ ЕВФРАТСКОГО ГРАБЕНА (СИРИЯ)

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АННОТАЦИЯ. На основе региональной структурной и стратиграфической геологический модели с использованием выбранных геолого-геофизическх данных и с помощью геологического программного обеспечения «Petrel Schlumberger» были изучены и обобщены тектонические и эрозионные особенности и их влияние на зональное распространение и изменение мощности осадочных отложений верхнетриасовых (формация Мулусса Ф) и нижнемеловых (формация Рутба) отложений вдоль Евфратского грабена.

Верхнетриасовые и нижнемеловые отложения (суммарная мощность около 800 м), считающиеся основными пластами-коллекторами углеводородов вдоль месторождений Евфратского грабена, содержат приблизительно от 80 до 90 % объема углеводородов, сохранившихся в этом районе. Осадочные зоны верхнетриасовых и нижнемеловых отложений Евфратского грабена подвергались различным изменениям в зональном распространении и мощности из-за эрозии, вызванной комплексом региональных несогласий вдоль Евфратского грабена. Этими несогласиями являются базовое верхнемеловое несогласие (BKU) и базовое нижнемеловое несогласие (BKL). Максимальная мощность 480 м верхнетриасовых отложений сохранилась в центральной части Евфратского грабена и в направлении с северо-запада на юго-восток, это направление погружения верхнетриасовой формации Мулусса Ф. Мощность верхнетриасовых отложений постепенно уменьшалась к северо-восточным флангам грабена вблизи поднятия Хлейсса и к юго-западным флангам вблизи поднятия Рутба из-за частичного или полного среза этих отложений в результате эрозии, вызванной несогласием BKL, и из-за меньшего пространства для накопления осадков вблизи этих поднятий. Максимальная мощность нижнемеловых отложений приблизительно 320 м, при этом толщина осадков увеличивается на северном, северо-западном и северо-восточном флангах Евфратского грабена. Наибольшая степень эрозии вследствие влияния несогласия BKU на нижнемеловые отложения отмечается вдоль южного, юго-восточного и юго-западного флангов Евфратского грабена. Толщина верхнетриасовых и нижнемеловых отложений вдоль районов Жора и Пальмира к северо-западным флангам грабена сохраняется неизменной из-за меньшего влияния эрозии, вызванной несогласиями BKL и BKU, а также из-за большего пространства для накопления осадков вдоль этих районов.

КЛЮЧЕВЫЕ СЛОВА: тектонические особенности; эрозионные особенности; верхнетриасовые отложения; нижнемеловые отложения; Евфратский грабен; Сирия

ФИНАНСИРОВАНИЕ: Работа выполнена при поддержке Министерства науки и высшего образования Российской Федерации (Договор № 075-15-2020-931) в рамках программы развития Научного центра мирового уровня (НМЦУ) «Рациональное освоение запасов жидких углеводородов планеты».

1. INTRODUCTION

Based on the data collected during two decades of intensive hydrocarbon exploration, production and field development activities in the Euphrates graben area of East Syria (Fig. 1), it is emphasized that the availability of structural geology datasets and a proper knowledge of the geomechanics is the basis for improving the structural geological understanding of the graben system in the study area.

Additionally, the definitions of the tectonism, regional unconformities, erosion processes, zonal geometries and distribution of the Upper Triassic and the Lower Cretaceous sediments along the graben area have proven to be very critical to the geometrical integrity of the geological and geophysical models. In the static geological models of the Upper Triassic and the Lower Cretaceous sediments over the Euphrates graben fields, the thickness changes and zonal distribution of the reservoir layers of these sediments are mainly controlled by faults, erosion, and the regional unconformities complex [Yousef et al., 2016].

Using the structural and stratigraphical geological models presented in this article, we attempt to address issues related to the local and specific characteristics of the Euphrates graben setting for better understanding of the regional unconformities, their distribution and their influences on the thickness changes and zonal distribution of the Upper Triassic and the Lower Cretaceous sediment in the study area. Furthermore, we aim at providing the data that can be used by field operators for better positioning of drilling locations, which is critically dependent on the knowledge of faults, areas eroded by unconformities, and other structural and/or sedimentological factors. In this study based on the available geological and geophysical data and using the

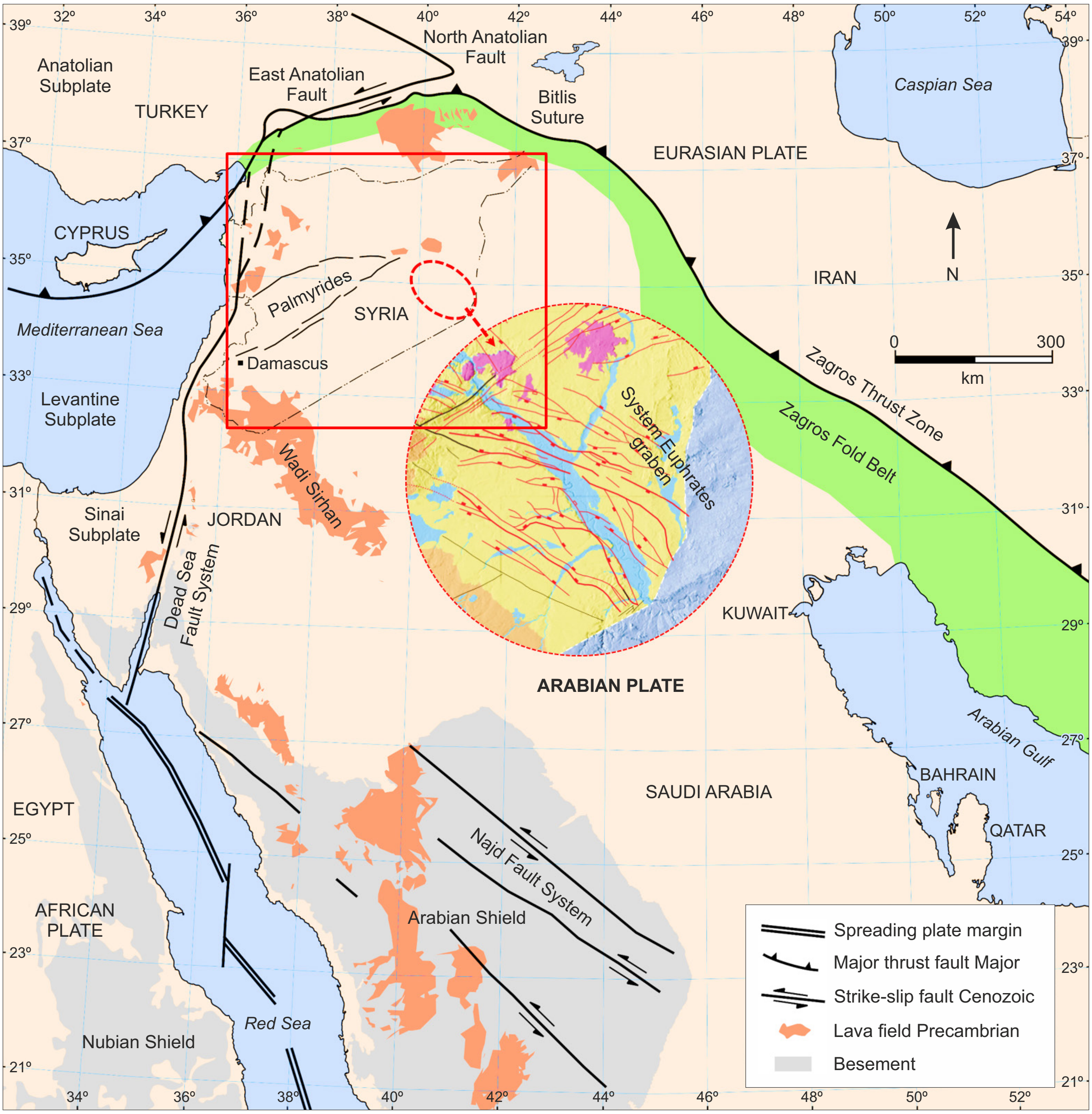

Fig. 1. Simplified map showing the main tectonic structures of the Arabian plate and the surrounding areas [Brew et al., 2001].

Рис. 1. Схема основных тектонических структур Аравийской плиты и прилегающих районов [Brew et al., 2001].

geological modeling software of Petrel Schlumberger, we have attempted to obtain a better understanding of the influences of erosion processes caused by the regional unconformities on the zonal distribution and thickness changes of the Upper Triassic and Lower Cretaceous sediments in the study area.

2. REGIONAL SETTINGS OF THE EUPHRATES GRABEN AREA

The 160-km-long Euphrates graben system is one of the most important oil and gas-bearing basins in Syria. This system is interpreted as a discontinuous intercontinental faulting system striking in the NW-SE direction, which is a part of the Cretaceous rift structure in East Syria [Sharland et al., 2004]. The Euphrates graben system has many characteristics of an intracratonic rift basin formed due to crustal extension during the Middle to Late Cretaceous time [Barazangi et al., 1993]. This rift basin is characterized by a complex pattern of interlocking faults (Fig. 2), different trends, and the differential subsidence predominantly controlled by normal faults [Brew et al., 2001].

Rifting of the Euphrates graben system by crustal-scale extension was followed by the development of two regional unconformities, the Base Upper Cretaceous Unconformity (BKU) stretching across a wide area of the Euphrates graben (Fig. 3), and the Base Lower Cretaceous Unconformity

(BKL), marked by widespread erosion and possibly deeply eroded in the Jurassic age (Mulussa G Formation) [Best, 1991; Best et al., 1993].

In the stratigraphic section of the Euphrates graben, the main reservoir sediments are the Upper Triassic sediments (Mulussa F Formation) composed mainly of fluvial sandstone bodies interbedded with floodplain clays (Fig. 3), and the Lower Cretaceous sediments (Rutbah Formation) composed of shallow marine clastic sediments ranging from non-marine sandstone at its base to lower-shore-face shales at its top [Yousef et al., 2019].

The Mulussa F and Rutbah Formations/reservoirs contain from 80 to 90 % of the total hydrocarbon reserve in the graben area. The BKL and BKU unconformities are the

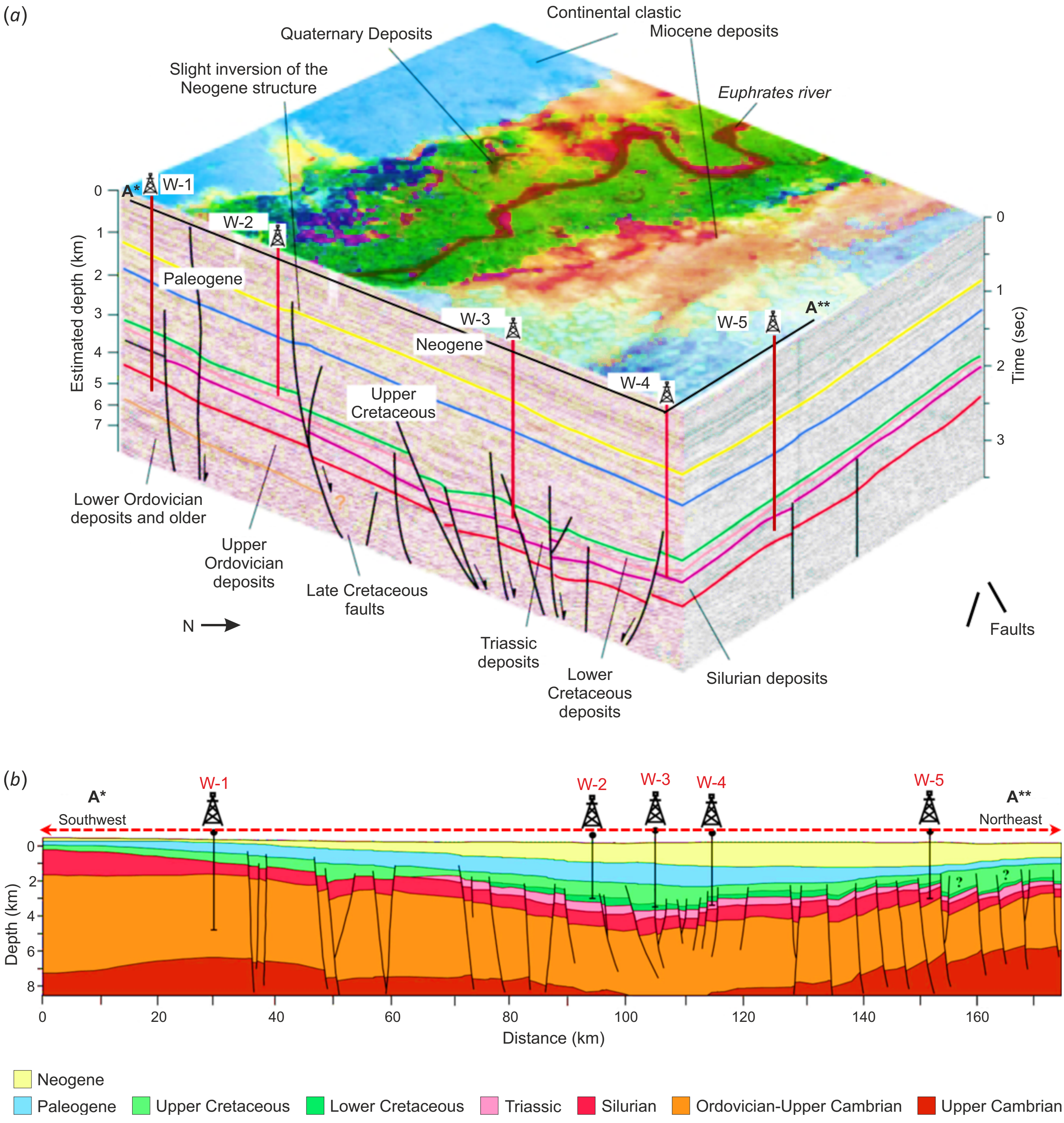

Fig. 2. Schematic showing: (*a*) – 3D model of the Euphrates graben area based on seismic interpretation [Brew et al., 2001]; (*b*) – structural and stratigraphical cross-section (A*–A**) across the Euphrates graben system after [Brew et al., 2001].

Рис. 2. Схема показывает: (*a*) – трехмерную модель Евфратского грабена на основе сейсмической интерпретации [Brew et al., 2001]; (*b*) – структурный геологический разрез (A*–A**) Евфратского грабена (по [Brew et al., 2001]).

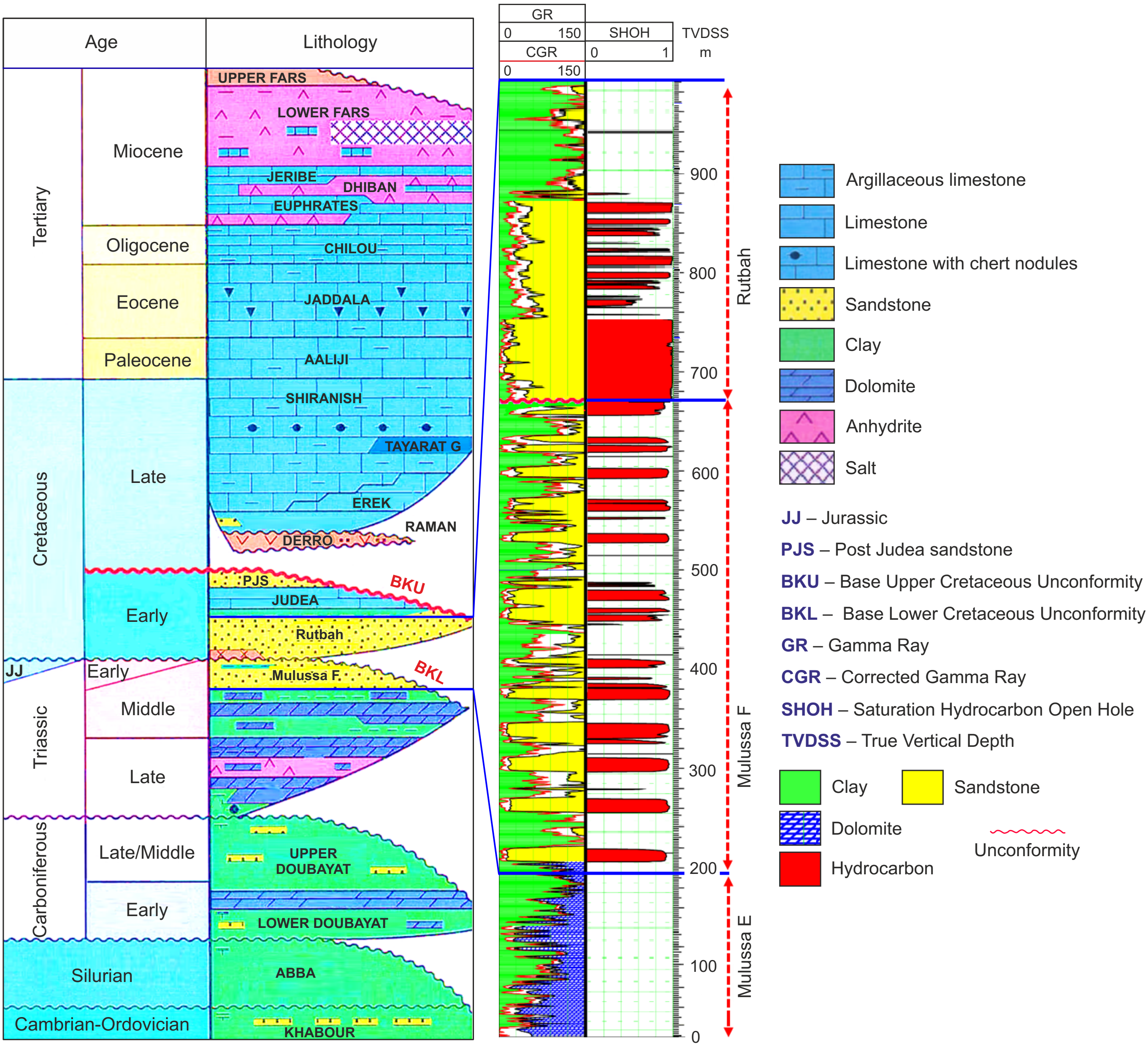

Fig. 3. Schematic stratigraphy of the Euphrates graben area.

Рис. 3. Схема стратиграфии района Евфратского грабена.

major ones in the graben area, i.e. the major base-level faults (most probably tectonically induced) and can, therefore, be referred to as sequence boundaries [Brew et al., 1999].

3. REASONS FOR THE RESEARCH, AND RESEARCH MATERIALS AND METHODS

The study area of the Euphrates graben (Fig. 4) is rather complex, regarding the regional tectonics and structural settings resulting from the multi-phase structural history of the whole graben area, with mainly synthetic faults, antithetic faults cutting and further tilting, and inversion of the aborted rift [Brew et al., 1997; Alsouki, Taifour, 2015].

Studying of the regional unconformities and erosion with respect to the zonal distribution and the thickness changes of the Upper Triassic and Lower Cretaceous sediments (Mulussa F and Rutbah Formations/reservoirs) is very important for oil and gas exploration in promising areas and the development of the graben fields. It should be noted that the graben area has been mainly covered by field studies. Here, we present the first regional comprehensive study that attempts to understand the influence of the regional unconformities and erosion on the zonal distribution and thickness changes of the Upper Triassic and the Lower Cretaceous sediments. Besides, this study provides additional information that can help the operators improve the oil and gas exploration activities in the graben fields by finding the thicknesses of the Upper Triassic and the Lower Cretaceous sediments, which are less impacted by the unconformities and the related erosion processes. For this study, Al Furat Petroleum Company (Syria) provided huge geological and

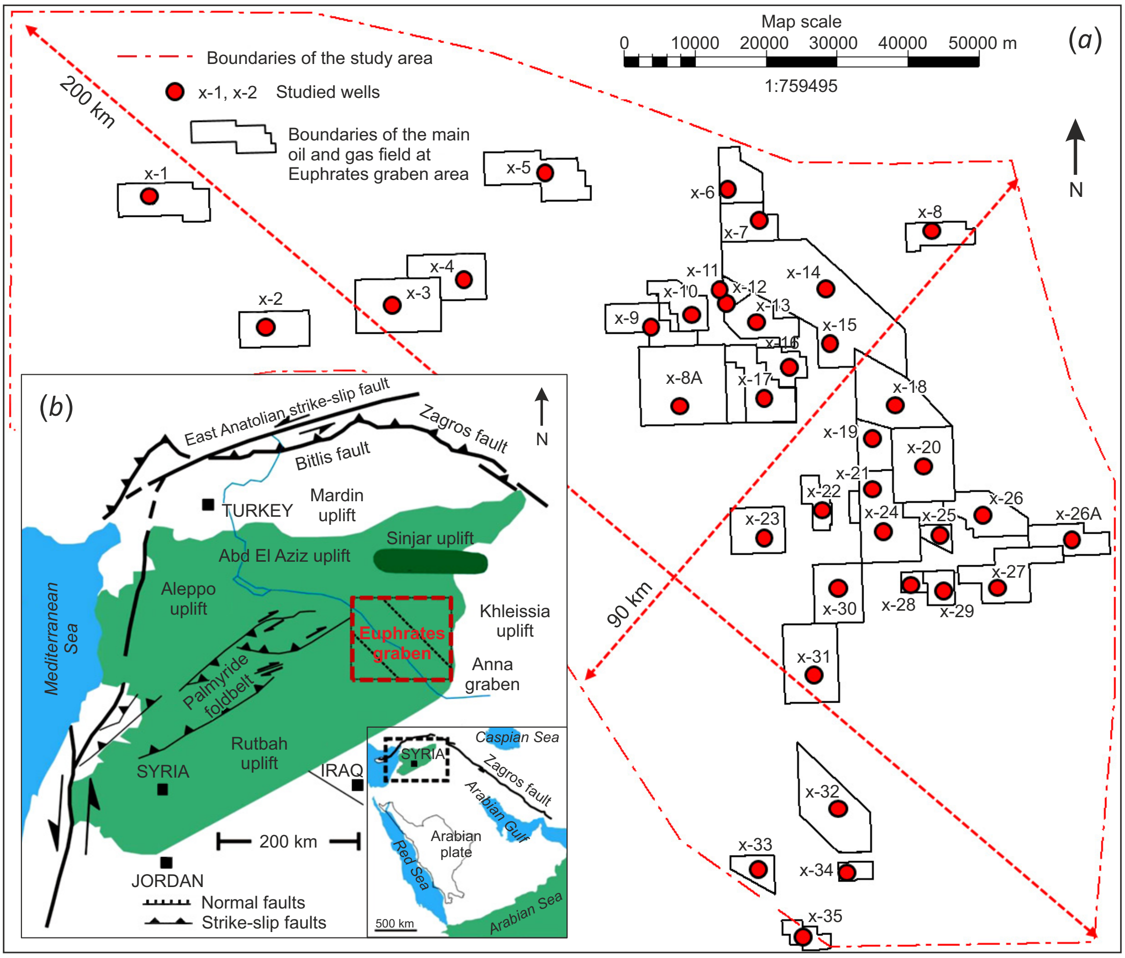

Fig. 4. Simplified map showing the location of the study area [Yousef et al., 2020] (*a*). Main tectonic features of Syria is shown in the inset [Brew et al., 2001] (*b*).

Рис. 4. Схема района исследований [Yousef et al., 2020] (*a*). На врезке показаны основные тектонические особенности территории Сирии [Brew et al., 2001] (*b*).

geophysical datasets, including 2D and 3D seismic data, well coordinates, field boundaries, well logs, and tops of the formations. The data were processed and interpreted by the geological modeling software of Petrel Schlumberger.

4. RESULTS AND DISCUSSION

4.1. Structural and stratigraphical framework of the Upper Triassic and Lower Cretaceous sediments in the Euphrates graben area

The structural and stratigraphic framework of the Upper Triassic and the Lower Cretaceous sediments in the Euphrates graben area is a product of a series of events that have shaped the graben area and caused its structural complexity. Highly variable changes in the thickness and zonal distribution of these sediments are due to the two major regional unconformities, BKL and BKU. The BKL unconformity (including two local unconformities, BKL1 and BKL2) is located between the top of the Upper Triassic Mulussa F Formation and the base of the Lower Cretaceous Rutbah Formation (see Fig. 3; Figs. 5, 6).

The BKL unconformity formed during the Late Triassic to Jurassic period when a tilted block dipping towards the northwest existed along the Euphrates graben area (see Fig. 5). The top of the Upper Triassic section first eroded with approximately up to 180m of the sediment missing in the eastern and SE parts of the Euphrates graben area relative to the western and NW parts of the graben creating the BKL unconformity itself. Later, the BKL horizon was deposited as an alteration soil horizon disconformably overlying the top of the non-eroded Mulussa G Formation (see Fig. 5; Fig. 6). The BKL soil horizon is possibly the most obvious result of the erosion and weathering processes caused by the regional unconformities in the Euphrates graben area. The BKL soil horizon in most of the Euphrates graben fields (especially at the centre of the graben) can be regarded as a barrier for hydrocarbons flows between the reservoir layers of the Upper Triassic Mulussa F Formation and the overlying sediments of the Lower Cretaceous Rutbah Formation (see Fig. 5).

The BKU unconformity located at the top of the Lower Cretaceous Rutbah sediments formed during the early rifting stage of the Euphrates graben system. It consists of the unconformity-affected (partially or completely) sediments of the Upper Triassic Mulussa F, Lower Cretaceous Rutbah,

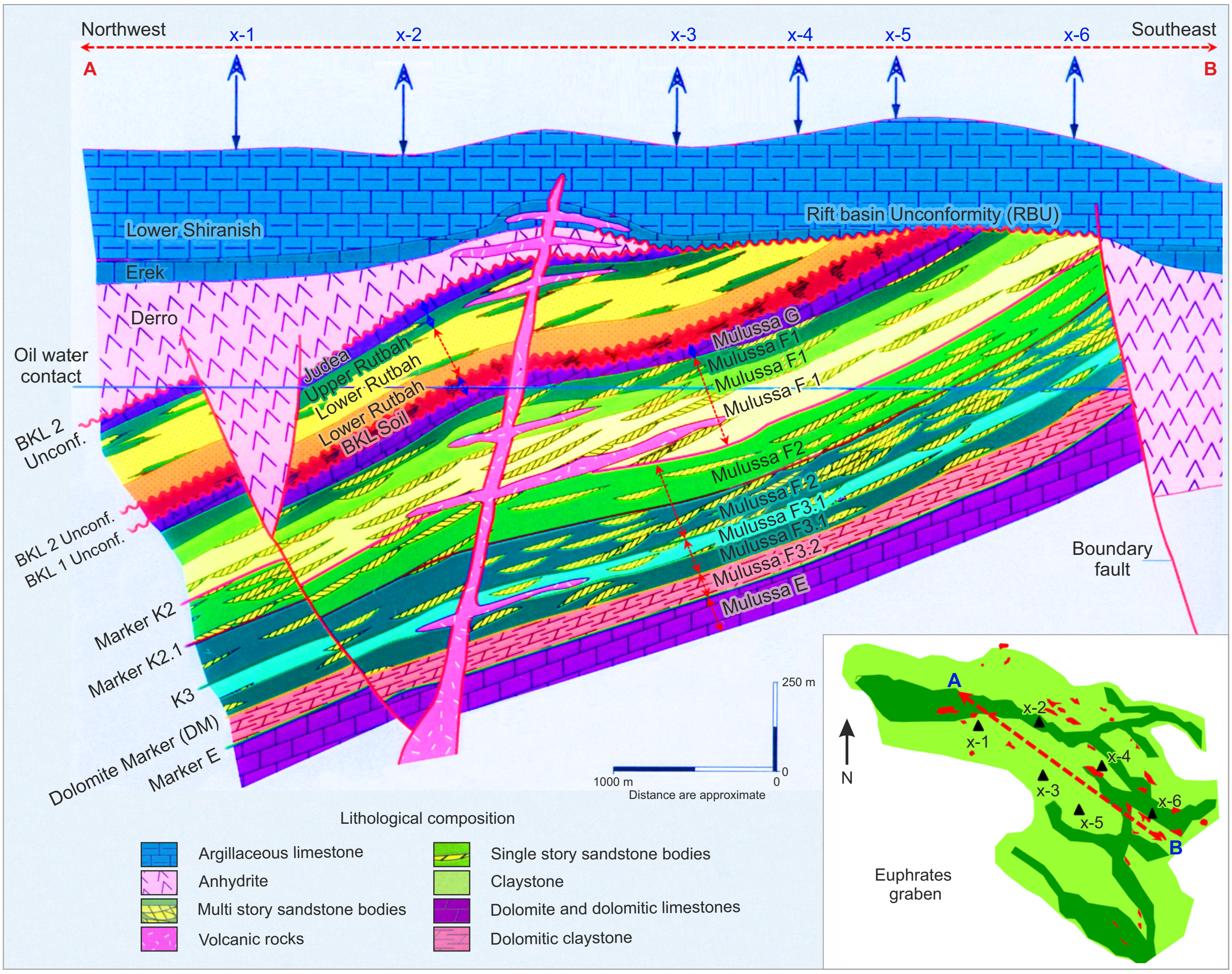

Fig. 5. Southeast-northwest stratigraphical longitudinal profile along the Euphrates graben.

Рис. 5. ЮВ-СЗ стратиграфический разрез Евфратского грабена.

Judea, and Post Judea Sandstone (PJS) Formations, which are laterally grading into the clastic and evaporite sediments of the Derro Formation (see Fig. 5; Fig. 6).

The BKU unconformity has a very strong angular component, it goes from an almost disconformably located deposit at the bottom of the Derro sediments in the west, NW and central blocks of the Euphrates graben to deeply eroded sediments of the Lower Cretaceous Rutbah Formation (up to 450 m thick). The Upper Triassic Mulussa F sediments are absent in the eastern and SE blocks of the graben close to the boundary fault where the BKL and BKU unconformities merged to form the Rift Basin Unconformity (RBU) (see Fig. 5; Fig. 6). Blocks tilting associated with the early rifting stage of the Euphrates graben system exposed progressively larger and larger portions of the central and eastern parts of the graben area leading to erosion of the uplifted crests (see Fig. 5).

Depending on how deep was erosion of the BKL and BKU unconformities in different zones, the Upper Triassic and the Lower Cretaceous sediments are preserved or eroded in such zones (see Fig. 5; Fig. 6). Where the erosion processes did not reach the Upper Triassic Mulussa F sediments, these sediments are overlaid by the Mulussa G sediments and/or by the BKL soil horizon. This boundary is sharp and conformable but not very clear in all the Euphrates graben fields and thus not defined as a formal marker along the graben area. It is determined by the chemostratigraphic analysis as a transition from a very high potassium content section at the top of the Upper Triassic Mulussa F sediments to a low potassium content section at the Mulussa G sediments and/or the BKL soil horizon (Fig. 6).

4.2. Regional stratigraphical zonal distribution framework of the Upper Triassic sediments in the Euphrates graben area

The Upper Triassic Mulussa F sediments spread out in almost the whole Euphrates graben area and cover some parts of Iraq lands (Fig. 7).

The maximum thickness of the Mulussa F sediments is approximately 480 m. In zones with volcanic sill intrusions, the thickness is increased up to 550 m (see Fig. 6). The Upper Triassic Mulussa F sediments consist mainly of floodplain claystones interbedded with mostly medium to fine-grained fluviatile sandstones. Lagoon-type and shallow-marine dolomitic claystone and dolomite interbeds are present in the lower part of the formation section [Yousef et al., 2016]. The Upper Triassic Mulussa F sediments are deposited conformably on the top of the Mulussa E sediments, and no sedimentary break is suggested by the available datasets at the time of the study. Different formations cap the Upper Triassic Mulussa F sediments depending on its position relative to how deep was erosion caused by the BKL and BKU unconformities along the Euphrates graben area (see Figs 5, 6).

The Upper Triassic Mulussa F sediments are subdivided into three zones from bottom to top, according to Spectral

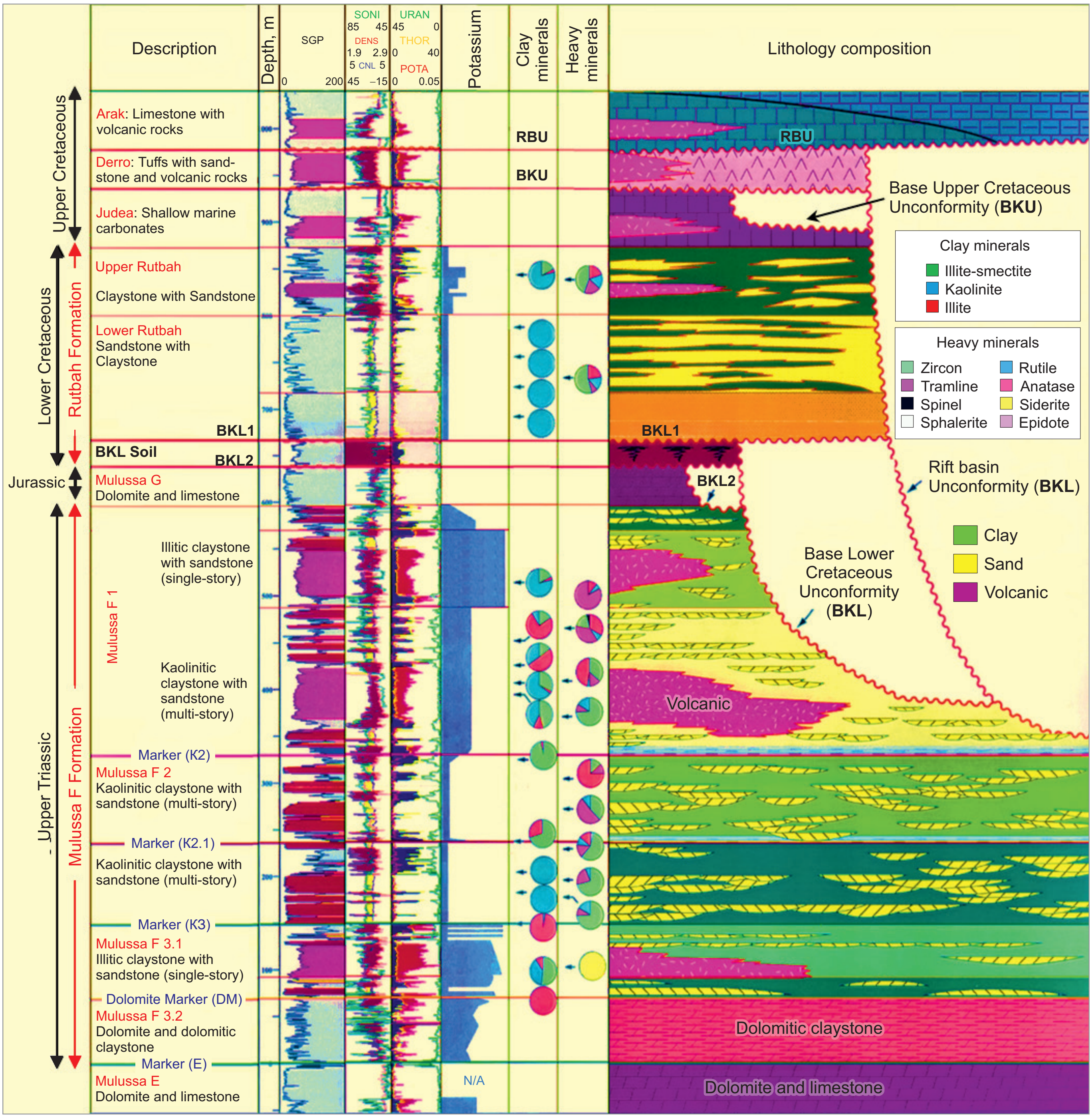

Fig. 6. Schematic stratigraphic column of the Upper Triassic and the Lower Cretaceous sediments in the Euphrates graben area [Yousef, Morozov, 2017a].

Рис. 6. Стратиграфическая колонка верхнетриасовых и нижнемеловых отложений в районе Евфратского грабена [Yousef, Morozov, 2017a].

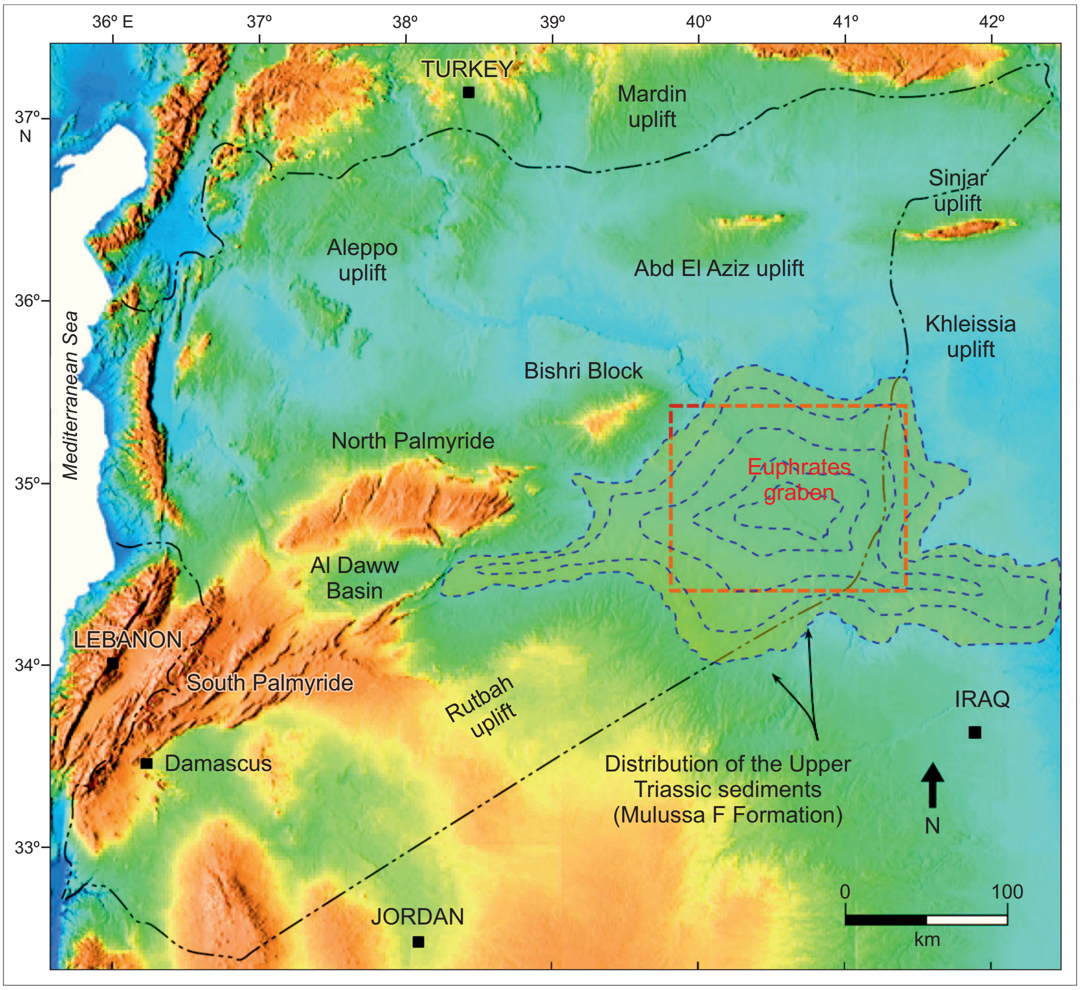

Fig. 7. Distribution map of the Upper Triassic Mulussa F sediments in Syria. Different colours reflect the topography of the area: yellow – highlands, blue – lowland after [Brew et al., 2001].

Рис. 7. Карта распространения верхнетриасовых отложений (формация Мулусса Ф) на территории Сирии. Топография местности отражена цветом: желтый – нагорья, синий – низины (по [Brew et al., 2001]).

Gamma Ray logs, Net to Gross (NTG) distribution, channel sandstone bodies dimensions and shapes, and lithology compositions (see Fig. 6) [Yousef et al., 2017, 2018]. The lower zone (Mulussa F3) is characterized by lower NTG of <20 %; it consists of laminated claystone rich in illite, and shows high potassium readings on the Spectral Gamma Ray logs. The middle zone (Mulussa F2) is characterized by NTG of 50 %; it comprises vertically stacked sandstone channels with interbeds of claystone rich in kaolinite, and shows low potassium readings on the Spectral Gamma Ray logs. The upper zone (Mulussa F1) is characterized by low NTG of 35 %; it contains predominantly single-channel sandstone bodies with interbeds of claystone dominated by illite and/or illite-smectite mixed layers, and shows high potassium readings on the Spectral Gamma Ray logs (see Fig. 6).

The Upper Triassic Mulussa F sediments in the Euphrates graben were affected partially or completely by the erosion processes caused by the BKL and/or BKU unconformities, which together with the structural complexity of the graben lead to high variations in thickness and distribution of these sediments in different zones of the graben area. The maximum thickness of the Upper Triassic Mulussa F sediments amounts to almost 480 m along the central parts of the Euphrates graben and along the NW-SE trend and towards the Jora high and the studied part of the Palmyra basin (Fig. 8).

Variations in the distribution and zonal thickness of the Upper Triassic Mulussa F sediments are controlled by the accommodation space (at the deposition time of the Upper Triassic Mulussa F Formation), which is a function of the depositional basin dip direction of the Upper Triassic Mulussa F sediments, i.e. practically in the MW-SE trend along the graben area. Additionally, these variations are controlled by the locations of paleo-uplifts – the Khleissia uplift towards the NE flanks, and the Rutbah uplift towards the SW flanks (Fig. 8).

The Euphrates graben system evolved using the same trend and depositional basin dip direction of the Upper Triassic Mulussa F sediments (i.e., NW-SE). This is evident from the NW-SE depositional thickness trend of the Upper Triassic Mulussa F sediments that are non- to slightly affected by the erosion processes caused by the BKL and/or BKU unconformities along this direction (Fig. 8). The available accommodation space at the deposition time of the Upper Triassic Mulussa F sediments is one of the dominating factors that controlled the thickness changes and zonal distribution of these sediments in the graben area, as opposed to the erosion processes caused by the BKL and/or BKU unconformities. This is evident from the relatively similar thickness of the Upper Triassic Mulussa F sediments along the Upper Triassic Mulussa F depositional basin strike (NW-SE), whereas the thickness of the Upper Triassic Mulussa F sediments always decreases perpendicular towards the NE flanks of the graben near the Khleissia uplift, and towards the SW flanks of the graben near the Rutbah uplift as shown in Fig. 8. Considering the fact that the Upper Triassic Mulussa F sediments have similar thickness in the central, eastern, SE and NW parts of the graben, there are grounds to suggests that the minimum (if any) graben structuration happened prior to the occurrence of the BKL unconformity. These zones were structurally not high, hence not exposed to the erosion processes caused by the BKL unconformity, and thus preserved their original thickness (Fig. 8).

The thickness of the Upper Triassic Mulussa F sediments gradually decreases towards the southern and SW flanks of the graben near the Rutbah uplift, and also towards the NE flanks near the Khleissia uplift. This evident reduction in thickness is due to the less accommodation space resulted from being close to the uplifts (Fig. 8). However, the thickness of the Upper Triassic Mulussa F sediments in the NE flanks of the graben towards the Khleissia uplift is even more rapid, which is a function of both the less accommodation space and the erosion processes caused by the BKL unconformity (Fig. 8).

Towards the NW part of the Euphrates graben, where the Jora high separates the Upper Triassic Mulussa F depositional basin from the Palmyra basin towards the far NW of the graben area (Fig. 8), the thickness of the Upper Triassic Mulussa F sediments along the Jora high area is slightly decreased due to the erosion processes caused by the BKL unconformity. The limited degree of erosion caused by the BKL unconformity along the Jora high area suggests that this area developed prior to the occurrence of the BKL unconformity. The thickness of the Upper Triassic Mulussa F sediments along the studied part of the Palmyra basin is high due to the more accommodation space there and a lower influence of erosion caused by the BKL unconformity (Fig. 8).

The sub-crop map or the zonal distribution map of the Upper Triassic Mulussa F sediments is shown in Fig. 9. In a small area of the central part of the Euphrates graben, where the erosion processes caused by BKL and/or BKU unconformities did not affect the Upper Triassic Mulussa F sediments, their thickness is completely preserved (Fig. 9).

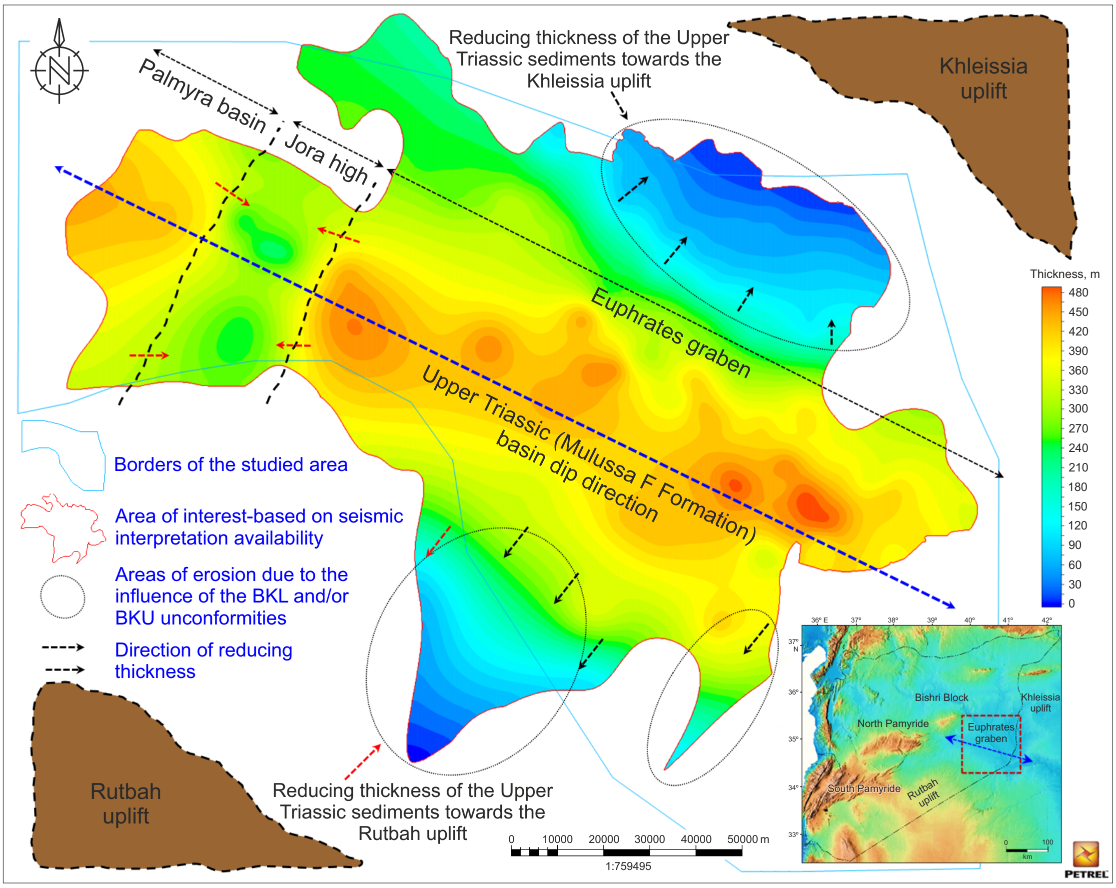

Fig. 8. Thickness map of the Upper Triassic Mulussa F sediments in the Euphrates graben area.

Рис. 8. Карта мощности верхнетриасовых отложений (формация Мулусса Ф) в районе Евфратского грабена.

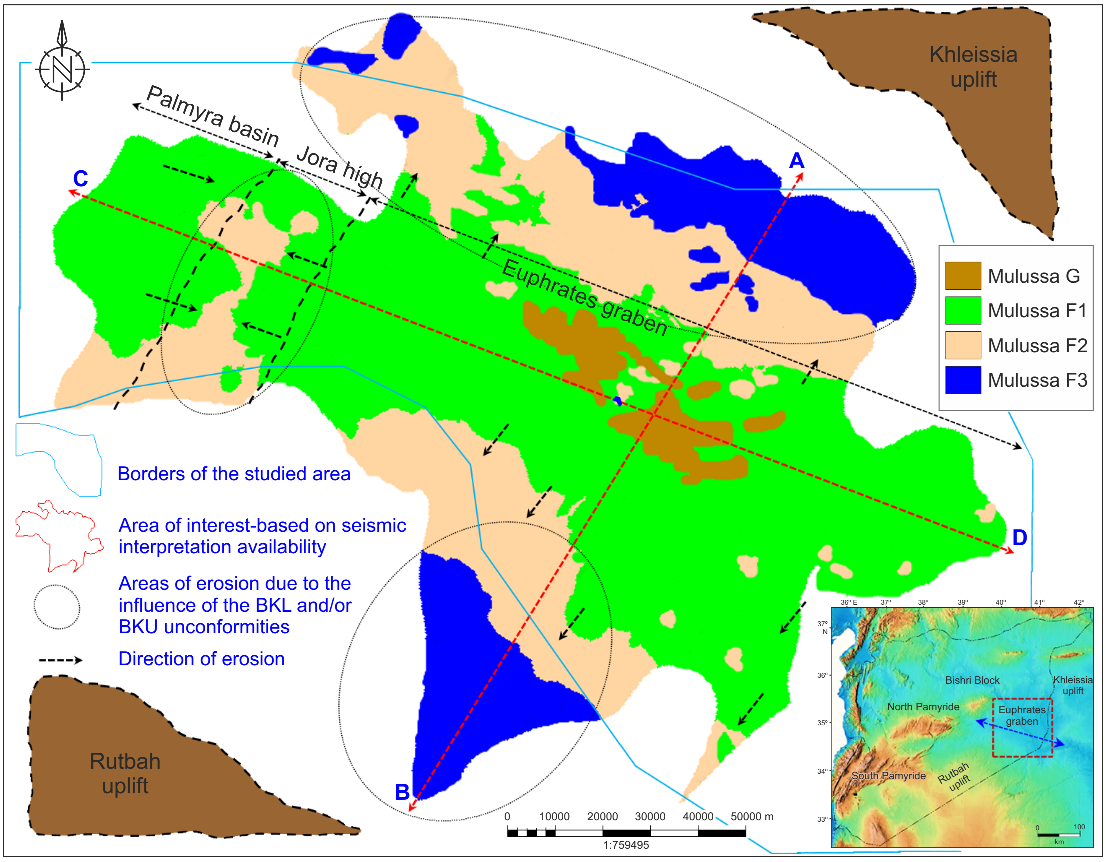

Fig. 9. Sub-crop map showing the distribution of the Upper Triassic Mulussa F sediments along the Euphrates graben area. The geological cross-section (A–B) is shown in Fig. 10. The geological longitudinal profile (C–D) is shown in Fig. 11.

Рис. 9. Карта зонального распространения верхнетриасовых отложений (формация Мулусса Ф) в районе Евфратского грабена. Геологический разрез (A–B) показан на рис. 10. Продольный геологический профиль по линии (C–D) показан на рис. 11.

Additionally, along the NW-SE trend of the Upper Triassic Mulussa F depositional basin, wherein the Mulussa G sediments are not preserved due to the erosion and/or non-deposition, the Mulussa F1 sediments (i.e. the younger zone of the Upper Triassic Mulussa F Formation) are partially eroded due to the BKL unconformity, while sediments of the older zones (Mulussa F2, and Mulussa F3) are preserved and not affected by the erosion. Along the Jora high, the Mulussa F1 sediments are partially to completely eroded due to the influence of the BKL unconformity (Fig. 9).

Moving towards the studied part from the Palmyra basin, we note that almost the full original thickness of the Upper Triassic Mulussa F sediments is preserved. Towards the NE and SW flanks of the graben, the Mulussa F1 sediments (i.e. the younger zone of the Upper Triassic Mulussa F Formation) are completely absent, while the sediments of the older zone (Mulussa F2) are partially preserved. Towards the far NE flanks near to the Khleissia uplift, and towards the far SW flanks near to the Rutbah uplift, only the Mulussa F3 sediments are preserved, while sediments of the younger zones (Mulussa F2, and Mulussa F1) are completely absent. This results from the non-deposition of such sediments and the less accommodation space near the uplift areas, as well as due to the erosion processes caused by the regional BKL and/or BKU unconformities (Fig. 9).

In Fig. 10, a NE-SW geological profile (A-B) flattened at the BKU surface shows that sediments of all the zones of the Upper Triassic Mulussa F Formation (Mulussa G) are completely preserved locally in the central parts of the graben. Gradually moving away from the central parts of the Euphrates graben along the trend of the cross-section (A-B) towards the NE flanks (i.e. towards the Khleissia uplift), we note that the effects of the erosion begin to appear on the Mulussa F sediments. Here, it is clear that the sediments of the younger zones of the Upper Triassic Mulussa F Formation (Mulussa F1) were eroded more than the sediments of the older zones (Mulussa F2, and Mulussa F3). In general, this leads to a gradual decrease in the thickness of the Upper Triassic Mulussa F sediments along this trend until they completely disappear near the Khleissia uplift to the NE. This is interpreted due to the less accommodation space along these flanks, as well as due to the erosion processes caused by the BKL unconformity (since the zones of the Lower Cretaceous Rutbah and the Judea sediments are preserved there), and the higher degree of erosion caused by the BKL unconformity exactly near to the Khleissia uplift (wherein the Mulussa F sediments are absent) (Fig. 10).

Towards the SW flanks near the Rutbah uplift, the thickness of the Upper Triassic Mulussa F sediments is gradually

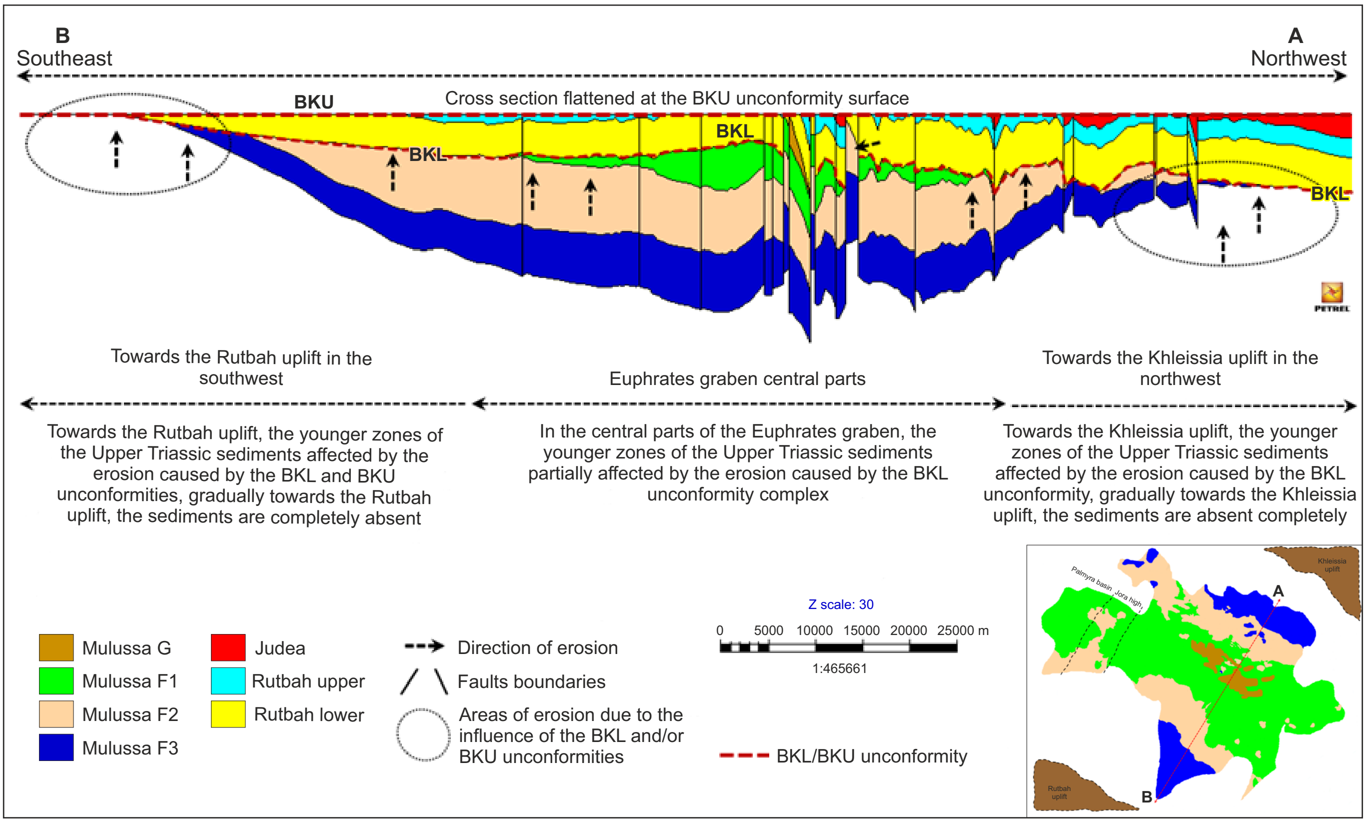

Fig. 10. The NE-SW geological cross-section (A–B) flattened at the BKU surface.

Рис. 10. Поперечный геологический профиль по линии (A–B) (СВ–ЮЗ), сглаженный по поверхности несогласия BKU.

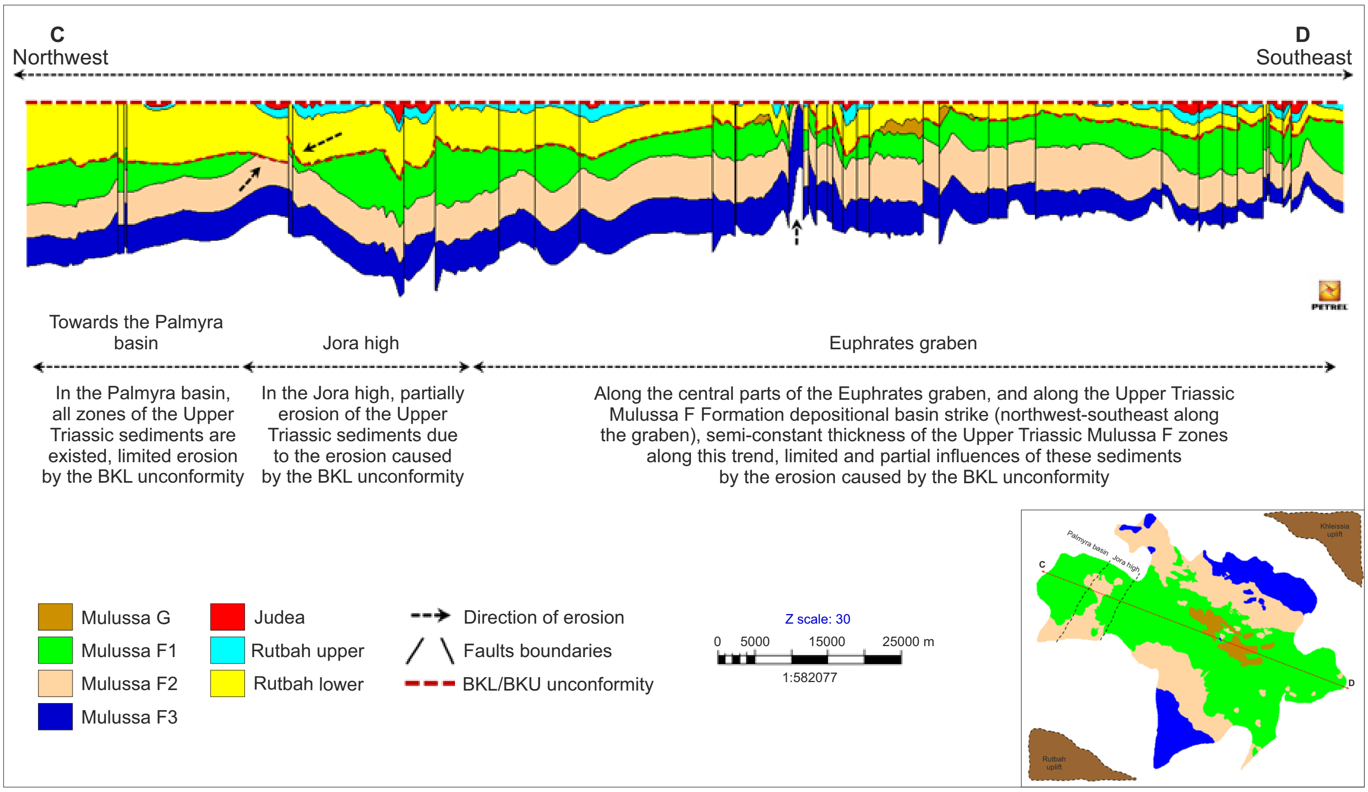

Fig. 11. The NW-SE longitudinal geological profile (C–D) flattened at the BKU unconformity surface.

Рис. 11. Продольный геологический профиль по линии (C–D) (СЗ–ЮВ), сглаженный по поверхности несогласия BKU.

reduced until they completely disappear exactly near to the Rutbah uplift. This is interpreted due to the erosion processes caused by the BKL and BKU unconformities since the Lower Cretaceous Rutbah and the Judea sediments are completely absent there (Fig. 10).

In Fig. 11, a NW-SE longitudinal geological profile (C-D) flattened at the BKU surface shows a semi-constant thickness of the Upper Triassic Mulussa F Formation zones along the NW-SE trend. Limited changes are noted in the thickness of the Mulussa F1 sediments along the profile. This is due to the limited effects of the erosion processes caused by the BKL unconformity since the zones of the Lower Cretaceous Rutbah Formation are preserved there.

A limited influence of the erosion processes caused by the BKL unconformity along the Jora high is evidenced by the absence of the Mulussa F1 sediments (i.e. the younger zone of the Upper Triassic Mulussa F Formation). The Jora high area is expressed in the profile (C-D) as a pre-BKL unconformity event since the zones of the Lower Cretaceous Rutbah Formation are preserved there. Towards the studied part from the Palmyra basin, the sediments section of the Upper Triassic Mulussa F Formation is almost complete and not affected by the erosion processes caused by the regional BKL and BKU unconformities.

4.3. Regional stratigraphical zonal distribution framework of the Lower Cretaceous sediments in the Euphrates graben area

Sediments of the Lower Cretaceous Rutbah Formation cover almost the entire Euphrates graben area and some parts of Iraq lands (Fig. 12).

Stratigraphically, the Lower Cretaceous Rutbah sediments lie disconformably on the top of the BKL soil horizon and on the top of the Jurassic Mulussa G sediments in the zones wherein the erosion caused by the unconformities did not remove the Jurassic Mulussa G sediments. However, in the zones wherein the BKL soil horizon and/or sediments of the Jurassic Mulussa G sediments were completely eroded, the Lower Cretaceous Rutbah sediments lie disconformably on the top of the Upper Triassic Mulussa F sediments (see Fig. 6).

The Lower Cretaceous Rutbah sediments along the Euphrates graben area are subdivided into two zones from bottom to top (Lower Rutbah and Upper Rutbah, respectively),

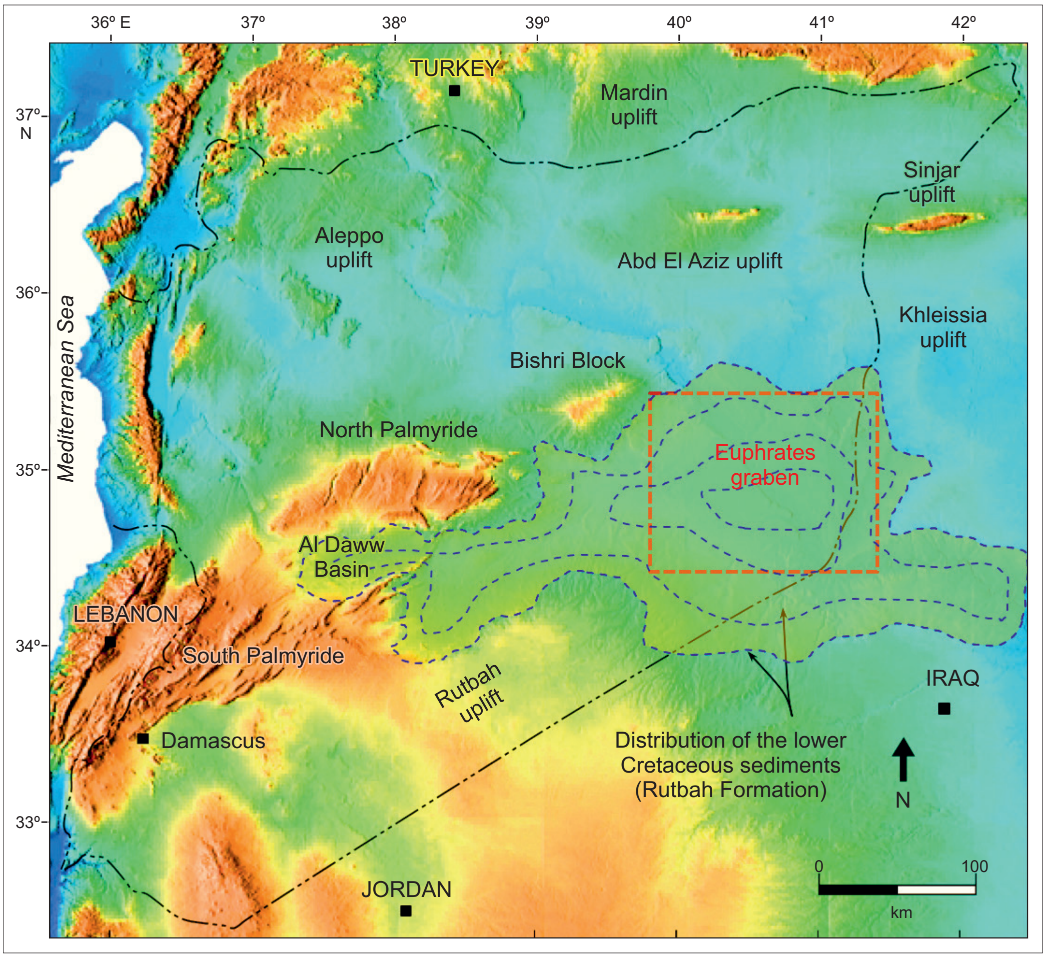

Fig. 12. Distribution map of the Lower Cretaceous Rutbah Formation sediments in Syria, different colours reflect the topography: yellow – highlands, blue – lowland after [Brew et al., 2001].

Рис. 12. Карты распространения нижнемеловых отложений (формация Рутба) в Сирии. Топография местности отражена цветом: желтый – нагорья, синий – низины (по [Brew et al., 2001]).

according to Spectral Gamma Ray logs and lithology compositions (see Fig. 6), [Yousef et al., 2016, 2017, 2018]. The Lower Cretaceous Rutbah sediments are partially or completely eroded due to the influence of the BKU unconformity, which leads to high variations in the thickness and zonal distribution along the graben area. The maximum thickness of the Lower Cretaceous Rutbah Formation along the Euphrates graben area is approximately 320m. The thickness increases gradually towards the northern, NE and NW flanks of the graben, and towards the Jora high area, as well as towards the studied part of the Palmyra basin and the far NW flank of the graben (Fig. 13). This trend of thickness increasing reflects the increase in the accommodation space during the deposition time of the Lower Cretaceous Rutbah sediments along this trend. Considering a lower or limited degree of erosion caused by the BKU unconformity that affected the Lower Cretaceous Rutbah sediments along the northern, NE and NW flanks of the graben, and towards the Jora high and Palmyra basin, there are grounds to suggest that these flanks were structurally lower prior to the erosion caused by the BKU unconformity during the deposition time of the Lower Cretaceous Rutbah Formation. Hence, the maximum thicknesses of these sediments along these flanks is preserved (Fig. 13). The Jora high area shows a smaller thickness of the Lower Cretaceous Rutbah sediments mainly due to the less accommodation space and less erosion caused by the BKU unconformity. The Lower Cretaceous Rutbah sediments in Palmyra basin are thicker due to the more accommodation space and less erosion caused by the BKU unconformity. However, the erosion processes caused by the BKU unconformity affected the thickness trend and zonal distribution of the Lower Cretaceous Rutbah sediment. As a result, areas with minimum thickness of these sediments formed towards the southern, eastern, SE and SW flanks of the graben and especially near the Rutbah uplift (Fig. 13).

A higher degree of erosion caused by the BKU unconformity that affected the Lower Cretaceous Rutbah sediments along the above-mentioned flanks of the graben means that these flanks were structurally higher prior to the erosion processes caused by the BKU unconformity along the graben during Lower Cretaceous Rutbah Formation deposition time. Furthermore, this indicates that the accommodation space near these flanks during the deposition time was limited, which prevented these sediments from being deposited near the flanks and near the Rutbah uplift towards the southwest (Fig. 13).

The sub-crop map showing the distribution of the Lower Cretaceous Rutbah sediments along the Euphrates graben area is shown in Fig. 14. The full section of these sediments is preserved towards the NE flanks, partially to the west and NW areas along the Jora high and the Palmyra basin, and partially towards the far eastern flanks. The section of the Lower Cretaceous Rutbah sediments along these flanks

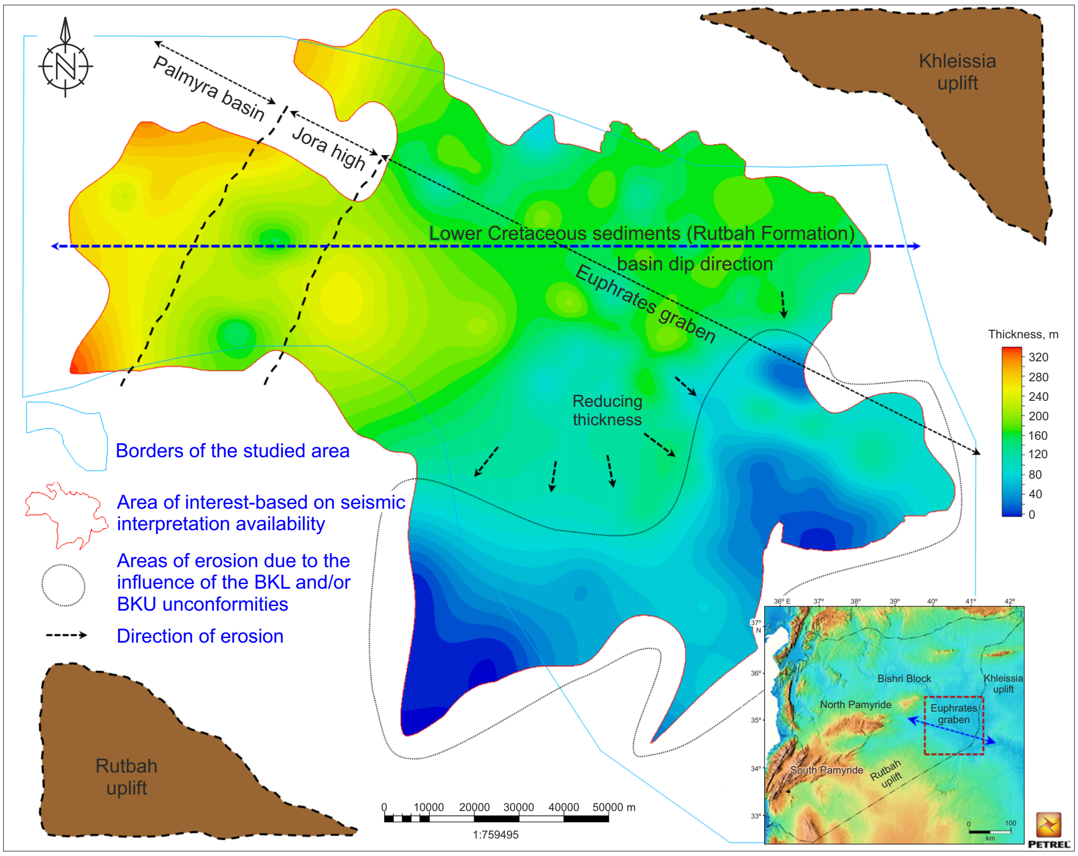

Fig. 13. Thicknesses map of the Lower Cretaceous Rutbah Formation sediments in the Euphrates graben area.

Рис. 13. Карта мощностей нижнемеловых отложений (формация Рутба) в районе Евфратского грабена.

is overlaid by carbonates of the Judea Formation (which are older than the Lower Cretaceous Rutbah sediments, as shown in the stratigraphical section of the Euphrates graben). Thus, the carbonate sediments of the Judea Formation contributed to protecting the Lower Cretaceous Rutbah sediments from being exposed to the erosion processes caused by the BKU unconformity. Along the central parts of the Euphrates graben area, the Lower Cretaceous Rutbah sediments are partially or completely eroded due to the influence of the BKU unconformity. The sub-crop map shows that exactly in the central parts of the graben, the erosion processes strongly affected the younger zone of the Lower Cretaceous Rutbah Formation (Upper Rutbah), and these sediments were completely removed. The only preserved sediments are those of the older zone of the Lower Cretaceous Rutbah Formation (Lower Rutbah).

Moving onwards away from the central parts of the graben, the sub-crop map (Fig. 14) also shows that the erosion processes mainly affected the younger zone of the Lower Cretaceous Rutbah Formation (Upper Rutbah), while the sediments of the older zone (Lower Rutbah) are preserved there (Fig. 14). Towards the far southern, SE and SW flanks of the Euphrates graben near to the Rutbah uplift, the Lower Cretaceous Rutbah sediments are partially and strongly eroded due to the influence of the BKU unconformity, and only the sediments of the Upper Triassic Mulussa F Formation are preserved there (Fig. 14).

In Fig. 15, a NE-SW geological profile (A”-B”) flattened at the BKL surface shows that towards the northeast near to the Khleissia uplift, the Lower Cretaceous Rutbah sediments are almost fully preserved and only slightly affected by the erosion processes caused by the BKL unconformity. These sediments are overlaid by the carbonate sediments of the younger Judea Formation. Towards the SW flanks near to the Rutbah uplift, the Lower Cretaceous Rutbah sediments are partially to completely eroded due to the

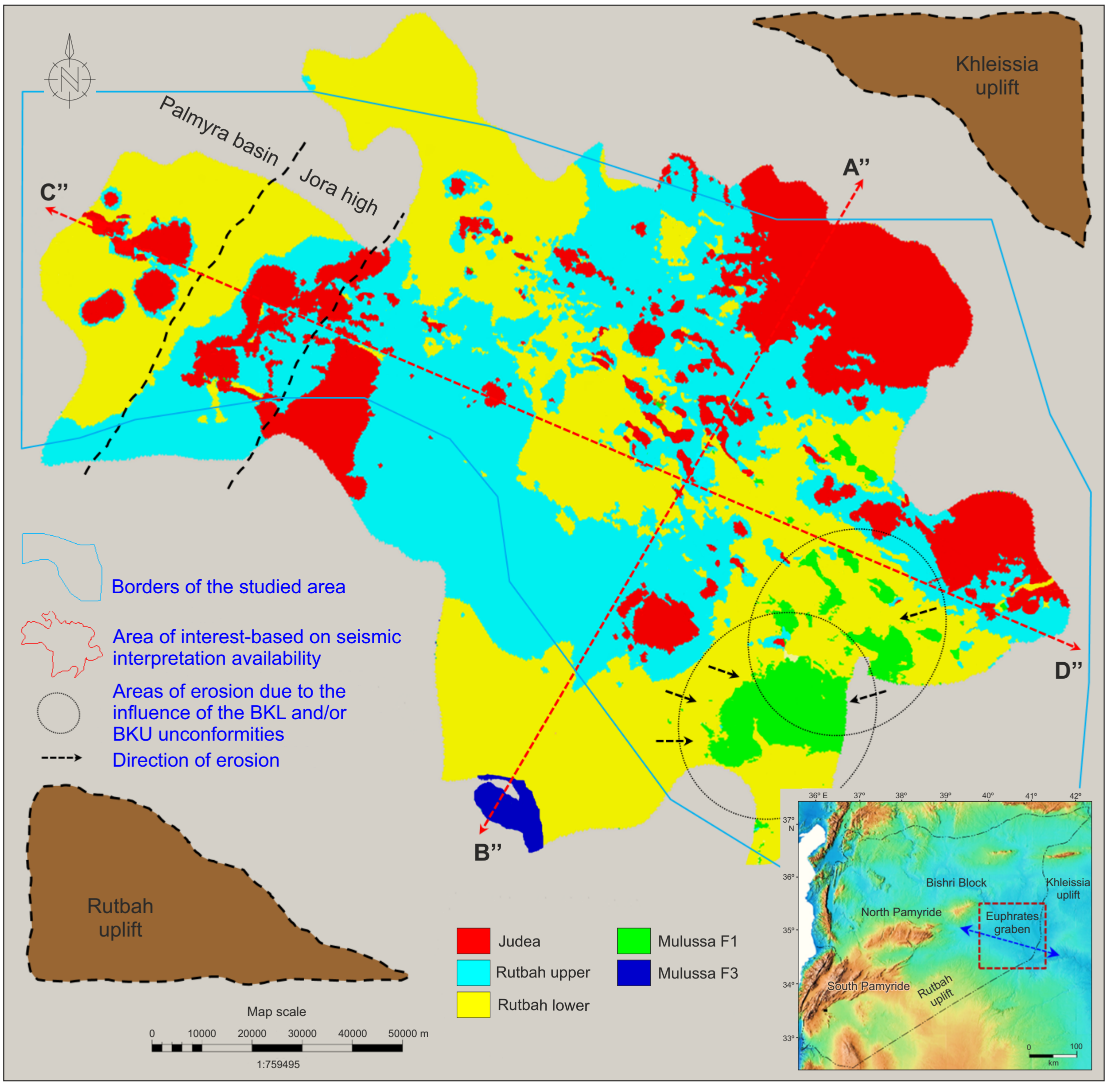

Fig. 14. Sub-crop map showing the distribution of the Lower Cretaceous Rutbah sediments along the Euphrates graben area. The geological cross-section (A”–B”) is shown in Fig. 15. The geological longitudinal profile (C”–D”) is shown in Fig. 16.

Рис. 14. Карта зонального распространения нижнемеловых отложений (формация Рутба) в районе Евфратского грабена. Геологический разрез (A”–B”) показан на рис. 15. Продольный геологический профиль (C”–D”) показан на рис. 16.

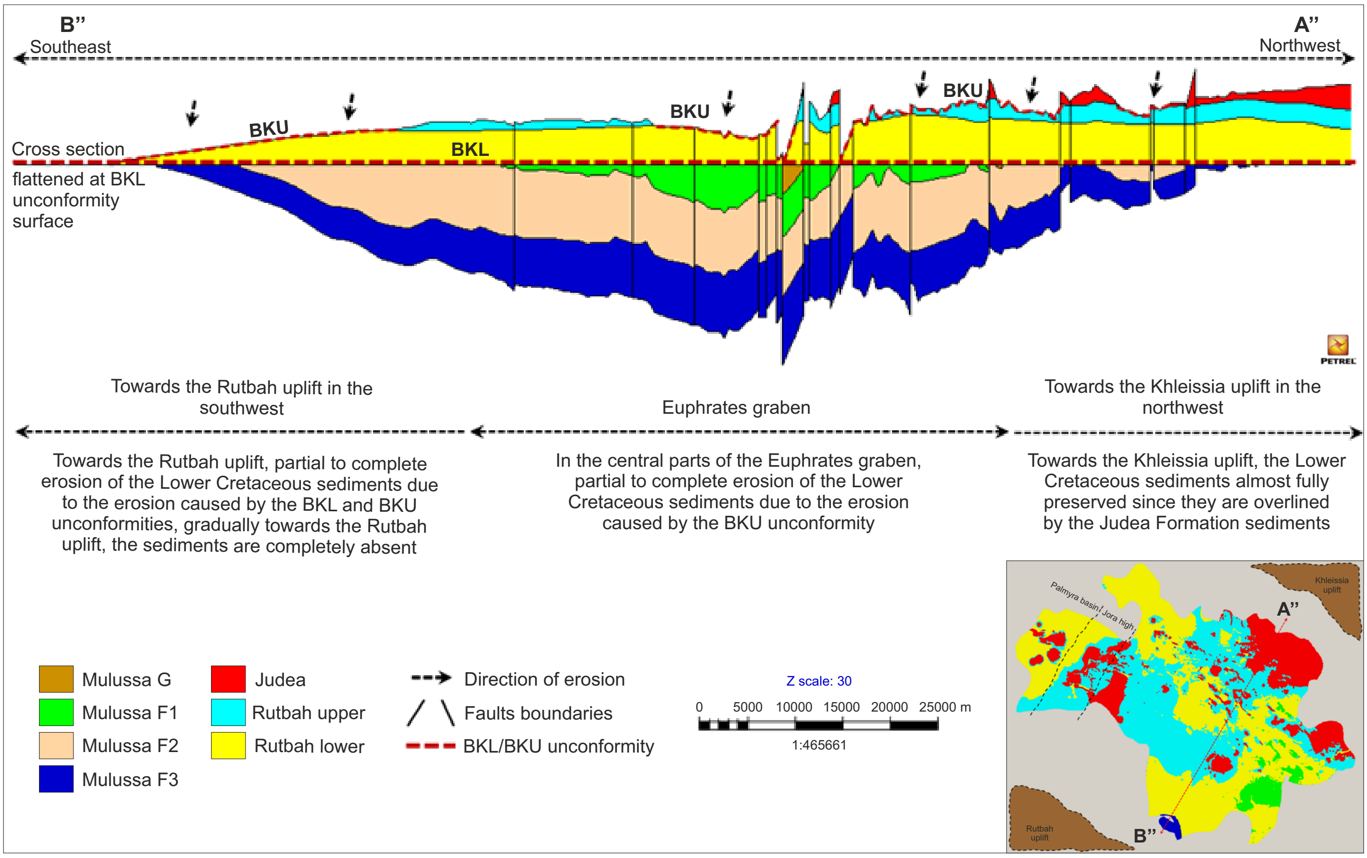

Fig. 15. The NW-SE geological cross-section (A”–B”) flattened at the BKL surface.

Рис. 15. Поперечный геологический профиль (A”–B”) (СВ–ЮЗ), сглаженный по поверхности несогласия BKL.

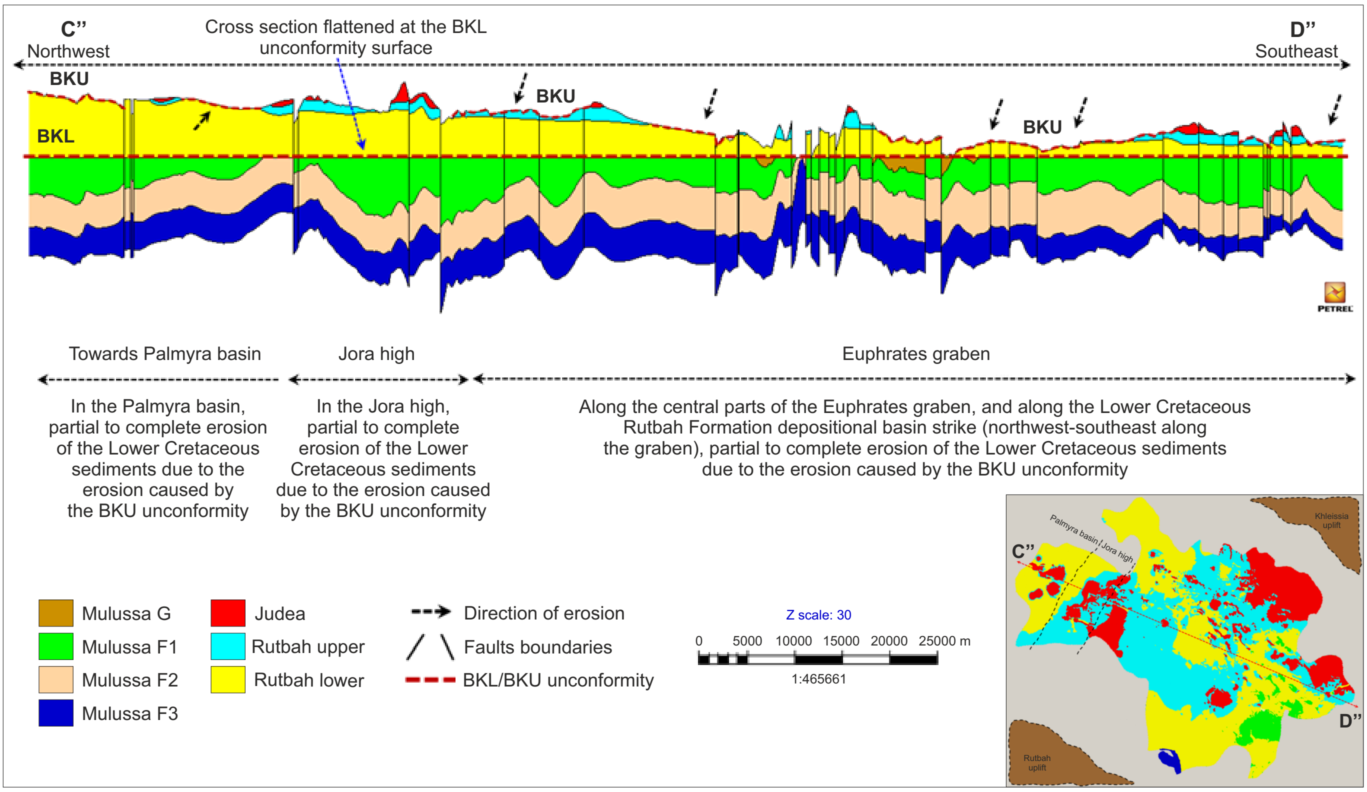

Fig. 16. The NW-SE longitudinal geological profile (C”–D”) flattened at the BKL unconformity surface.

Рис. 16. Продольный геологический профиль (C”–D”), сглаженный по поверхности несогласия BKL.

influence of the BKU unconformity, and the erosion mainly removed the sediments of the younger zone of the Lower Cretaceous Rutbah Formation (Upper Rutbah). Gradually, towards the far SW flanks exactly near to Rutbah uplift, the Lower Cretaceous Rutbah sediments become completely lacking, and only the sediments of the older zone of the Upper Triassic Mulussa F Formation (Mulussa F3) are preserved there. Moving inwards the central parts of the Euphrates graben along the geological cross-section (A"–B"), we note partial to complete erosion of the younger zone of the Lower Cretaceous Rutbah Formation (Upper Rutbah) due to the BKU unconformity. The sediments of the older zone of the Lower Cretaceous Rutbah Formation (Lower Rutbah) were less affected by the erosion processes caused by the BKL unconformity and are thus partially preserved there (Fig. 15).

In Fig. 16, a NW–SE longitudinal geological profile (C"–D") flattened at the BKL surface shows that the erosion processes affected the sediments of the Upper Rutbah zone more than those of the Lower Rutbah zone. This is evidenced by a comparison of their thicknesses along the profile, which clearly shows that the Lower Rutbah sediments are thicker than the Upper Rutbah sediments (Fig. 16). This is due to the difference in the erosion degree caused by the BKU unconformity, as well as the difference in the available accommodation space – there was more accommodation space along the NW flanks than along the SE flanks, and the Lower Cretaceous Rutbah sediments were deposited along the NW flanks. Along the central parts of the Euphrates graben, the Upper Rutbah sediments are partly presented, and the erosion degree depends mainly on how structurally high these areas were relative to the BKU unconformity.

5. SOURCE OF THE UPPER TRIASSIC AND LOWER CRETACEOUS SEDIMENTS IN THE EUPHRATES GRABEN AREA

Our study have identified dominating deposits in the study area. Marine carbonates dominate in the Mulussa E Formation; shallow marine sediments in the Mulussa F3.2 zone; and lagoon-type and coastal fluviatile sediments in the Mulussa F3.1 zone. Continental fluviatile deposits dominate in the Mulussa F2 zone; and coastal fluviatile sediments in the Mulussa F1 zone. Shallow marine carbonates are dominant in the Mulussa G Formation; and shallow marine sediments in the Lower Cretaceous Rutbah Formation. This gentle modification in the depositional sequence from marine to continental and back to marine deposits corresponds to a regressive-transgressive pair followed by two major sequence boundaries, i.e. the BKL and BKU unconformities, respectively (see Fig. 6).

By studying the clay mineral composition of the Upper Triassic (Mulussa F Formation) and the Lower Cretaceous sediments (Rutbah Formation), we establish the source material composition and assess the amount of weathering or maturity of the clay sediments, which directly depends on the duration of exposure of the clay materials to erosion

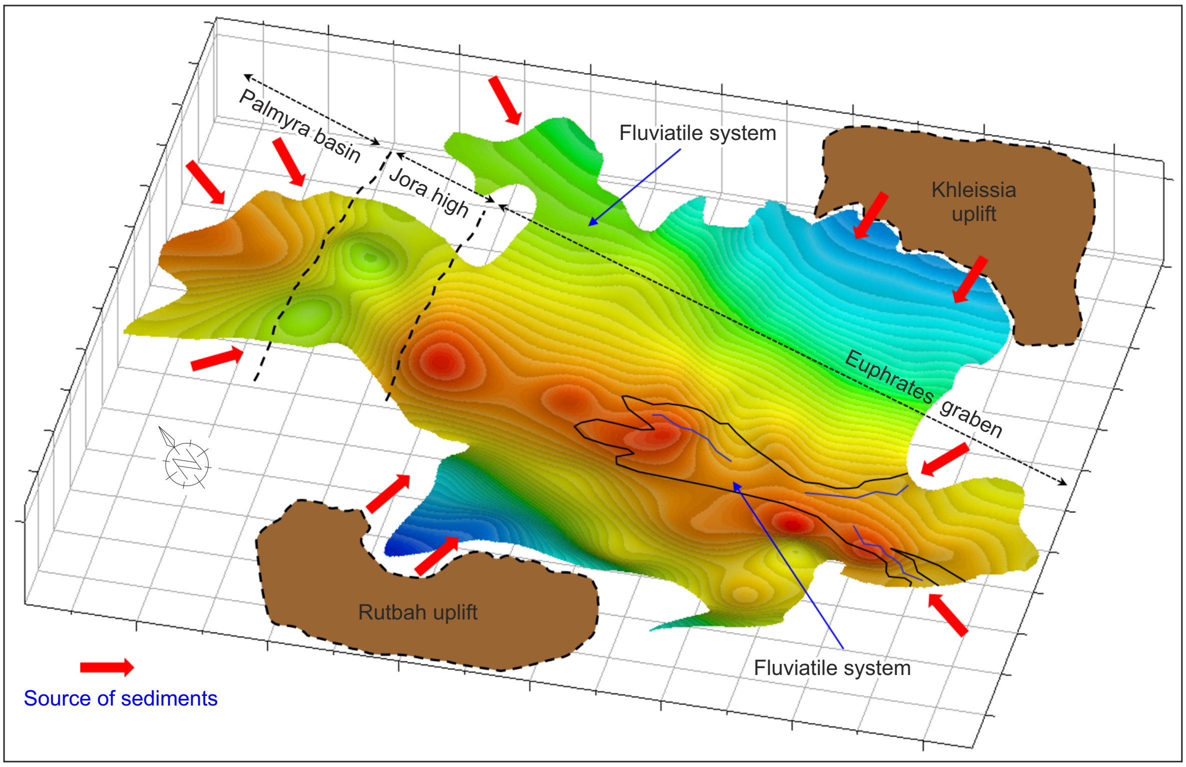

Fig. 17. The 3D depositional model showing possible sources of the Upper Triassic and Lower Cretaceous sediments in the Euphrates graben area.

Рис. 17. Трехмерная модель осадконакопления, показывающая возможные источники верхнетриасовых и нижнемеловых отложений в районе Евфратского грабена.

and indicates the accommodation space. The modifications in the clay materials composition of the Upper Triassic and Lower Cretaceous sediments are therefore entirely due to the change in weathering abilities of the sedimentological system and ultimately to the availability of the accommodation space. For the same source material composition, the more mature are the clays, the lower is the rate of the accommodation space. The abundance of highly mature clay materials in the Upper Triassic and the Lower Cretaceous sediments in the Euphrates graben area suggests that these sediments derived from deep acidic volcanic rocks, or developed from metamorphic rocks which were exposed for a long time and subjected to long-term chemical and physical weathering processes in conditions of a tropical humid climate [Caron, Mouty, 2007; Yousef, Morozov, 2017b].

The high maturity of quartz minerals that are mixed with heavy minerals (e.g. zircon and tourmaline) (see Fig. 6) [Yousef et al., 2016, 2017] suggest that these sediments were transported into the deposition basin from an area located at a long distance. The sources of the Upper Triassic and the Lower Cretaceous sediments in the Euphrates graben area derived from the Rutbah uplift towards the SW flank of the graben and/or from the Khleissia uplift towards the NE flank of the graben. This interpretation is supported by the fact that both the Upper Triassic Mulussa F sediments and the Lower Cretaceous Rutbah sediments are preserved only in the central parts of the Euphrates graben. They are absent in the areas of the Khleissia and Rutbah uplifts due to the impacts of tectonic uplifting and erosion related to the creation of the Euphrates graben during the Early Cretaceous (Barremian) [Litak et al., 1997, 1998].

In Fig. 17, a three-dimensional depositional model shows possible sources of the Upper Triassic and Lower Cretaceous sediments in the Euphrates graben area. In [Laws, Wilson, 1997; Ziegler, 2001; Sadooni, Alsharhan, 2004; Mouty, Gout, 2010], the palaeogeographic reconstruction for the Middle East Upper Triassic shows that the non-marine Upper Triassic sediments are also observed outside the Euphrates graben area. Therefore, the fluviatile system of the Upper Triassic Mulussa F Formation in the Euphrates graben area occupied probably a relatively small area.

In Fig. 18, a two-dimensional depositional model shows possible deposition settings and possible sources of the Upper Triassic and Lower Cretaceous sediments in the Euphrates graben area. This model is based on sedimentological interpretations described in [Yousef et al., 2019]. In the fluviatile system of the Upper Triassic sediments, the flows are directed from NNE to SSW (Fig. 18).

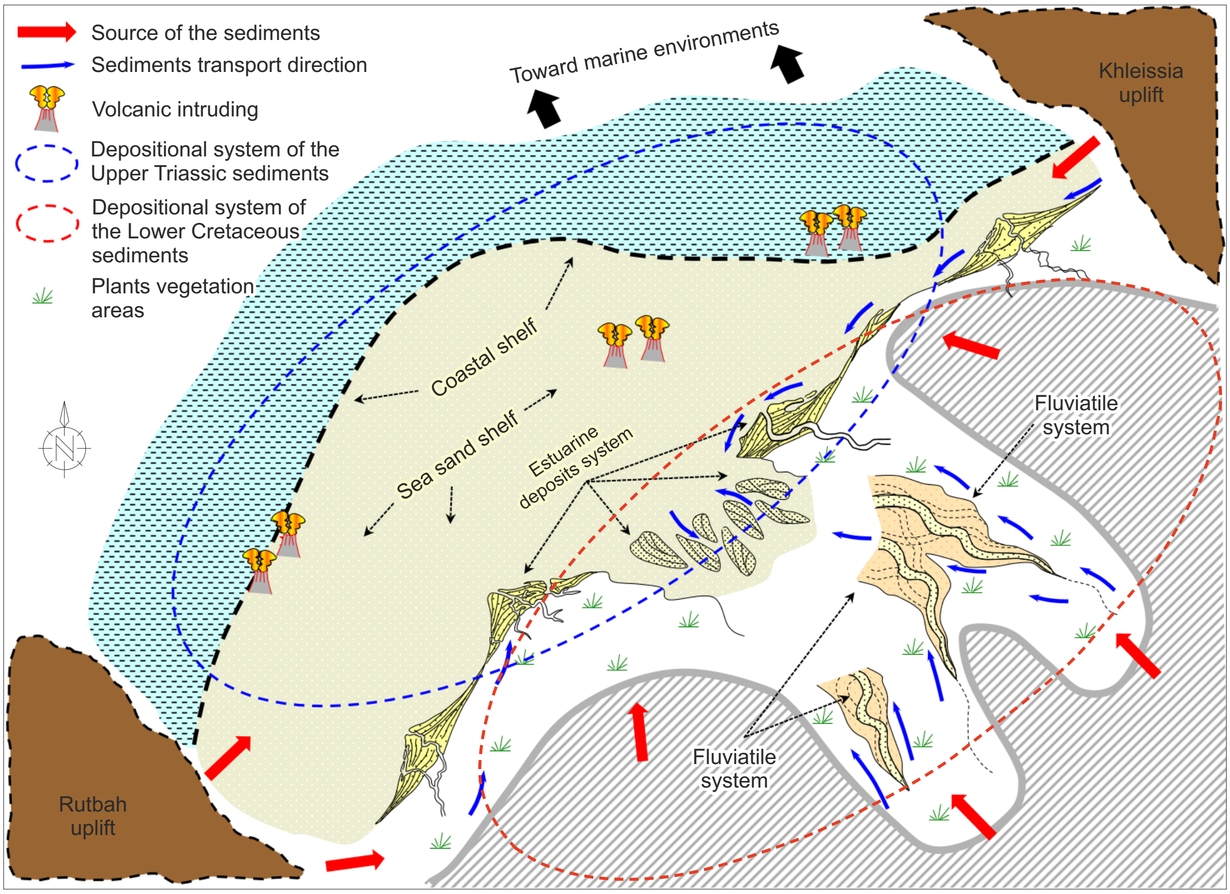

Fig. 18. The 2D depositional model showing possible deposition settings and sources of the Upper Triassic and Lower Cretaceous sediments in the Euphrates graben area.

Рис. 18. Двумерная модель осадконакопления, показывающая условия осадконакопления и источники верхнетриасовых и нижнемеловых отложений в районе Евфратского грабена.

6. CONCLUSION

Improved understanding the regional structure of the Euphrates graben and clarifying the influences of the regional unconformities on the graben area is very important for future exploration of the currently non-explored areas, as well as for the developments of the graben fields. Such knowledge is critical for identifying the most promising thicknesses of the reservoir sediments and zones that were not influenced by the erosion processes caused by the unconformities in the graben fields. Using the geological modeling software of Petrel Schlumberger, we have constructed the regional structural and stratigraphical geological models of the Upper Triassic Mulussa F Formation and Lower Cretaceous Rutbah Formation. Based on these models, it becomes possible to properly clarify the zonal distribution and thickness changes of the sediments, which result from the influence of the two major unconformities, the Base Upper Cretaceous Unconformity (BKU), and the Base Lower Cretaceous Unconformity (BKL). The 480 m maximum thickness of the Upper Triassic Mulussa F sediments is preserved in the central parts of the graben and along the NW-SE trend (i.e. practically the dip direction of the Upper Triassic Mulussa F Formation depositional basin). Towards the NE flank near to Khleissia uplift, as well as towards the SW flank near to Rutbah uplift, the thickness of the Upper Triassic Mulussa F sediments gradually decreases to the minimum. These sediments are completely absent near these uplifts, which is mainly due to the erosion processes caused by the BKL unconformity in combination with the less accommodation space available near these areas. The 320 m maximum thickness of the Lower Cretaceous Rutbah sediments is preserved in the central parts of the graben and towards the northern, NW and western flanks of the graben, as well as along the Jora high and Palmyra basin. These flanks and areas are the main depositional basin of the Lower Cretaceous Rutbah sediments. The maximum thickness of the Lower Cretaceous Rutbah sediments is preserved there due to the sufficient availability of the accommodation space. Furthermore, these sediments were less influenced by the erosion processes caused by the BKU unconformity. The thickness of the Lower Cretaceous Rutbah sediments decreases towards the southern, SE and SW flanks near the Rutbah uplift mainly due to the less accommodation space and due to the higher degree of erosion caused by the BKU unconformity along these flanks and areas.

7. ACKNOWLEDGEMENTS

This study was supported by the Ministry of Sciences and Higher Education of the Russian Federation (Agreement 075-15-2020-931) within the framework of the development program for a world-class research center – Efficient Development of the Global Liquid Hydrocarbon Reserves.

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