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The Paleogene Forebulge Carbonate Banks, Zagros Foreland Basin, Northern Iraq: their Paleogeography, Basin Evolution, and Economic Implications

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Abstract

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The Paleogene sequence of Zagros foreland basin NE Iraq during the Late Paleocene-Middle Eocene is punctuated by linear and disconnected chains of carbonate bank-ramp associations. These carbonate units had developed over the NW-SE trending Paleogene basin forebulge. Discussion of origin, facies type, and stratigraphic architecture of these banks and associated facies was fully covered by the first part of this research project. In this part the chronostratigraphic syntheses of the sequence, the paleogeography, and basin evolution is examined as an integral part of the investigation of the evolution of the Paleogene Zagros foreland basin. Research methods include regional stratigraphic correlation, and biostratigraphic data compilation to infer the chronostratigraphic sequence of the events. The paleogeographic facies mapping and basin history are reviewed accordingly. Research data are collected from 15 master surface sections. In addition to the re-examination and re-interpretation of 40 previously studied surface and subsurface well logs, which are compiled for basin-wide study and regional paleogeographic mapping. The analysis of the compiled biostratigraphic data shows that the inferred age of the associated stratigraphic units is as follows: Sinjar Formation (E. Thanetian – L. Ypresian), Khurmala Formation (Ypresian - E. Lutetian), Kolosh Formation (Daian - Thanetian), and Aaliqi Formation (Danian - Ypresian). Based on this chronostratigraphic synthesis, the basin forebulge history during the Paleogene period is divided into 5 stages: the Pre-bank, Early Bank Development, Bank-ramp Development, Back-bank Lagoon, and Lagoonal dolomitization stage. The paleogeography and paleofacies maps of each stage is discussed in terms of the basin forebulge evolution. An alternative hydrocarbon play of the forebulge-controlled Paleogene sequence is discussed, with a case study from the Sufaiyah oil field of northwest Iraq.

Keywords: Paleogeography; Paleogene; Chronostratigraphy; Carbonate banks; Zagros; Iraq

1. Introduction

The importance of Zagros foreland basin comes from the fact that it contains about 98% of Arabian plate hydrocarbons, which make up about 66% of oil and 31.5% gas of the world's oil and gas reserve (Beydoun, 1991). The Zagros foreland basin is developed upon the protracted closure of the Neotethys

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Ocean, with of ophiolite-radiolarite emplacement over the Arabian margin (Saura et al., 2011). This generated an active and rapid flexural subsidence of the Arabian margin into the Zagros foreland basin, which commenced as early as Late Turonian (Stoneley, 1990; Alavi, 2004; Robertson, 2006; Homke et al., 2009; Leturmy and Robin, 2010; Saura et al., 2010; Al-Qayim et al., 2012; and Al-Qayim et al., 2021). The basin extends mostly over northeastern Iraq and southwestern Iran. The depositional history of this basin passes during the Paleogene period through a complete cycle of a foreland basin evolution including a final filling and shoaling stage (Al-Qayim et al., 2012; Al-Qayim, 2019). The basin included a full set of the foreland basin depozones (DeCelles and Giles, 1996). The foredeep zone is represented by the flysch sediments of the Kolosh Formation, and the back-bulge zone with the basinal marlstone of the Aaliji Formation (Al-Qayim, 2021). To the northeast of the foredeep zone of the basin, an intermontane basin is developed with a thick sequence of subcontinental red siliciclasts of the Suwaiss Red Beds Series (Al Barzinji, 2005; Karim et al., 2008). The latter makes the wedge-top depozone of the basin (Al-Qayim, 2021). The forebulge depozone of the basin had been developed as a NW-SE trending chain of intra-basinal highs, which is marked by a series of carbonate banks known as the Sinjar Formation (Al-Qayim, 2021; Al-Qayim, 2022; and Al-Qayim, 2023). The origin, stratigraphic architecture, and sedimentary facies associations of these banks, which are considered key event to the basin's depositional history and evolution, had been discussed in Al-Qayim (2024). This study represents the second part of the research project, which focuses on the chronostratigraphic sequence of the events, as well as the regional paleogeographic distribution of the different stratigraphic units and facies. The overall basin history of these banks and associated facies during the Paleogene period is reviewed.

The focus of the paper is northern Iraq, but references were made to the equivalent units, and geologic history of the basin from the Iranian side. Regional correlations were attempted to support the overall understanding of the basin's evolution.

The relationship between bank-ramp facies and the adjacent basinal sediments is reviewed to provide an alternative hydrocarbon play of the basin. This possibility is discussed with a case study from the Sufaiyah oil field of northwestern Iraq.

2. Geologic Setting

The Zagros foreland basin evolved during the Late Cretaceous time of the tectonic convergence between the Afro-Arabian continental margin and Eurasia (Agard et al., 2005). The sequence of the tectonic events involved in the basin formation process includes 1) subduction of the Afro-Arabian margin, 2) obduction of the Tethyan masses (Radiolarites, Ophiolites, the exhumed Mesozoic slices of the Afro-Arabian margin) over the Arabian margin. 3) The generation of flexuring and rapid subsidence which leads to the formation of the Zagros foreland basin (Stoneley, 1990; Beydoun et al., 1991; Sharland et al., 2001; Alavi, 2004; Robertson, 2006; Agard et al., 2005; Homke et al., 2009; Leturmy and Robin, 2010; Saura et al., 2015; and Al-Qayim et al., 2012; AL-Qayim et al., 2021). These events were leading, through the Neogene to a subsequent continental–continental collision between the two plates, which culminated in the development of the Zagros orogeny (Alavi, 2004; Agard et al., 2005; Jassim and Goff, 2006; Homke et al., 2009; Moutheraue, 2011; Al-Qayim et al., 2012; Al-Qayim, 2021). The resulting Zagros Fold-Thrust belt represents the external and spectacular part of the Zagros Orogeny. In northern Iraq this belt is tectonically divided into the Imbricate, High Folded, Low Folded, and Mesopotamian Zone (Fouad, 2015) (Fig. 1). The Zagros foreland basin has a regional NW-SE trend, and extends mainly, over the folded belt and beyond into the Mesopotamia zone of northern Iraq, even over southwestern part of Iran, (Beydoun, 1991).

Outcrops of the Paleogene stratigraphic units are distributed over the folded zone of the Zagros fold-thrust belt as shown in (Fig. 1). These folds are aligned in a NW-SE trend parallel to the Zagros

tectonic trends. At the high folded zone, the outcrops of the Paleogene sequence swing around the flanks of these folds. At the foothill or low folded zone, outcrops of this sequence occupy anticline cores. The low folded zone consists of a series of widely spaced, low amplitude gentle for separating the high folded zone from the low folded zone. The high folded zone includes higher, tighter and closed folds. The line, which separates the high folded zone from the low folded zone, is trending NW-SE and approximately marks the chain of the Paleogene carbonate banks.

The foreland basin sequence is considered to range in age from the Middle Turonian up to the Recent time including the full record of AP9, Ap10, and Ap11 megasequences of the Arabian plate (Sharland et al., 2001). Megasequence AP9 represents the complete sequence of the Early Zagros foreland basin of the Upper Turonian-Lutetian (Al-Qayim, 2021). The boundaries and subdivision of this megasequence AP9 is discussed and revised by Al-Qayim (2019). Three important divisions were recognized in this megasequence: the Middle Turonian-Middle Campanian (AP9a), the Middle Campanian-Maastrichtian (AP9b), and the Paleocene-Middle Eocene supersequence (AP9c).

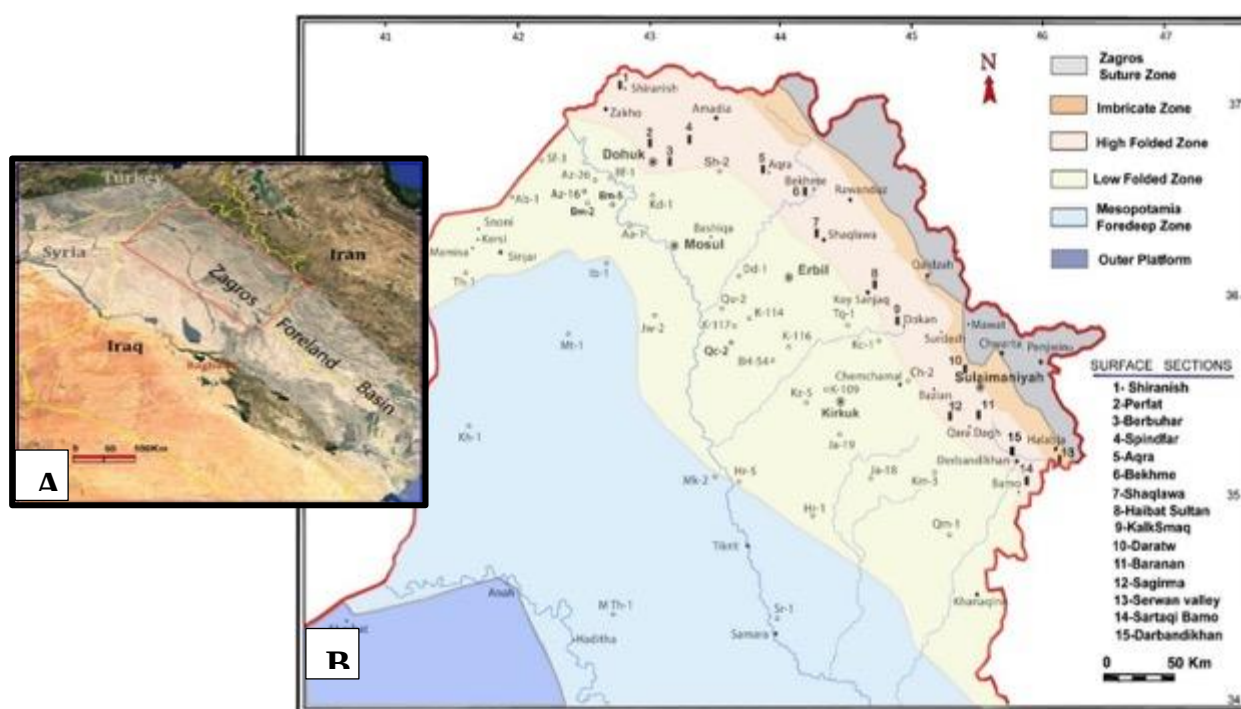


Fig.1. (A) Location map (Google-Earth satellite image) of the study area within the Zagros foreland basin, and (B) tectonic divisions of northern Iraq (Tectonic division nomenclature after Fouad, 2015).

The latter sequence which includes northern Iraq is the carbonate banks of the Sinjar Formation, which cover the forebulge area, the flysch sequence of the Kolosh Formation (the foredeep area), the Khurmala dolostone Formation of the back-bank area and the pelagic marlstone of the Aaliji Formation which occupy the back-bulge area (Al-Qayim, 2022; 2024) (Fig. 2). The sequence of these Formations can be given as:

The Kolosh Formation, which occupies the foredeep area is represented by a thick sequence of flysch sediments. The formation generally consists of thin-bedded sandstone and siltstone, which alternate with thick dark gray silty shale interlayers. Occasional lenses of conglomerate are reported. The formation is often intercalated at its upper part and in many localities with fingers from the Sinjar limestone (Bellen et al., 1959). The thickness of this formation is variable and ranges from few tens of meters at Agra to more than 700 meters at the type area. The Aaliji Formation, on the other hand represents the offshore basinal equivalent of the Kolosh Formation. In the supplementary type section

in Iraq (well K-109), the formation is consist of 167 meters of gray to brown marlstone, marly limestone, and shale (Bellen et al., 1959). Unfortunately the formation has no complete outcrops, and most of its studied sections are from subsurface wells of oil fields, located within the back-bulge area. Thickness is variable and ranges from 15 m. at well Shaikhan-2 to 300 meters at well Rafan-1 (Al-Qayim, 2024).

The carbonate banks which are developed over the evolving forebulge of the basin is represented by the Sinjar Formation, which consists of algal-foraminiferal carbonate reefs and shoals of hard gray massive and thick-bedded limestone. It's thickness ranges from 25 meters near Shaqlawa to more than 100 meters at Branam Mountain (Al-Qayim, 2023). Upon basin shoaling a back-bank lagoon is developed over the filled foredeep area. At certain area of this lagoon, a local dolostone and dolomitic limestone is developed forming the Khormal Formation, which marking the final phase of marine sedimentation of the basin (Al-Qayim, 2022).

According to Al-Qayim (2024), the carbonate banks are disconnected reef bodies associated with ramp facies on both sides. The reef limestone consists mainly of corallgal reef limestone, Nummulitic shoals, back-bank lagoonal limestone, and a limited occurrence of tidal flat facies. This facies association forms the inner ramp deposits. The ramp facies, where faces the west-southwest side into the basinal sediment of the Aaliqi Formation of the back-bulge area is called windward ramp. On the other side of the banks which, faces east-northeastward, a leeward carbonate ramp is developed, which intermixed with the upper part of the siliciclastic sediments of the Kolosh Formation at the foredeep area. Three localized banks were recognized from NW to SE: Dohuk Bank to the NW of Dohuk City, Kirkuk Bank along the Kirkuk structure, and Sulaimaniah Bank, which is the largest and well- developed one. The latter extends from Dokan southeastwards into the Sartaki Bamo area near the Iraqi-Iranian borders (Fig. 2). Following the termination of the basin marine sedimentation, a wedge of subcontinental red siliciclastic sediments of the Gercus Formation prograde from the northeastern hinterland covering the foredeep and forebulge areas and marking the molasses phase of the basin.

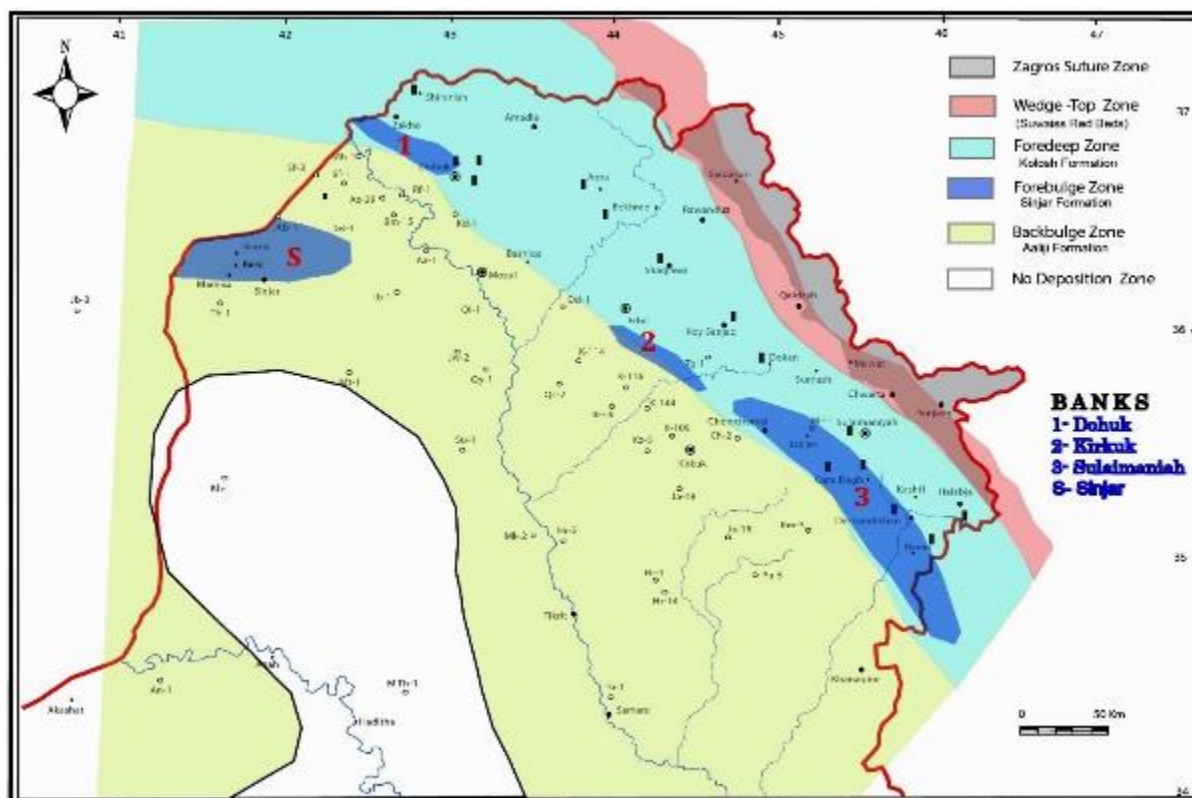


Fig. 2. Regional paleogeographic map of the Paleogene Early Zagros Foreland Basin showing regional facies belts and depozones.

3. Materials and Methods

Stratigraphic data and measurements were collected from fifteen localities distributed over the Zagros foreland basin in northern Iraq. These localities include: Shiranish, Dohuk (Perfat and Berbuhar sections), Spindar, Aqra, Bekhme, Shaqlawa, Haibat Sultan, Dokan, Daratw, Branat Mt., Sagirma Mt., Derbandikhan, Sirwan Valley, and Sartaki Bamo (Fig. 1) above. Regional stratigraphic correlation and cross-correlation of other 40 surface and subsurface sections previously presented by other workers, which distributed over the most parts of the basin were attempted. Stratigraphic data of these sections are reinterpreted, and used in basin-wide paleogeographic mapping and the development of the basin history as well. For subsurface stratigraphic measurements, data are approved from final well reports and the formation's top correlation charts of the Northern Iraq Oil Company (1986) such as: (AZ-26, Rf- 1, Aa- 1, Kd-1, Sh- 2, Jw- 2, Qu- 2, Dd- 1, BH- 54, K- 116, Tq- 1, Kz- 5, K- 109, KC- 1, Ja- 19, CH- 2, Ja -18, Qm- 1).

Chronostratigraphic evaluation of basin stratigraphic units and the key events are inferred from the compilation, analysis, and interpretation of biostratigraphic data, which are presented by previous workers.

4. Results

4.1. Chronostratigraphic Assessments

Biostratigraphic analysis and age determination of the studied stratigraphic units, were attempted by many workers since the regional and masterwork of Bellen et al. (1959). Most of these studies used planktonic or benthonic foraminiferal biostratigraphy. Few recent studies, however, applied calcareous nannofossils (Starkie, 1994; Kharajany et al., 2020). Although comparison between these studies shows some variability, probably due to variability in study date, scientific depth and details, and research methodology of each study. Attempt is made, however, to compile these data and to constrain the age of the basin Paleogene stratigraphic units for paleogeographic mapping and basin evolution review. This is done by plotting the age range of each previous study for each unit to average the most common and accepted time interval.

The chronostratigraphic chart of the Sinjar formation is interesting in elucidate the stratigraphic evolution of these carbonate banks (Fig. 3). Most of the previous studies in general, suggested that the deposition of the formation did not start before the Late Selandian to Early Thanetian (Bellen et al., 1959; Shathaya, 1980; Al-Hashimi and Amer, 1985; Daod, 2009; Al-Dulaimi and Al-Dulaimi, 2017; Salih, 2013) (Fig. 4). Others more specific studies suggest Early Ypresian for the beginning of the Sinjar Formation (Al-Siddiki, 1968; Kassab, 1978; Khadouri, 1989; Lawa, 2006; Lawa and Mardan, 2019). The termination of the formation on the other hand, is agreed by most of the reviewed studies to be through the Ypresian (Metwalli et al., 1974; Bellen et al., 1959; Amer, 1977; Al-Hashimi and Amer, 1985; Khadouri, 1989; Kassab, 1978; Al-Dulaimi and Al-Dulaimi, 2017; Daod, 2009; Salih, 2012; Lawa et al., 2023). Except the Sulaimaniyah area, where shows a younger age up to the Lutetian (Lawa, 2006; Lawa and Mardan, 2019) (Fig. 3). It is noteworthy that the age of the Sinjar Formation at the Sinjar area, and Syria and the northwestern part of the basin start earlier than other areas (Metwalli et al., 1974; Bellen et al., 1959; Al-Hashimi and Amer, 1985; Lawa et al., 2023). On the other hand, the Sinjar Formation in the southeastern part of the basin such as the Sulaimaniyah area, shows a younger age (Lawa, 2006; Salih, 2012; Lawa and Mardan, 2019). Further southeastward in Iran, the age of its equivalent Taleh Zang Formation reaches the Lutetian age (Rajabi, 2014). By taking these chronostratigraphic evaluations with considerable reliability, it is possible to suggest with an overgeneralized statement, that the Sinjar Formation banks start at the northwestern part of the basin earlier than that of the southeastern part of the basin.

Age Authors	PALEOCENE			EOCENE		
	Danian (4.4)	Selandian (2.4)	Thanetian (3.2)	Ypresian (8.2)	Lutetian (6.6)	Bartonian (3.4)
Hamed <i>et al.</i> (1974)					Jibeessal Syria	
Bellen <i>et al.</i> (1974)				Sinjar		
Amer & Al-Hashimi (1985)				Sinjar		
Lawa <i>et al.</i> (2022)					Dohuk	
Al-Siddiki (1988)					Sinjar	
					AZ-28	
					Dd-1	
					K-116	
					CH-2	
Khadouri (1988)					Abtah - 1	
Kassab (1978)					K-117	
Al-Dulaimi & Al-Dulaimi (2017)				Amadiyah		
				Qaradagh		
				Derbandikhan		
Daod (2009)				Branan Mt.		
Salih (2012)					Tasluja	
Shalhaya (1980)				Chinarook		
				Bazian		
				Derbandikhan		
Lawa (2008)						Sulaimaniyah
Lawa & Mardan (2019)						Sulaimaniyah
Rajabi (2014)						Taleh Zang / Iran

Fig. 3. Age assessment of the Sinjar Formation as compiled and interpreted from biostratigraphic data of different sources.

Age Authors	Selandian (2.4)	Thanetian (3.2)	Ypresian (8.2)	Lutetian (6.6)	Bartonian (3.4)
Bellen <i>et al.</i> (1974)				K - 114	
Sessakian & Youkhana (1978)				Shaqlawia	
Kassab (1978)				K - 117	
Al-Hashimi & Amer (1985)				Shaqlawia	
Barwary (1983)				Bashiqia	
Starkie (1994)				Ch - 2	
Al-Banna <i>et al.</i> (2006)					Dohuk
Al-Banna <i>et al.</i> (2012)				Bekhme Gorge	

Fig. 4. Age assessment of the Khurmala Formation as compiled and interpreted from biostratigraphic data from different sources.

The lagoonal carbonates of the basin is developed after the beginning of the Ypresian (Fig. 4). This is because the lagoonal conditions are not started to develop until establishing a good barrier of the Sinjar Formation bank over the forebulge area, which provides the required environmental conditions for a back-bank lagoon to be established.

The Khurmala Formation, which represents the dolomitized part of the lagoonal sediments of the Sinjar Formation, is believed to have extended in age through most of the Ypresian up to the Early Lutetian time (Fig. 4).

The Kolosh Formation age determination studies, in general, indicate a Paleocene age, with few studies extending the age to the Ypresian (Fig. 5). These few studies, which include the Ypresian time most probably include the Sinjar finger on top of the Kolosh Formation into the age estimation. On the other hand, the studies that come short of the Danian age either missed it by a low-resolution sampling or incomplete sections. Therefore, the age of the Kolosh Formation without the carbonate unit on top, is considered here to be through most of the Paleocene time.

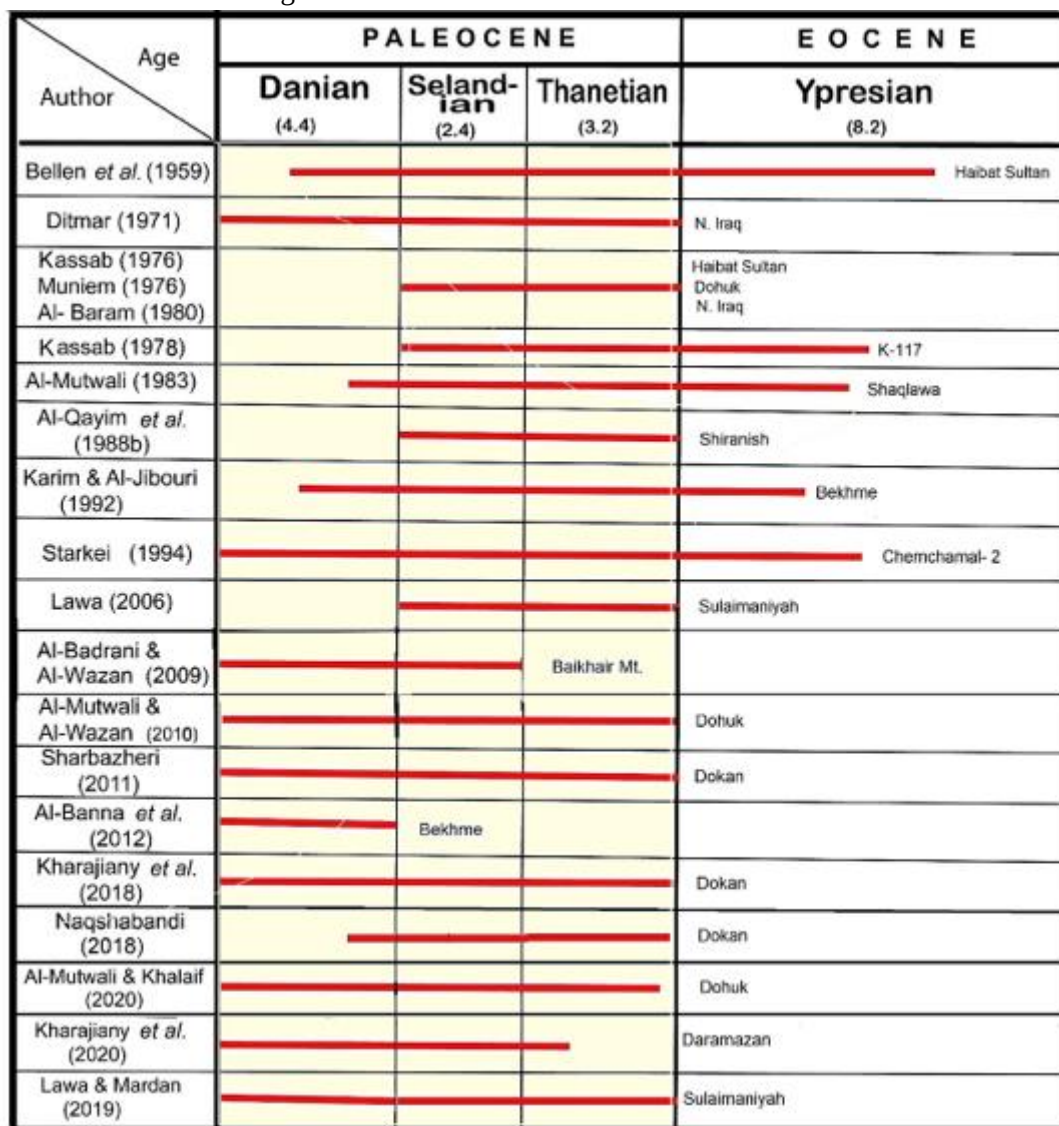


Fig. 5. Age assessment of the Kolosh Formation as compiled and interpreted from biostratigraphic data in different sources.

Most of the previous studies for the Aaliji Formation age assessment suggest that it extends from the Paleocene to Early Eocene (Fig. 6). Most of these studies are based on subsurface studies of well

samples which excludes the Danian from the Paleocene interval. However, two outcrop studies by Amer (1977) for the Sinjar area and Bamerni et al. (2020) from the Dohuk area show that a lower finger offshoot of the formation below the Kolosh Formation has limited occurrence, which shows only the lower part of the Paleocene sequence (Danian) been present. This is understandable if we consider the Aaliqi and Kolosh Formations are time equivalent and often replace one by the other whereby only a limited part can be recognized.

Age Author	PALEOCENE			E O C E N E
	Danian (4.4)	Seland- ian (2.4)	Thanetian (3.2)	Ypresian (8.2)
Bøllén <i>et al.</i> (1959) Buday (1980) Jassim & Goff (2006)				K-109
Kassab (1978)				AZ-16
Amer (1977)				Sinjar
Starkei (1994)				CH-2
Al-Omari & Al-Hadidi (2004)				EB-2
Shihab (2008)				K- 229
Kassab (1975)				In- 5
Al-Hyaly & Al-Badrani (2019)				K-116
Bamarni <i>et al.</i> (2020)		Dohuk		

Fig. 6. Age assessment of the Aaliqi Formation as compiled and interpreted from biostratigraphic data in different sources.

4.2. Paleogeography and Basin Evolution

The stratigraphic architecture of these banks and associated units is explained in (Al-Qayim, 2024). The chronostratigraphic assessments of the stratigraphic units as inferred from the compiled biostratigraphic data of the previous studies are used to review the history and evolution of the Paleogene Zagros foreland basin. This history is divided into five chronostratigraphic stages associated with the history and evolution of the carbonate banks and the associated units. A set of (5) paleogeographic maps of the foreland basin were constructed to show the facies relations, stratigraphic association, and tectonic evolution of the basin. These maps were established to show five time slices, each representing important events in the evolution of the forebulge carbonate banks and its relation to the basin stratigraphic architecture (Figs. 7, 8, 9, 10, and 11). These stages represent periods of the pre-bank stage,

early bank development stage, mature bank with ramp association stage, basin shoaling and lagoonal development stage, and finally the development of the lagoonal dolostone stage. Each map is accompanied by a schematic generalized cross-section across the basin in the NE – SW direction to show the lateral stratigraphy and facies relations.

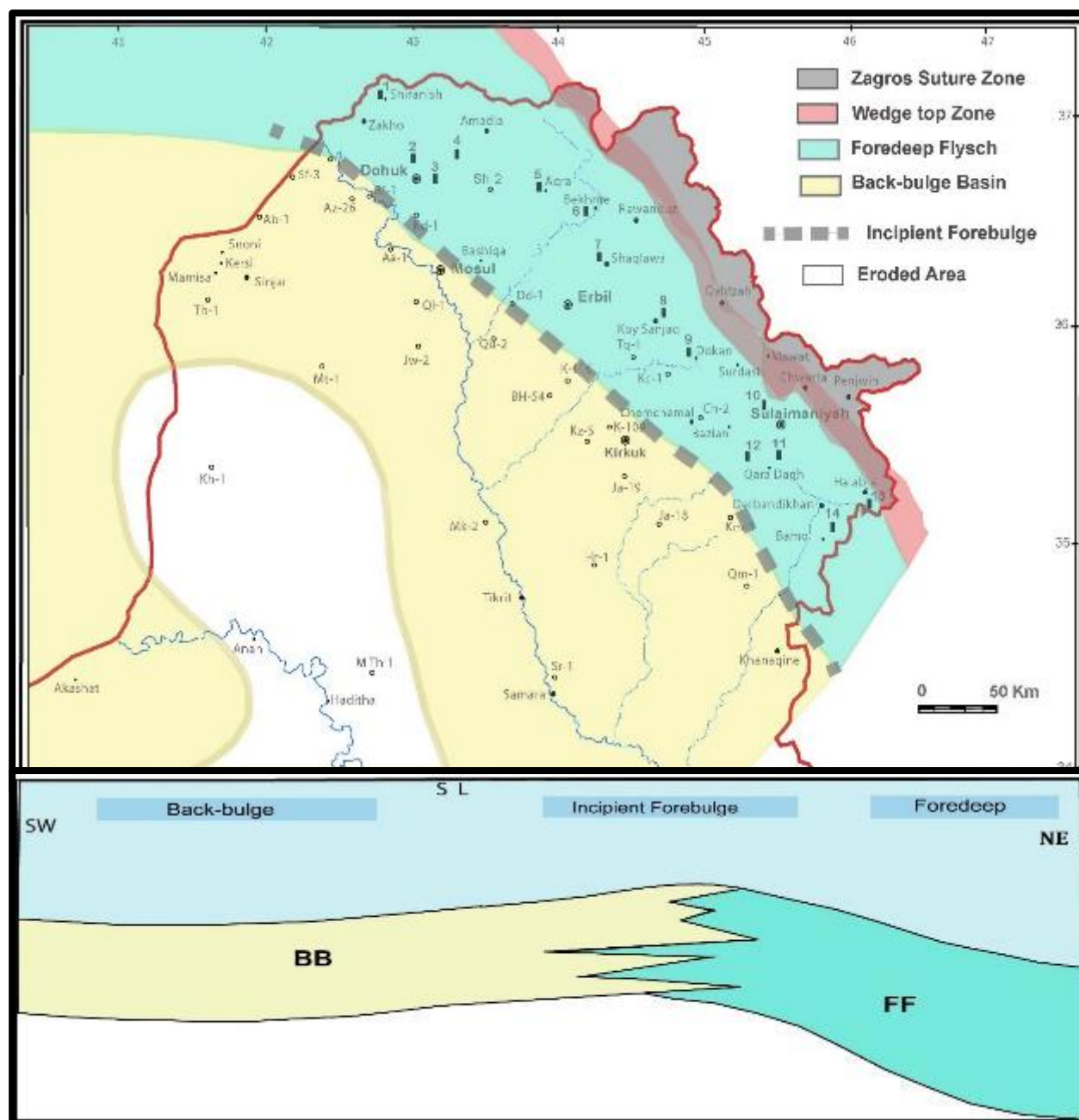


Fig. 7. Paleogeographic map and a schematic NE-SW cross-section of the Paleogene Zagros Foreland Basin of north Iraq during the Danian-Selandian time of a pre-bank stage. (BB- Back-bulge basin, FF- Foredeep Flysch).

4.2.1. Pre-bank Stage (Danian - Selandian)

During the Early Paleogene stage (most probably during Danian and Selandian) the basin have developed the basic foreland depozones of De-Celles and Giles (1996). The depozones of the basin are fully developed. The wedge top depozone is developed at the front area of the thrust masses of the

Zagros suture zone and occupied by the thick siliciclastics of the Suwaiss Red Beds Series. These sediments were developed as a fan-delta depositional system of an intermountain basin prograding from the northeastern hinterland (Karim et al., 2008; Hassan, 2012). Southwestwards an elongated asymmetrical and rapidly subsiding trough is developed, which is filled by up to 750 meters of dark gray to grayish green siliciclastic flysch sediments of the Kolosh Formation (Fig. 7).

These sediments represent recycled distal turbidites (Al-Qayim and Salman, 1986; Al-Qayim et al., 1988; Al-Qayim, 1995b). This trough represents the basin's foredeep depozone which forms the most representative feature of the basin, and extends from SE Turkey to Western Iran. The petrofacies analysis of the Kolosh Formation sediments shows features indicating deposition at the peripheral foreland basin (Al-Qayim, 1994). The back-bulge basin is filled by the pelagic, light-colored, marlstone and marly limestone of the Aaliqi Formation.

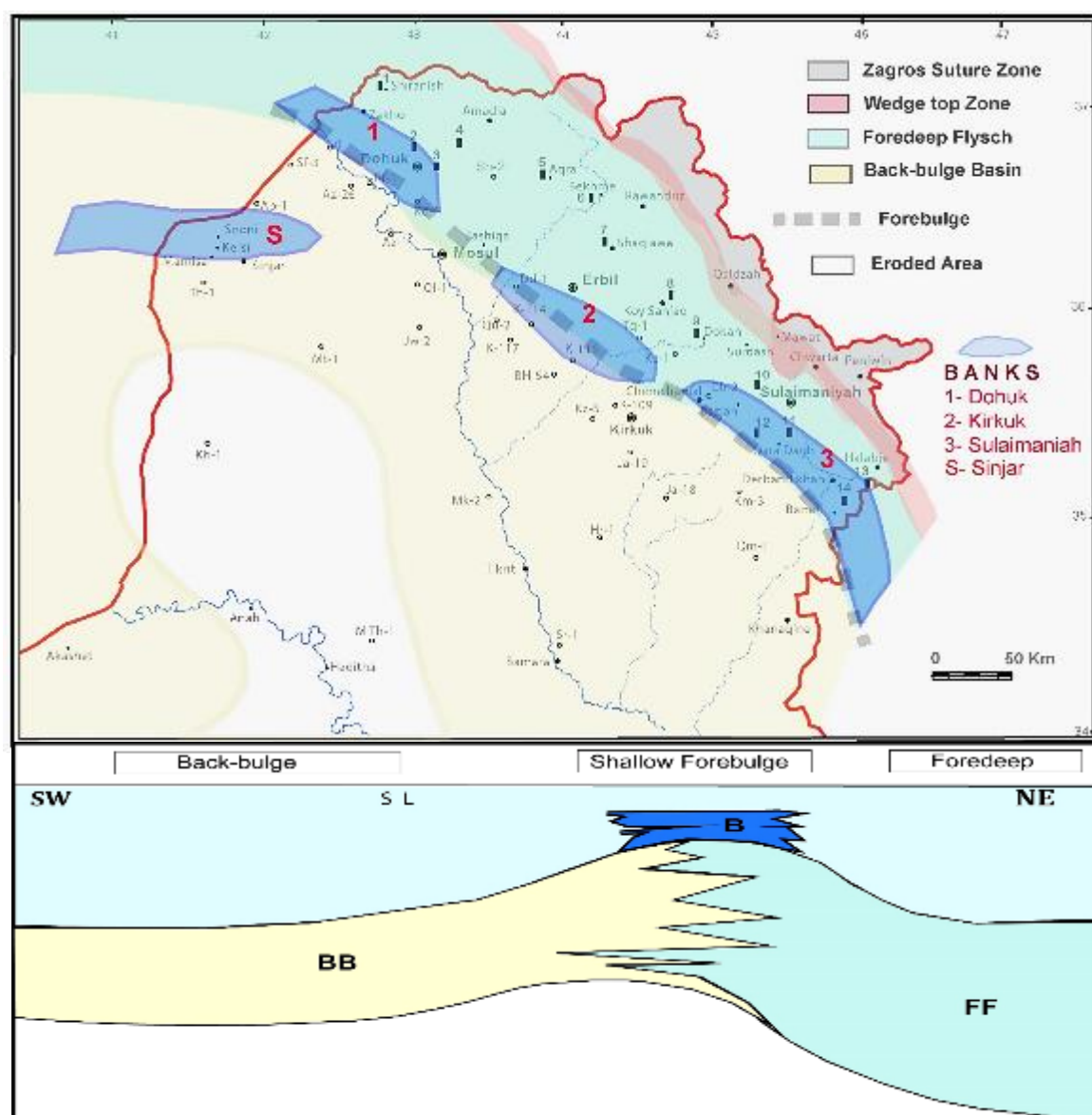


Fig. 8. Paleogeographic map and a schematic NE-SW cross-section of the Paleogene Zagros Foreland Basin of north Iraq during the Thanetian time of the early bank development stage. (BB- Back-bulge basin, FF- Foredeep Flysch, B- Bank)

The forebulge area at this time was an incipient area, where no evidence of its occurrence is reported. This is indicated by the intermixture and intercalations between Kolosh Formation sediments (foredeep) with Aaliiji Formation marlstone (back-bulge). This situation has been reported in many localities by (Bellen et al., 1959). These intercalations of both types sediments at the lower part of the Paleogene sequence are also noticed by many workers in several examined sections such as Shiranish, Dohuk, and wells Refan-1, Alan-1, Damir Dagħ-1, Quair-1, Kirkuk-116, Chemchamal-2, and TaqTaq-1 (Final Well Reports). The occurrence of this intercalations at the lower part of the sequence implies Early Paleocene timing, as well as the ineffective role of the forebulge as a barrier between the two depozones. No carbonate banks were developed yet at this stage of the basin evolution. Since most of the carbonate banks are dated as Thanetian age and younger, therefore, this stage probably lasted during the Danian-Selandian period i. e. (Pre-Thanetian time).

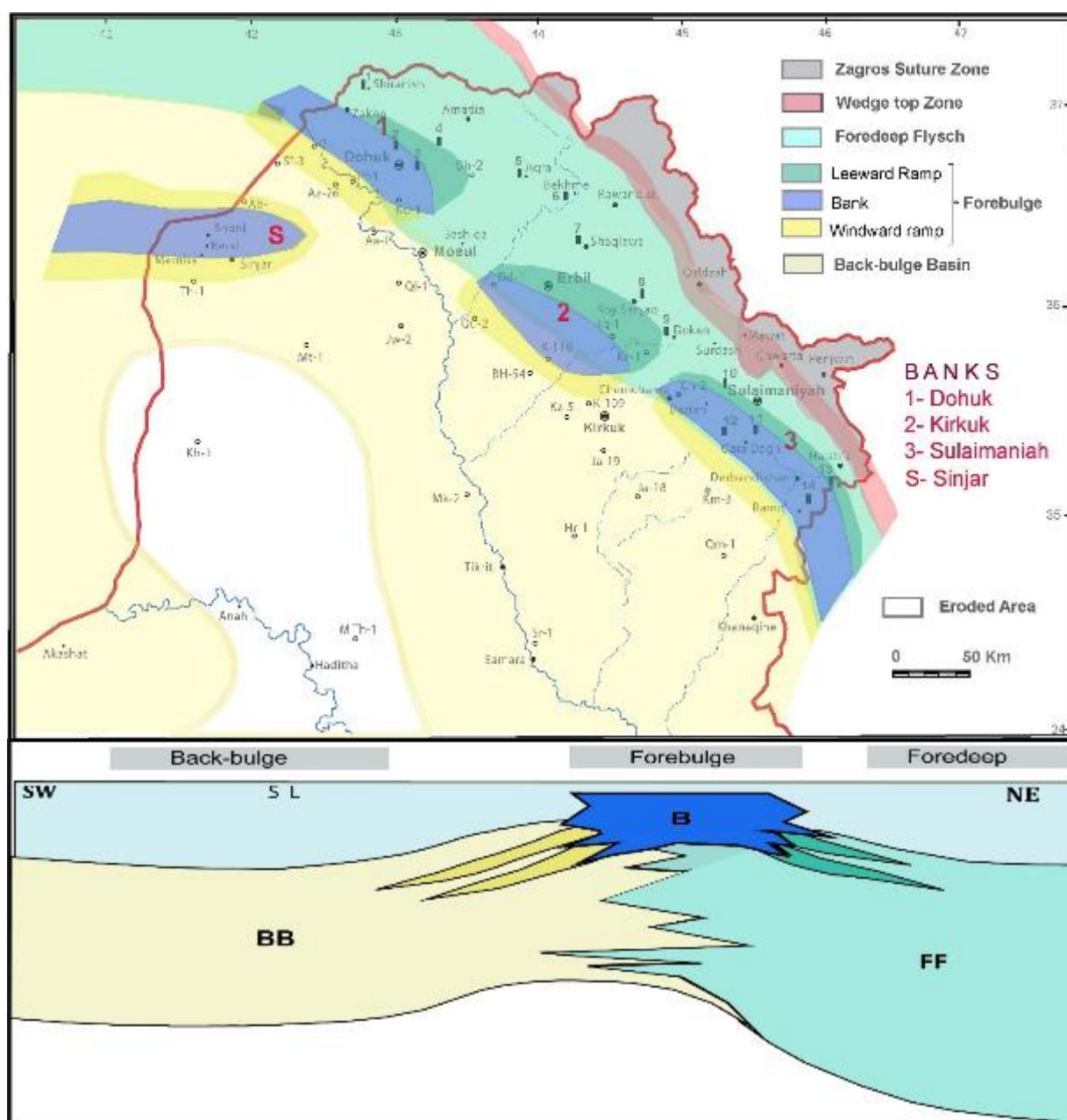


Fig. 9. Paleogeographic map and a schematic NE-SW cross-section of the Paleogene Zagros Foreland Basin of north Iraq during the Late Thanetian- Ypresian time of a bank- ramp development stage. (BB- Back-bulge basin, FF- Foredeep Flysc, B- Bank)

4.2.2. Early bank development (Thanetian)

During the Thanetian time, and as basin compressional tectonics continued, the basin flexural wave was contracted, whereby the foredeep zone became deeper and the forebulge area simultaneously, raised up into an intra-basinal high with shallow sea bottom. At this time the corallgal-foraminiferal carbonate reef-shoal banks were initiated and grew over parts of the newly evolving forebulge area (Fig. 8). These carbonate banks are represented by the bioclastic limestone of the Sinjar Formation. The time at which these carbonates were started might extend earlier into the Late Selandian, however, most studies suggest Thanetian is the early occurrence as shown in Fig. 4 above. This and older age assignments of these carbonate banks had been determined from the Sinjar area, which is not related to the forebulge development, but represents a tectonically isolated and inverted basin.

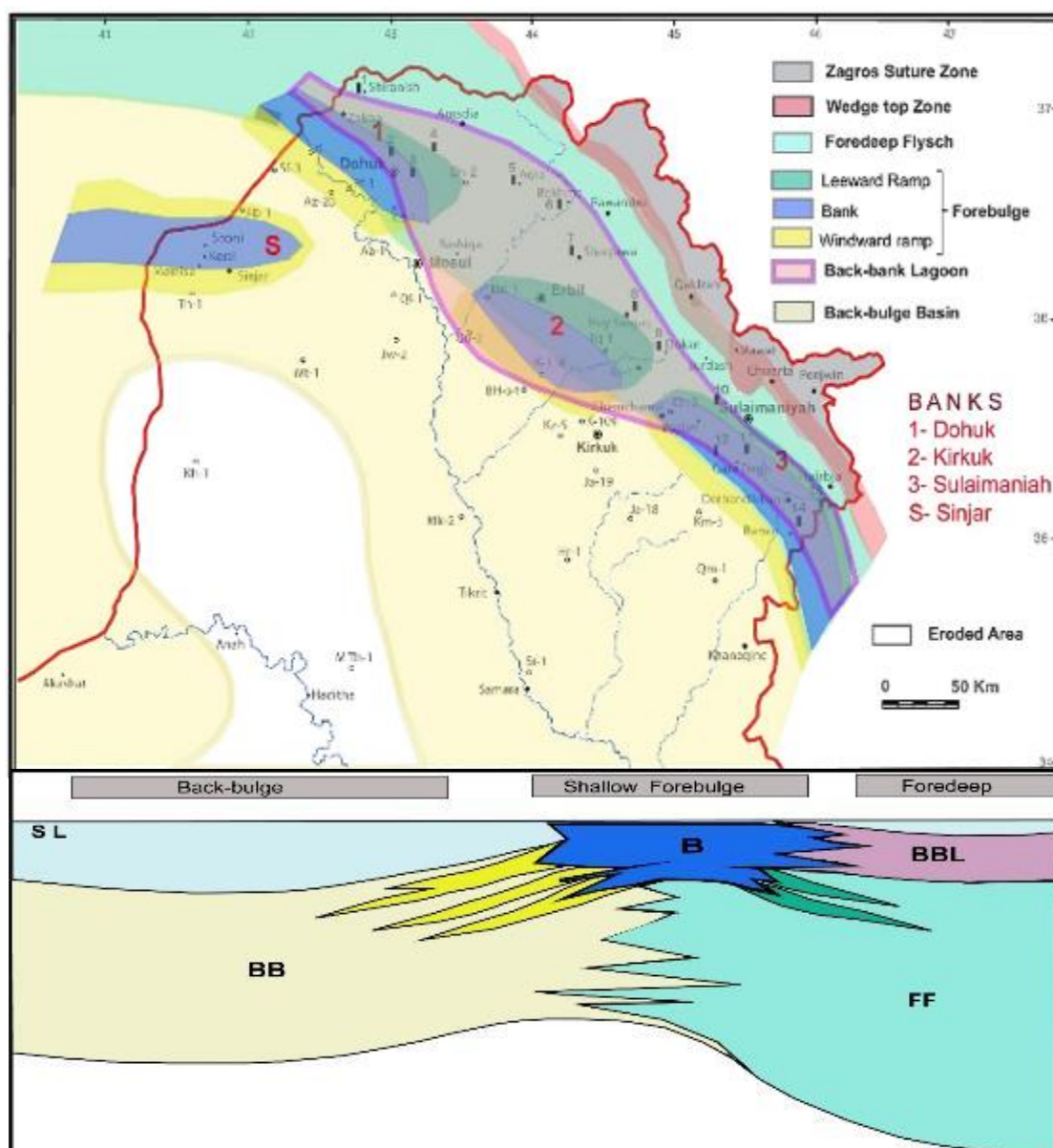


Fig. 10. Paleogeographic map and a schematic NE-SW cross-section of the Paleogene Zagros Foreland Basin of north Iraq during the Late Ypresian to Early Lutetian time of a lagoonal development stage of the Khurmala Formation. (BB- Back-bulge basin, FF- Foredeep flysc, B- Bank, BBL Back-bank lagoon)

The carbonate bank facies of the Sinjar Limestone Formation are typically recognized by many localities such as Sinjar, Dohuk, Bekhme, Dokan, Daratw, Branan, Sagirma, Sartaq Bamo, Derbandikhan, and Serwan Valley. It was also reported from wells such as Aa-1, Dd-1, Tq-1, K-116, CH-2, and KC-1. It forms isolated carbonate bodies of three important and localized areas distributed over the forebulge zone: Dohuk, Kirkuk and Sulaimaniyah bank (Al-Qayim, 2023) (Fig. 9). These carbonates show variability in thickness, local facies type and altogether form the inner ramp facies of a bank-ramp association.

4.2.3. Bank-ramp development (L. Thanetian- Ypresian)

Limestone fingers from the bank limestone are often intercalated with the upper part of the Kolosh Formation in a northeastwards direction. Such a relation is recognized at localities like Haibat Sultan, Daratw, Dokan, Branan Mt., Sagirma Mt., Sartaqi Bamo, and Serwan Valley, as well as in the subsurface sections of well Rf-1, Aa-1, Kd-1, Tq-1, and KC-1. Most of these fingers represent part of the leeward ramp facies (Al-Qayim, 2023). On the other hand, the Sinjar limestone is reported to have been interfingering with the Aaliji marlstone in a southwestward direction, which is reported from many subsurface sections such as well Az-26, Qu-2, Dd-1, K-116, K-109, and Ch-2. These interfingering relations represent the windward ramp facies (WRF) (Al-Qayim, 2023).

The ramp facies grew on both sides of the forebulge especially when the slope became gentle enough for the ramp depositional setting (Fig. 9). In most cases, the bank facies usually overlay the ramp sediments indicating regressive development of the sequence. The WRF shows evidence of early development as compared to the Larger Benthic Foraminifera (LRF) of the foredeep area. This is probably due to a gentler slopping of the southwestward margin of the back-bulge zone as compared to the steepest margin toward the foredeep trough. The ramp facies development have most probably took place after bank development during Late Thanetian to Ypresian time.

4.2.4. Lagoonal carbonate development (L. Ypresian –E. Lutetian)

As basin shoaling progressed, the banks grew over the forebulge and expand laterally to an extent that establish an efficient barrier separating the shoaling foredeep from the open sea of the back-bulge area. At this stage, the foredeep area especially the part next to the bank body develops an extensive lagoon with shallow marine carbonates and siliciclastic intercalations (Fig. 10). The lagoonal facies show cyclicity and argillaceous admixture which indicate strong eustatic effects (Al-Qayim, 1995a; Barzani and Al-Qayim, 2019; Al-Qayim, 2024). The lagoonal facies is often intermixed with the bank facies indicating the close relations. The lagoonal facies is reported from many outcrop and subsurface sections over most parts of the basin, especially the foredeep area, indicating extensive lagoonal developement (Al-Qayim, 2023).

4.2.5. Lagoonal dolomitization (Khurmala Fm.) (Late Ypresian- E. Lutetian)

At a later time of the lagoonal development and in a certain part of the basin the lagoonal limestone was subjected to extensive dolomitization, forming lagoonal dolostone of the Khurmala Formation (Fig. 11). The lagoonal dolostone sequence is consisting of thick to medium bedded, fine to medium crystalline dolostone alternate with thin mudstone and shale in a cyclic fashion. Relics of the original facies indicate subtidal, lagoonal, and tidal flat environments (Al-Qayim, 1995a; Barzani and Al-Qayim, 2019; Al-Qayim, 2024). The dolostone of the Khurmala Formation distributed at limited area within the lagoonal carbonate (Al-Qayim, 2023). This indicates that the intensive dolomitization seems to affect certain parts of the lagoonal carbonate. This part is found to be confined to an area of a triangular shape with corners passed by Amadia, Bekhme, and Kirkuk structures (Al-Qayim, 2023; 2024).

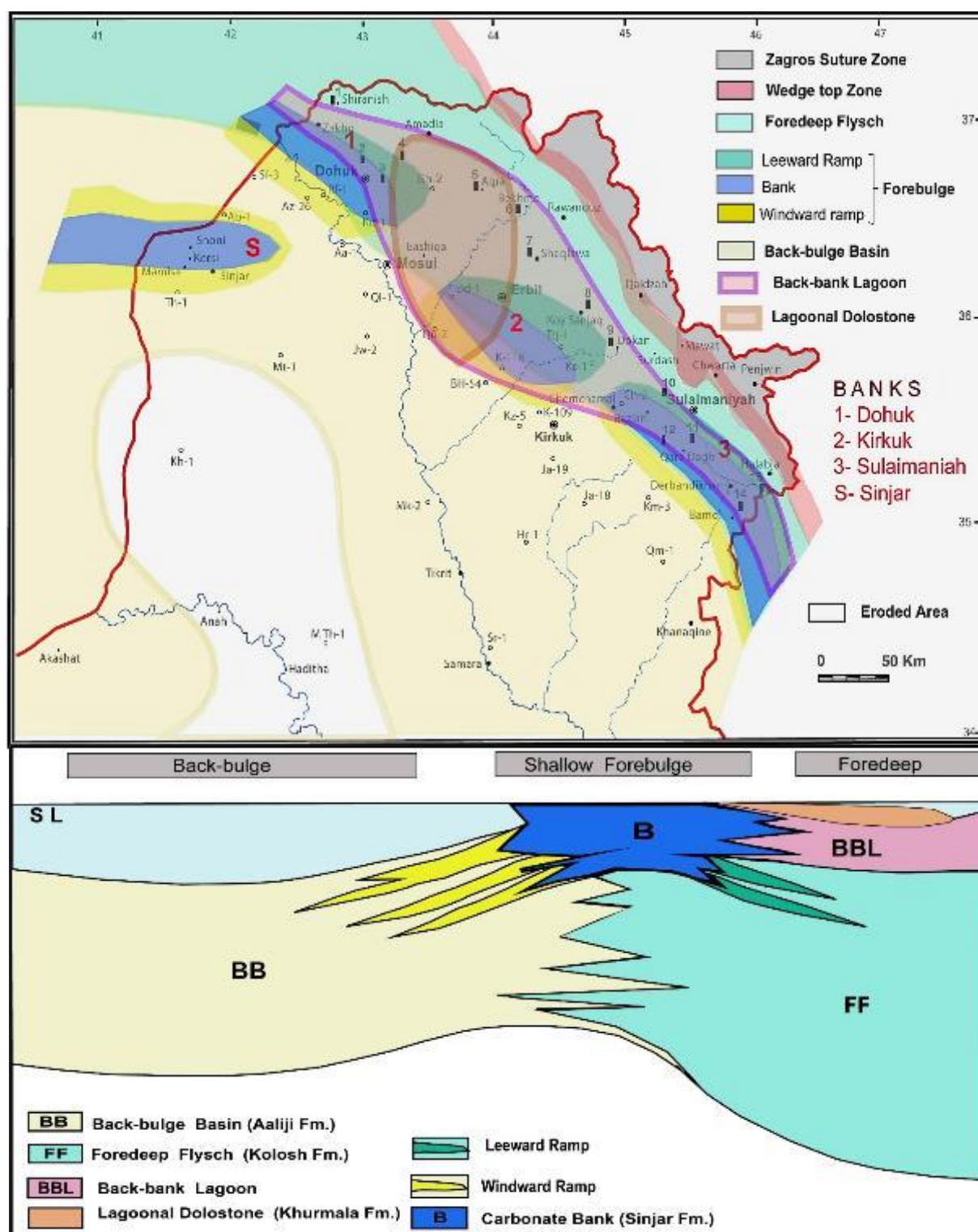


Fig. 11. Paleogeographic map and a schematic NE-SW cross-section of the Paleogene Zagros Foreland Basin of north Iraq during the Early Lutetian time of a lagoonal dolomitization stage of the Khurmala Formation. (BB- Back-bulge basin, FF- Foredeep flysch, B- Bank, BBL- Back-bank lagoon)

5. Discussion

The chronostratigraphic development of the Paleogene carbonate banks explains several points regarding the basin's history. The newly initiated forebulge of the basin had a new trend at the beginning

of the Paleogene, which is different from the forebulge of the Upper Cretaceous Zagros foreland basin. These changes reflect different stages of basin history, which indicate different stages of the mechanism of the basin subsidence. Foreland basin subsidence is characterized by frequent episodic events in response to the foreland migration of the tectonic load coupled with a curved flexural profile (Xie and Heller, 2009). Such events could be responsible for the foreland shifting position of the forebulge from the Upper Cretaceous to the Paleogene.

The second point is that the basin forebulge was incipient at the beginning of the basin history. It was immature and deeply submerged during the pre-Thanetian period as shown in Fig. 3 above. According to the chronostratigraphic assessment of the sequence this situation lasted through most of the Danian and the Selandian. The mature forebulge become shallow and forms an effective barrier by the Thanetian time. At this time, conditions become suitable for organic buildup with regard to water depth and associated ecological conditions leading to the flourishment of the carbonate banks.

The third point is that the development of the ramp depositional setting on both sides of the forebulge area has occurred. The elevated forebulge area forms an intra-basinal high with carbonate banks on top and ramp settings on both sides. The ramp sedimentation is demonstrated by the mixture of bank bioclastic sediments with the foredeep sediments of the Kolosh Formation, forming the leeward ramp facies. On the other side, the intercalation of the bank bioclastic sediments with the back-bulge sediments of the Aaliji Formation, forms the windward ramp facies. Both ramp facies had been developed during period associated with the growth of the carbonate banks, which is estimated as Late Thanetian through the Ypresian. Biostratigraphic dating of ramp nummulitic limestone samples from many localities shows that these ramp sediments belong to the Ypresian time (Al-Siddiki 1968; Lawa 2004). However, the ramp facies on the windward side seem to be established earlier than the other side of the leeward ramp. This is inferred from the intercalations of ramp facies with the middle and upper parts of the Aaliji Formation sequence of the back-bulge area (Al-Siddiki 1968; Al- Banna et al., 2014; Hassan et al., 2022). On the contrary, the intercalations of the ramp facies with the Kolosh Formation at the foredeep zone are always characterized the upper part of the formation (Bellen et al., 1959; Al-Qayim et al., 1989; Surdasy, 2001; Daod, 2009; Tamar-Agha et al., 2014; Al-Dulaimi and Al-Dulaimi, 2017). The explanation for this timing difference is related to the nature of the forebulge geometry. As basin fluxing proceeds with compressional tectonics, the slopes on both sides of the forebulge are not equal. The forebulge leeward slope towards the foredeep area is steeper as compared to the windward slope towards the back bulge area (DeCelles and Giles, 1996; DeCelles, 2012). This difference in sloping made the windward gentler slope area to initiate ramp setting earlier. The steep leeward slope of the forebulge became suitable for ramp setting after filling and shoaling of the foredeep area later in time.

The fourth point is regarding the basin shoaling event, where the subsidence rate is reduced, especially at the foredeep area where shallow carbonate lagoonal sediments become dominating the back-bank area and turbidite siliciclastic sediments influx rate drops down. Dating of the lagoonal sediments from Sinjar Formation at Sulaimaniyah area is estimated to be of Ypresian time (Al-Siddiki, 1968; Daod, 2009; Salih, 2013; Lawa and Mardan, 2019). At certain areas of this lagoonal conditions were suitable for early to late diagenetic dolomitization. The origin of this dolomite is believed to be developed during the early to late diagenetic stage (Omer et al., 2014), due to a possible combined effect of lagoonal reflux flow, and sabkha evaporation mechanisms (Barzani and Al-Qayim, 2019). At the end of this stage, the lagoonal limestone and/or dolostone, become increasingly intercalated with marly, buff to gray continental shale.

The basinal sediments of the Aaliji Formation seem to continue through most of the Paleocene up to the Ypresian age as shown in (Fig. 7) above. A high-resolution biostratigraphic study of the Aaliji Formation sequence at the Dohuk area shows that it is represented by thin unit below the Kolosh Formation and dated by the complete Danian stage (Bamerni et al., 2020). Other studies show that it extends through the Paleocene and most of the Ypresian (Fig. 7) above. However, an important

foraminiferal hiatus is reported between the formation and the overlying basinal Jaddala Formation in the Kirkuk field, which extends for (4) million years (Al-Banna et al., 2014). This study shows that the Aaliqi Formation ranges through most of the Paleocene.

Argillaceous material become increasingly overwhelming upward the sequence and is finally replaced by the continental red siliciclastic sediments of the Gercus Formation. These molasse sediments cover the whole area of the foredeep and the forebulge zones of the basin during the Lutetian time. The back bulge area to the southwest remains as an intrashelf basin and continues to receive the pelagic globigerinal marlstone sediments of the Aaliqi Formation mostly during lowstand stage.

6. Basin Alternative Petroleum Play

6.1. Introduction

The stratigraphic and tectonic evolution of a sedimentary basin is controlling the distribution of the potential source, reservoir and seal lithofacies. The study of factors which controlling the sedimentary basin formation and filling history helps in determining the locus and characteristics of hydrocarbon reserves (Kordi, 2019). Petroleum systems of the foreland basin occur within unstable tectonic settings and rapid rates of sedimentation. Source rocks often yield Type III kerogens. Their gas-prone characteristics may be enhanced by the formation of biogenic gas. Hydrocarbon migration takes place along both horizontal and vertical routes. Structural traps are plentiful (Perrodon, 1995). The type of petroleum plays to be expected in a foreland basin were discussed by Magoon (1988). The different elements of these plays, migration paths, and possible entrapment areas are shown in Fig. 12. One of these areas is the stratigraphic pinch out around the forebulge area.

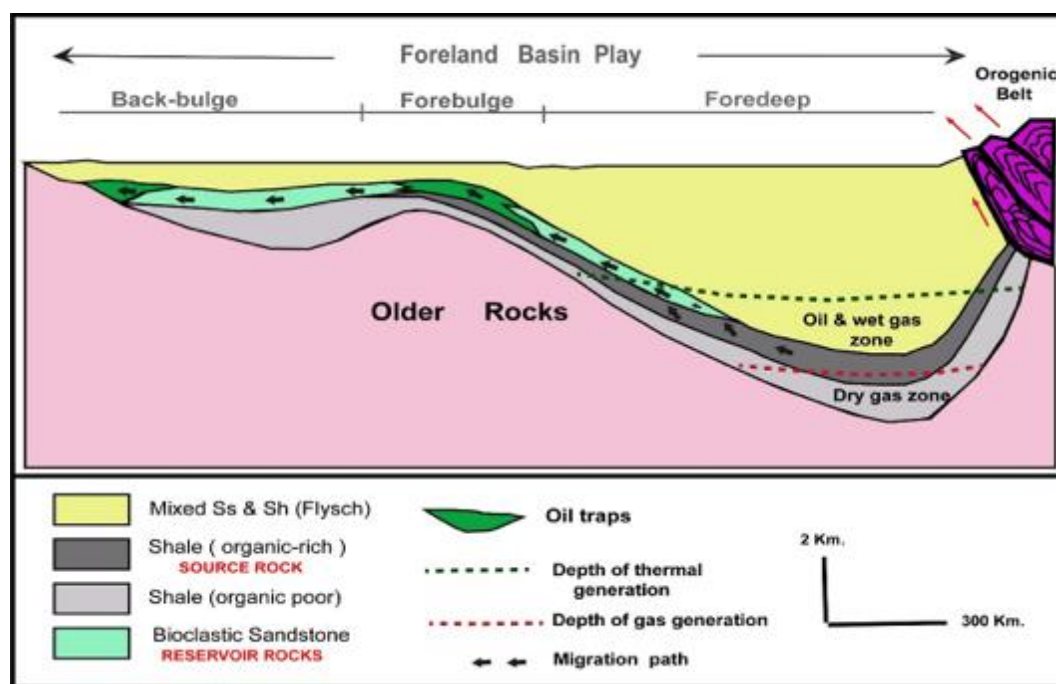


Fig. 12. Hypothetical cross section of a foreland basin showing essential elements of petroleum play, migration path, and potential area of hydrocarbon accumulation, (adopted after Magoon, 1988).

Kordi (2019) showed that the Late Cretaceous- Late Miocene petroleum systems (Late convergent and collision phase of the Zagros basin) host the largest oil reserves in the area. This sequence includes the studied Paleogene sequence of the carbonate banks. Hydrocarbons accumulated in similar settings worldwide are reported by (Loucks et al., 1998; Racey, 2001; Vennin et al., 2003; Beavington-Penney et al., 2008), which prompted the interest of the possible petroleum potential of these carbonate bodies and the associated units as an alternative play within the Zagros foreland basin. A case study from the

Sufaya oil field of NW Iraq has similar stratigraphic setting and points towards potential bank ramp facies.

The major Tertiary discoveries lie beneath the Middle Miocene Fatha Formation cap rock, and Paleogene reservoirs with light oil and gas are dominant around Kirkuk. Hydrocarbons in Cenozoic reservoirs in Iraq are, now, thought to be mainly to have migrated directly from mature Cretaceous and Jurassic source rocks into Eocene -Lower Miocene carbonates, which are sealed by middle Miocene evaporates (Aqrawi et al., 2010).

The Paleogene Aaliji Formation may have been a source potential (Jassim and Al-Gailani, 2006). However, (Baban and Ranyayi, 2012; Baban, 2014) shows that the Aaliji Formation has low Total Organic Carbon (TOC) and has proven to be immature to early mature source rock. The Sinjar Formation is considered the oldest Paleogene reservoir in the Kirkuk oil Field. The Paleogene Kolosh Formation siliciclastic and carbonate sediments may locally have reservoir potential (Jassim and Al-Gailani, 2006). The Thick evaporitic beds of the Fatha Formation provide a top seal for major discoveries of the Zagros foreland basin (Goff et al., 1994).

6.2. Sufaiyah Oil Field

6.2.1. Introduction

Sufaiyah oil field is located in northwestern Iraq close to the Syrian border, about 100km southwest of Zakho and 95 km. within the foot-hill zone of north Iraq (Fig. 13). The general information given here is based on the review of the Atlas of Iraqi Oil Fields by (Iraq Petroleum Potential, 2003).

The field was discovered in 1974 and brought downstream in 1984 by the Iraqi National Oil Company (INOC). The field has 39 drilled wells (28 of them are producing wells). Production was shut down in 1991 due to the war circumstances.

The field has proven reserve oil of 210 Mmbo, and proven gas reserve of 60 BCF. The field production comes from four potential reservoirs including the Cretaceous fractured carbonate reservoirs of Shiranish, Kometan, Gir Bir and the Triassic Kurra Chine limestone Formation (Fig.13). However, production comes mainly from the well-developed Kometan reservoir.

During the development of the field, oil shows well reported from the Eocene Sinjar Formation, which occurs as a tongue of bioclastic limestone within the Aaliji Formation (Fig. 14). This relation encouraged the company to further investigate the possible potentiality of the formation (Al-Hadidi, 2015, personal communication). This triggered the interest of the author to seek the possibility of these limestones within the Aaliji marlstone to make an alternative petroleum play within the Zagros foreland basin.

The field anticlinal structure crosses the borders into Syria forming the important field of Souidiya. The closest field is Mushorah to the northeast and Ain Zala field to the southeast. The structure is a subsurface asymmetrical double plunging fold with NW – SE axis. It is 11 km long and 3.5 km wide (Al-Hamdani and Al-Ajeli, 2005). The only exposed units are outcrops of the Fatha Formation.

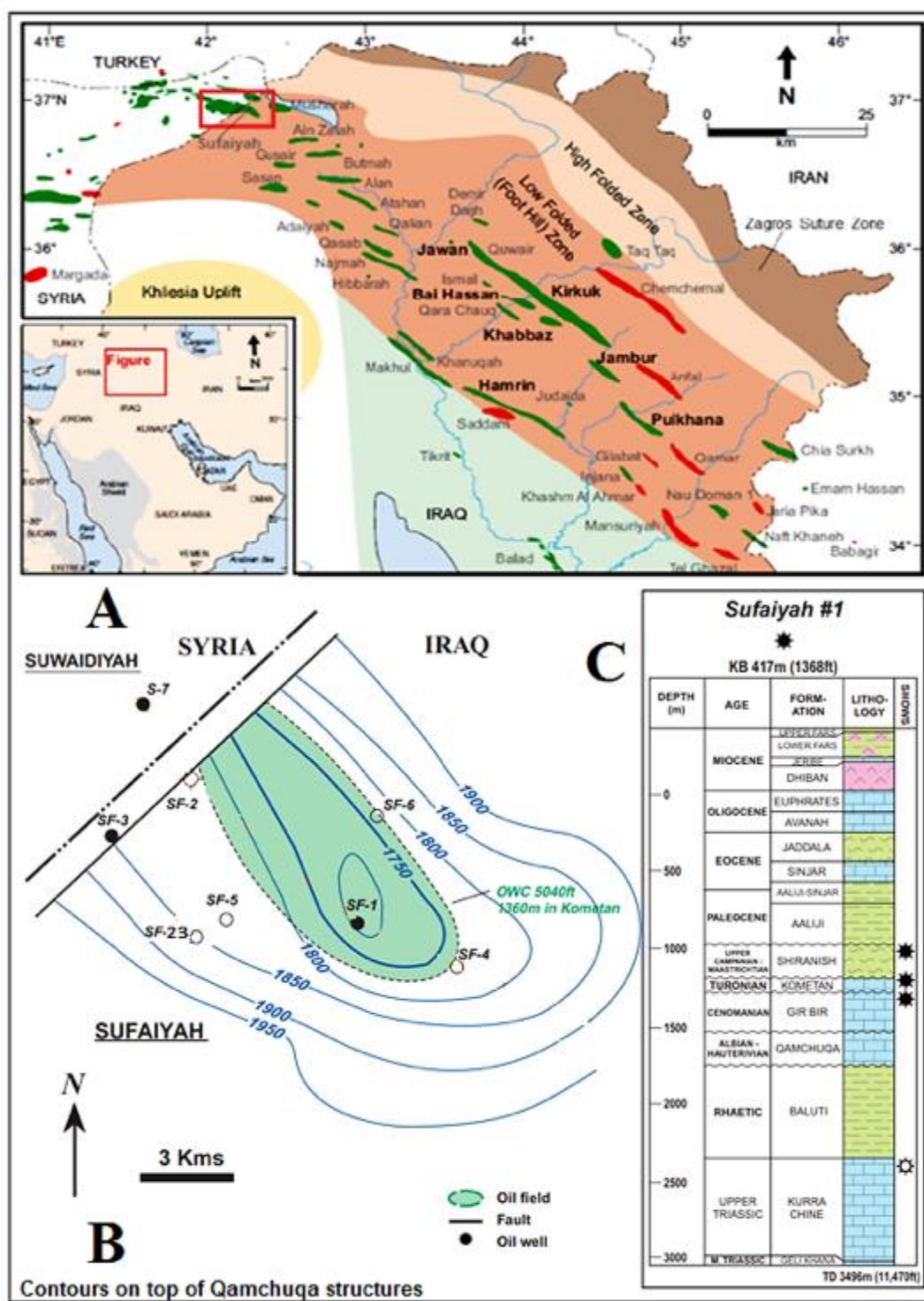


Fig. 13. (A) Location map of Sufaiyah field with respect to other fields of north Iraq. (B) Structural contour map of the field showing well location. (C) Stratigraphic column of well Sufaiyah – 1. (A from Al-Qayim et al., 2010, B & C from Atlas of Iraqi oil fields, 2003).

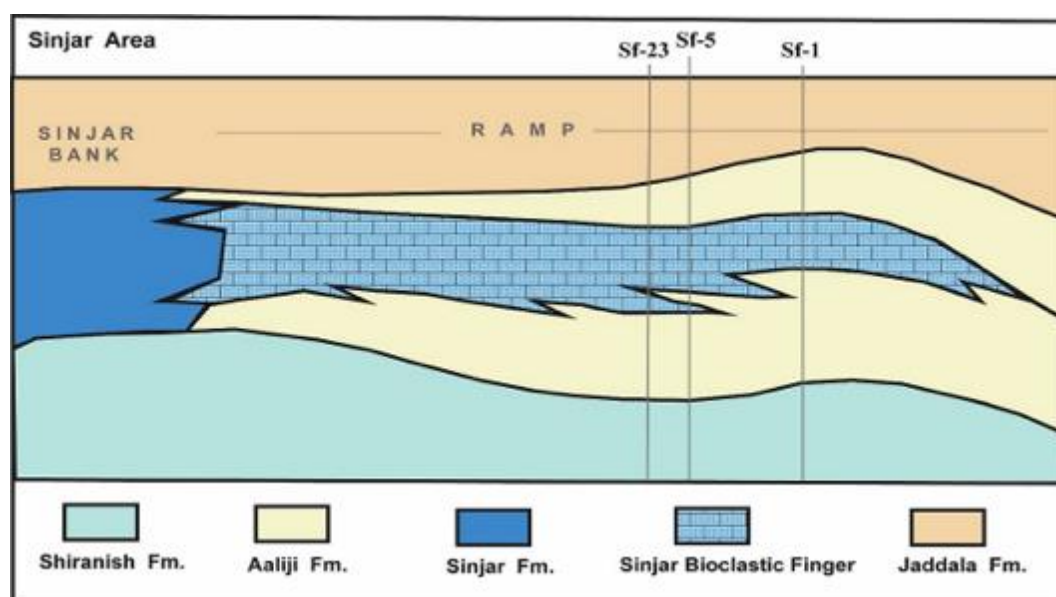


Fig. 14. Stratigraphic cross-section of Sufaiyah oil field of northwest Iraq, showing inter-tonguing relationship between the ramp facies of Sinjar Formation and the basinal marlstone of the Aaliji Formation

6.2.2. Stratigraphic relations

Stratigraphic data from three wells of the Sufaiyah oil field (Sf-5, Sf-23, and Sf-1) shows the association of an important tongue of Sinjar limestone inside the Aaliji Formation as demonstrated in Fig. 14. In this diagram, the cross-section is oriented almost in north-south trend, where the Sinjar Formation at Sinjar Mt. is represented by the thickness of 176 m, massive limestone of algal reef facies, lagoonal miliolid facies, and shoal nummulitic facies (Bellen et al., 1959). At the Sufaiyah oil field, the Sinjar Formation became a bioclastic limestone tongue that extended northwards into the basinal marlstone of the Aaliji Formation. The thickness of the tongue ranges from (97m.) at (Sf-5) and (68m.) at (Sf-1). The Sinjar tongue is characterized at the Sufaiyah field by thinning-upward limestone beds, which alternate with argillaceous marlstone of the Aaliji Formation. The limestone beds are of grainstone to packstone bioclastic microfacies. Grains are mainly skeletal and dominated by *Nummulites*, *Discosyclina* in addition to *Alveolina*, *Globogerina* and rotalids (final well reports, FWR, 1979). These limestone beds of the Sinjar Formation are intermixed with Aaliji Formation argillaceous sediments at Sufaiyah field. These intercalations are interpreted as the middle to outer ramp facies when compared to the situation in other cases (Buxton and Pedly; 1989, Vennin et al., 2003; Adabi et al., 2008; Taheri et al., 2008; Zamangni et al., 2008; DiCarlo et al., 2010; Hontzsch et al., 2011; Zohdi et al., 2013; Hadi et al., 2019; Martin-Martin et al., 2020; Vrsic et al., 2021).

6.2.3. Petroleum play

A potential reservoir unit had been anticipated from the forebulge carbonate banks of the Zagros foreland basin, which are represented by the middle ramp bioclastic grainstone to packstone limestone fingers. Such ramp deposits are reported from Sf-3 as Nummulitic- *Dicocyclina* bioclastic limestone fingers of the Sinjar Formation within the upper part of the Aaliji Formation (Khaddouri, 1978). Strong storm effects will eliminate fine argillaceous material and enhance intergranular porosity. The minor burial cementation would be anticipated for such a moderate water depth (Burchette and Wright, 1990). The early dolomitization effect would be limited due to the strong agitation and open sea environment (Tucker, 1993). Burial within fine-grained basinal sediments would help preserve the impervious sediments required to hold the oil in place. Fracturing is expected to be pronounced as folding traps

initiated with the Pliocene deformation phase of the Zagros orogeny. Streaks, nodules and lenses of bitumen were reported in the Sinjar Formation units at Syrian equivalent fields, and at the bottom of the Aaliji Formation (Bellen et al., 1959)

The neighboring basinal mudstone of the Aaliji Formation could furnish the potential source rock for these bioclastic fingers, although the maturity (TOC <1%) are still below the required level (Baban, 2014). Updip lateral migration would be immediate and natural as it is postulated around slopes of the forebulge area (Magoon, 1988). In the case of Cretaceous oil vertical migration, the bioclastic fingers of the middle ramp would be the immediate reservoirs on the way through, with facilities of a major faults avenue. Sealing is stratigraphically, provided either by the surrounding Aaliji mudstone or by the basinal marlstone of the overlying Jaddala Formation (Fig. 14). All these elements can provide the essential requirements of an alternative hydrocarbon play for the field and the surrounding areas.

7. Conclusions

Reviewing the stratigraphic data of the Paleogene carbonate banks of the Zagros foreland basin of northern Iraq from surface and subsurface sections reveals interesting results about chronostratigraphy of the sequence, basin paleogeography and evolution, which are summarized by the following points:

The biostratigraphic evaluation of the paleogene forebulge stratigraphic units indicate the following chronostratigraphy: Sinjar Fn. (E. Thanetian – L. Ypresian), Khurmala Fn. (Ypresian - E Lutetian), Kolosh Fn. (Daian-Thanetian), and Aaliji Fn. (Danian-Ypresian).

The evolution of the forebulge carbonate banks is discussed in terms of basin history. Five distinctive depositional stages were recognized including: a) Pre-bank, b) Early Bank Development, c) Bank-ramp Development, d) Back-bank Lagoon and e) the Lagoonal dolomitization stage.

A general chronostratigraphic trend in the growth timing of the forebulge carbonate banks is noticed. These carbonate units became younger in the southeast direction as continued into Iran. This trend indicates a diachronous growth of these banks from the northwest to the southeast. This can be linked to the diachronous growth of the forebulge itself, which is in support of the suggested oblique convergence of Arabia towards Eurasia.

The potentiality of the studied sequence is discussed with reference to the carbonate banks and associated ramp sediments as an alternative petroleum play using the Sufaiyah oil field northwest of Iraq as a case study.

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