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Sequence stratigraphic investigation of the Early Miocene Formations in the Zagros Folded belt using wireline well logs analysis

Devan Othman Hussein[1*]

[1] *Department of Geology, College of Science, University of Sulaimani, Sulaimani, Kurdistan region- Iraq*
**Corresponding author's e-mail: devan.hussein@univsul.edu.iq*

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Abstract

Based on the available core sample description and wireline log analysis, sedimentary facies, microfacies and lithofacies interpretation are evaluated to determine the large scale architecture in the Early Miocene formations, from close to the contemporaneous Lower Miocene depositional margin of the Zagros basin, as represented in outcrop sections, to productive oil field within the Kirkuk embayment equivalents ca. 100 km to the south-west and west. Sequence stratigraphic methods of sedimentary log interpretation and log correlation are used to construct a model of the overall regressive and transgressive or combined transgressive to regressive character of each of the formations, thus providing an indication of the gross reservoir stacking patterns over this distance. Based on outcrop descriptions and wireline log data the Dhiban Formation is interpreted as a lowstand system tract (LST) of a third order depositional sequence, lying between the Euphrates Formation regressive parasequence set that could represent a highstand systems tract (HST) of a third order sequence and the transgressive parasequence set (third order transgressive systems tract, TST) of the lower part of the Jeribe Formation. Several higher order transgressive and regressive cycles are evident within the Dhiban Formation in the subsurface sections. The transgressive cycles within the Dhiban formation are associated with the carbonate layers. Yellowish grey, friable anhydrite is recognized in the Dhiban Formation at outcrop, and thick anhydrite of low gamma ray and high density readings was identified in the subsurface sections. This lowstand evaporite system filling the basin centre can be confirmed as the relevant model for the mixed carbonate-evaporite basin at the scale of a third order cycle.

1.1 Introduction

Sequence stratigraphy has developed from the original seismic stratigraphy methods of Van Wagoner et al. (1988), through the incorporation and integration of exposure analysis, core analysis and well log correlation over the last three decades (e.g. Van Wagoner et al., 1990). Sequence stratigraphy is a method of identifying facies relationships and stratal architectures within a chronological framework. A sequence stratigraphic framework consists of genetic units that are produced from variations of supply of sedimentation and accommodation generation within a framework of key stratigraphic surfaces (Vail et al. 1997; Van Wagner, 1995; Catuneanu et al. 2009). The genetic strata are characterized by different stratal stacking patterns and bounding surfaces, and include tracts of age-equivalent depositional systems (system tracts) (Catuneanu et al., 2009). Relative sea level changes govern changes in accommodation space, with parasequence patterns often related to specific periodicities of relative sea level change (Ketzer, 2002).

The standard model of sequence stratigraphy designates system tracts, which extend from basin margin to deep water that are dependent on sea level changes, including lowstand, transgressive and highstand system tracts. In this classic model, the lowstand system tract represents the depositional sequence produced when sea level falls below the level of the shelf margins (in the case where a type 1 sequence boundary is identified). The transgressive system tract develops when sea level rises above the old shelf margin and the depositional setting moves landward. The highstand system tract develops when sea level continues to rise or remains high above the old shelf margins and depositional facies belts move seaword. The maximum flooding surface separates the transgressive and highstand systems tracts and their non-marine correlative surfaces. The classic triple systems tract model has sequence boundaries defined at the base of each lowstand systems tract (Van Wanger et al. 1988; Schlager, 1998, 1999, 2002).

Schalger (2005) outlined relative rates of sediment supply and accommodation production associated with the system tracts; as an instance the highstand system tract develops when the rate of sediment supply is more than the rate of accommodation creation, whereas the transgressive system tract develops when the rate of sediment supply is less than the rate of accommodation creation.

The original sequence stratigraphic model has been modified by various authors, the resulting versions being represented in Figure 1 and Table1. The depositional sequence II model uses the onset of sea-level fall as the sequence boundary. In contrast, the depositional sequence IV model identifies four systems tracts including a falling stage systems tract, with a sequence boundary that conforms to the boundary between the falling stage systems tract and the low sand systems tract (Figure 1).

(Vail et al. 1997; Van Wagner, 1995; Catuneanu et al. 2009). The genetic strata are characterized by different stratal stacking patterns and bounding surfaces, and include tracts of age-equivalent depositional systems (system tracts) (Catuneanu et al., 2009). Relative sea level changes govern changes in accommodation space, with parasequence patterns often related to specific periodicities of relative sea level change (Ketzer, 2002).

1.2 Geological setting and stratigraphy

The study area is situated in the Kurdistan region, geographically located in the northern part of Iraq and tectonically within the Low Folded Zone of the Iraqi main tectonic segments (Figure 2).

The outcrop descriptions and log data sets used in this work was collected from the Kurdistan region, which placed in the Azhdagh and Mamlaha anticlines (Figure 2) in the low folded zone. Five outcrop sections of the Jeribe Formation and the Euphrates Formation were chosen at Darzila, Awaspi, Timar, Mamlaha, and Pungala, and well data was collected from 10 drilled wells in the Kormor, Bai Hassan, Khbaz, Pulkhana, and Hamrine fields of the low folded zone (see Figure 2 for location).

Hussein et al., (2017) Investigated stratigraphy of the study area at outcrop sections. The Euphrates Formation is underlain by conglomeratic layers and reefal limestone of the Oligocene Anah Formation. The reefal facies of the Anah Formation were only observed in one of the studied outcrops (Darzila section) together with paleosol. However, the basal conglomeritic layer was observed at the other four outcrops. The Euphrates Formation is separated from the overlying younger Jeribe Formation by the Dhiban Formation. The Dhiban Formation consists of laminated to massive anhydrites with halite occurring locally at its base and has a maximum thick- ness of 173 m (Al-Juboury et al. 2007; Aqrawi et al. 2010).

The Jeribe Formation is of Burdigalian age and consists of bedded (1–2-m-thick beds) recrystallized and dolomitized limestones. The Euphrates and Jeribe Formations cannot be differentiated in the field when the intervening Dhiban Formation anhydrites are absent. The red claystone of the Fat ha Formation overlie the Jeribe Formation (Bellen et al. 1959).

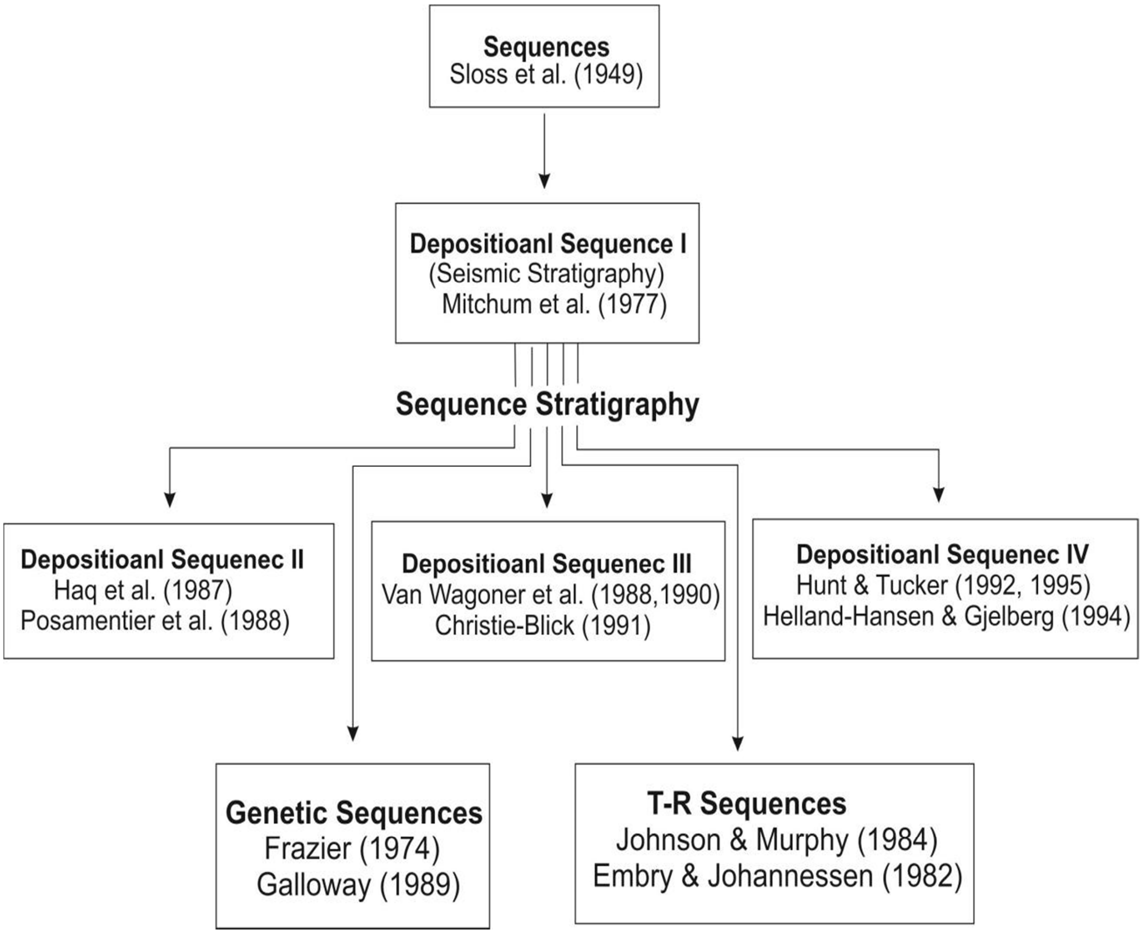


Figure1. Sequence stratigraphic models (Catuneanu, 2006 and references there in).

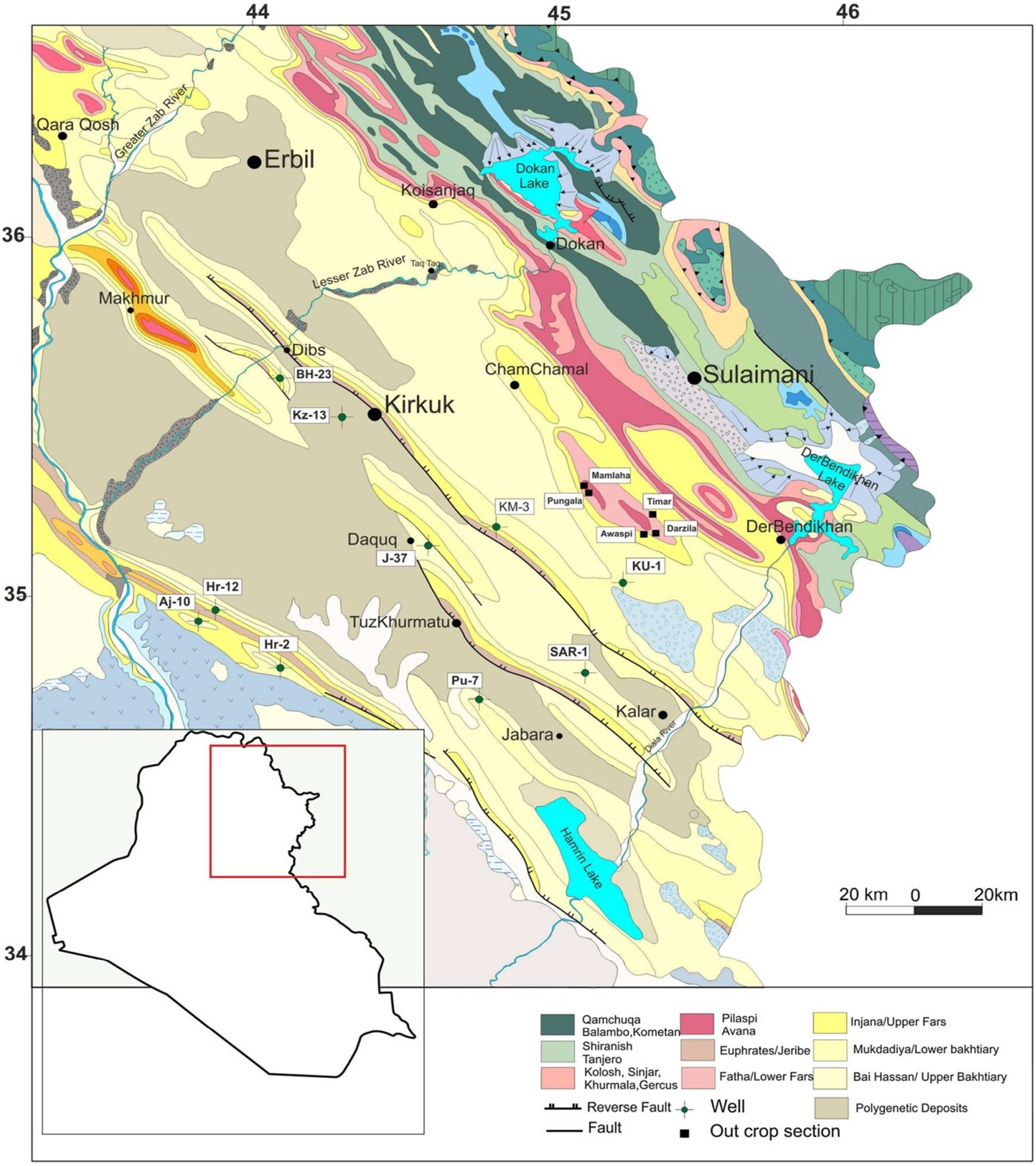
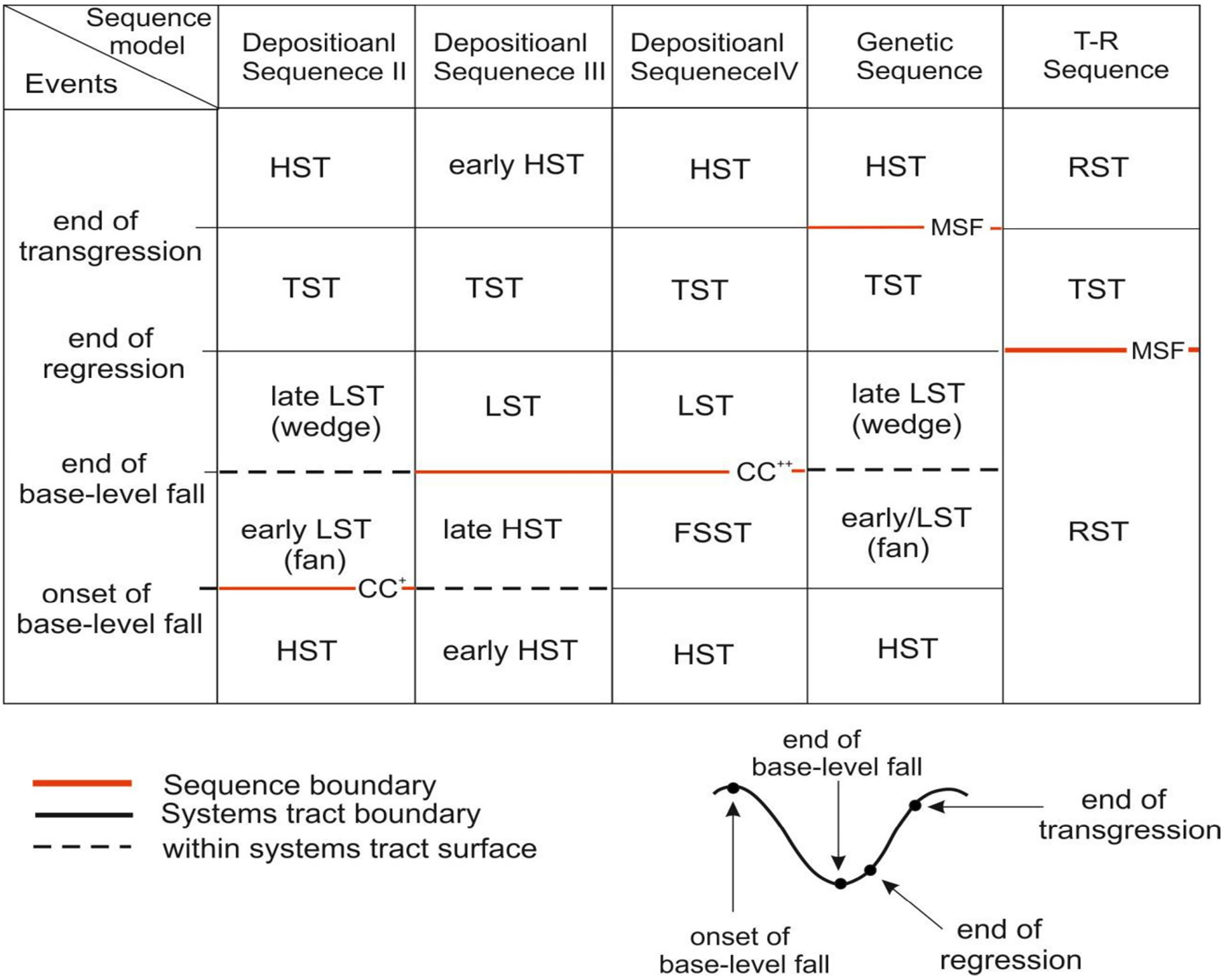


Figure 2 Geological map of Kurdistan region and northeast of Iraq shows the selected fields, blocks, and outcrop section of the study area. Modified from Sissakian et al. (2000).

Table 1 Sequence stratigraphic models, including nomenclature of system tracts and timing of sequence boundaries (Catuneanu, 2006 and references). LST: lowstand system tract; TST: transgressive system tract TST; HST: highstand system tract; FSST: falling-stage system tract; RST: regressive system tract; T-R: transgressive-regressive; CC*: correlative conformity; CC**: correlative conformity; MSF: maximum flooding surface: MRS: maximum regressive surface.



Events \ Sequence model	Depositioanl Sequenece II	Depositioanl Sequenece III	Depositioanl SequeneceIV	Genetic Sequence	T-R Sequence
	HST	early HST	HST	HST	RST
end of transgression				MSF	
	TST	TST	TST	TST	TST
end of regression					MSF
	late LST (wedge)	LST	LST	late LST (wedge)	RST
end of base-level fall			CC⁺⁺		
	early LST (fan)	late HST	FSST	early/LST (fan)	
onset of base-level fall	CC⁺				
	HST	early HST	HST	HST	

The dominant sequence stratigraphic models in the literature are those recognized by Van Wagoner et al. (1990) followed by Galloway (1989) and to a lesser extent by Embry and Johannessen (1992) (after Catuneanu, 2006). Generally, the main models that have been used in recent studies to characterize the sequence architecture of carbonate ramps are the genetic sequence and depositional sequence III models, for example Vaziri-Moghaddam et al. (2010), Embry et al. (2010),Pierre et al. (2010), John et al. (2011), Ghafur (2012) and Amirshahkarami and Karavan (2014).

1.3 Previous sequence stratigraphic interpretations of the Lower Miocene Formations

The Lower Miocene Euphrates and Jeribe Formations are underlain by Oligocene carbonate formations and overlain by either gypsum or a clay layer of the Fatha Formation (Hussein et al. 2017). Their sequence stratigraphic architecture has previously been interpreted by Sharland et al. (2004), Aqrawi et al. (2010) and Jassim and Goff (2006).

Al-Hietee (2012) interpreted fourth order cycles in the Lower Miocene formations (Euphrates, Dhiban and Jeribe Formations) in the Kirkuk area, from the Hamrine and Jambour wells. Highstand system tracts (HST) and transgressive system tracts (TST) were interpreted in the Euphrates Formation in both the Hamrine and Jambour wells. In the Jambour well the Euphrates Formation is interpreted to be underlain by a transgressive system tract (TST) of the Serikagni Formation, while in the Hamrine well an underlying unconformity is described without referring to its sequence architectural significance. In the Dhiban Formation two sequences were interpreted, the first sequence was recognized as a thick LST and thin layers of TST and HST, and the second cycle being defined by a TST and a HST. In the Jeribe Formation five sequences were identified in the Hamrine well and four sequences in the Jambour well. In both studied wells, the Jeribe Formation was interpreted as being overlain by a type two sequence boundary (SB2) with evaporitic layers of the Fatha Formation above.

Fourth order cyclicity was also interpreted in the Euphrates Formation in western Iraq at the Wadi Al-Baghdadi and Wadi Hjar sections by Al-Ghreri (2013). At both locations the Euphrates Formation is described as being bounded by a type one sequence boundary (SB1) at the bottom with Oligocene Formations below, and at the top with the Fatha Formation above. Furthermore, Grabowski et al. (2008) investigated the sequence stratigraphic architecture of Eocene–Miocene carbonates and evaporites in the subsurface of the northern Mesopotamian Basin. These were interpreted as the Euphrates Formation, with multiple higher-order cycles and surrounded by subaerial exposure and anhydrites, and with argillaceous limestone beds with anhydrite filling the basin during Dhiban Formation deposition (Figure 3). Aqrawi et al. (2010) explained that the Dhiban Formation fill inherited accommodation in the basin centre and it displays the final stage of infilling of the basin centre accommodation, while sometimes this formation does not occur between the Euphrates and Jeribe Formations. These anhydrites are dated to 21.0-22.2 Ma, establishing the Euphrates and Dhiban Formations to lie within the Late-Aquitanian, interpreted as a lower order lowstand, with the upper part of the early Miocene Jeribe Formation placed in a Late-Aquitanian HST of the basal Burdigalian sequence and bounded by regional subaerial exposure surfaces, while shoaling-upward parasequences stack gradationally and lap onto the margins of the basins.

Recently, Lawa and Ghafur (2015) identified a depositional super-sequence from the Late Aquitanian to the Early Burdigalian, including the Euphrates-Serkagni-Jeribe and Dhiban Formations in the Foothill Zone, although there was no detail provided of the Euphrates and Dhiban Formations. Sequence boundary type two (SBT2) was identified between Oligocene and Jeribe with placing of the isolated basin of the Jeribe Formation.

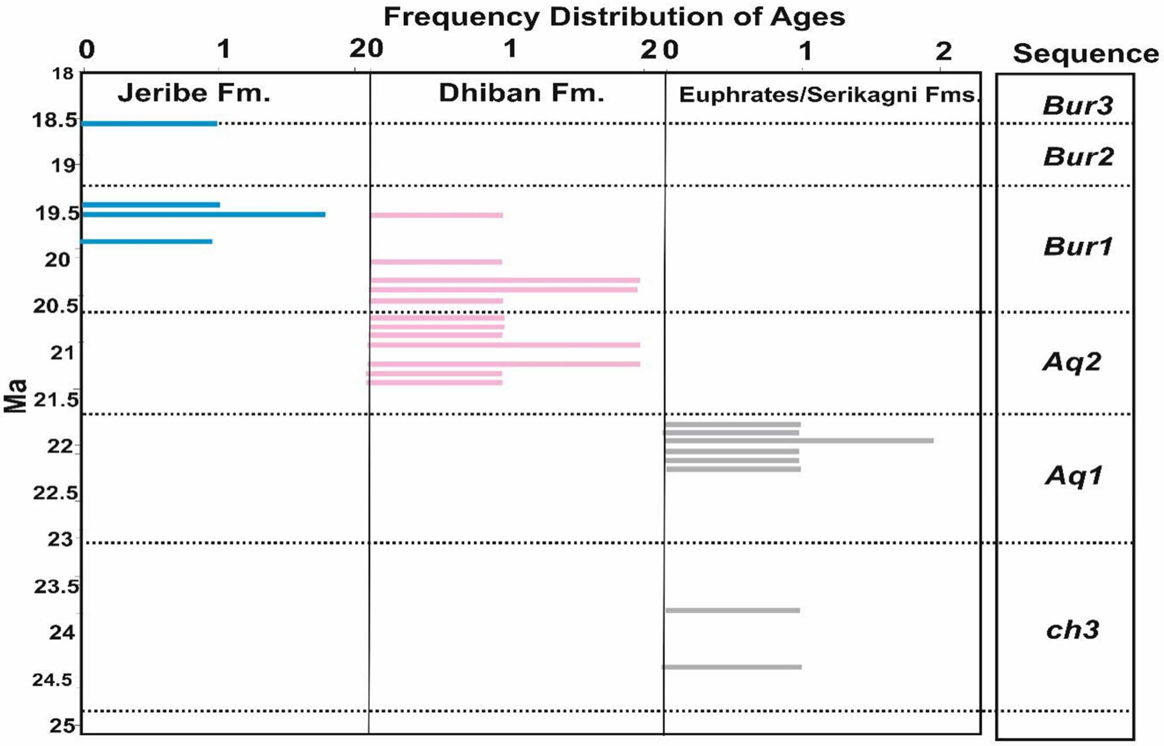


Figure 3 Age distribution of the Lower Miocene Formations with Identified sequences, after (Grabowski and Liu, 2008).

1.4 Interpretation of the sequence stratigraphy of the Lower Miocene Euphrates and Jeribe Formations

With respect to this study of the Euphrates and Jeribe Formations, it is noted that the prior depositional surface was exposed up-dip, as represented by the Limestone Conglomerate and Palaeosol Layer (Hussein et al., 2017). There is no evidence of incised valleys being present either at the top of these conglomerates or at the top of the underlying Oligocene Anah Formation carbonates. Therefore, no shelf break is evident at the base of the Euphrates Formation. Rather, the lateral continuity of stratal units that is evident from outcrop sections to wells ca. 100 km to the south-west or west implies that the Euphrates Formation was deposited over a very low angle dipping surface with neglible relief. Within both the Euphrates and Jeribe Formations, no lowstand systems tracts are identified as a result. Rather, transgressive-regressive cycles (T-R sequences of Johnson and Murphy, 1984; Embry and Johannessen, 1992) will be seen to characterize both the Euphrates and Jeribe Formations. This model for sequence stratigraphic interpretation will therefore be used in this study.

Sedimentary logging, sedimentological facies characterization and thin section studies have been used to analyse the sequences and sequence boundaries of the Lower Miocene formations (Hussein et al. 2017), in addition to wireline well log interpretation and correlation combined with sedimentological interpretation of the core samples. The sequence stratigraphy of the Early Miocene Euphrates, Dhiban and Jeribe successions is interpreted from bottom to top. This complete stratigraphy is available in outcrop sections and some drilled wells, while in other wells only the Jeribe Formation and Dhiban Formation have been penetrated (Figure 4). The sequences and sequence boundaries of the Lower Miocene formations are analysed in each section, using the preferred model as it applies to surface sections and subsurface sections to correlate cycles and relative sea level changes.

1.4.1 Surface sections

The Lower Miocene Formations in the surface sections (Awa Spi, Darzila, Timar, Mamlaha and Pungala) are bounded by reefal limestone of the Oligocene Anah Formation below and the Middle Miocene Fatha Formation above the upper boundary. The lower boundary has the alluvial Limestone Conglomerate and Palaeosol Layer (Hussein et al. 2017) unconformably above the Anah Formation, with the marine Euphrates Formation overlying this and therefore separated from the conglomerates and palaeosols by a marine flooding surface. At outcrop, as represented by the Awa Spi section (Figure 6), the Euphrates Formation shows one shallowing-upward (shoaling-upward) package ~4.5 m thick (Hussein et al. 2017). Degraded remnants of Dhiban Formation evaporitic material overlie this single Euphrates cycle, and then another marine flooding surface is indicated by the overlying, initially fine-grained facies of the Jeribe Formation. The Jeribe Formation at outcrop is also in the form of a single shallowing-upwards cycle at outcrop (Figure 6) and is terminated by the first marine flooding surface at the base of the overlying Fatha Formation. The Jeribe Formation regressive package is ~6m in thickness. Because it is bounded at the base and at the top by marine flooding surfaces, it is appropriate to call this a parasequence. Whether each of the Euphrates and Jeribe parasequences may be a higher order sequence is discussed later, taking into account the more extensive cyclicity apparent in the subsurface.

1.4.2 Subsurface sections

The Lower Miocene successions are evaluated by sequence stratigraphic analysis of wireline well logs from six drilled oil field boreholes, two of which are adjacent to the surface sections (Figure 4). Gamma ray logs are used as the main tool to determine continuity of the main flooding surfaces, and then to indicate the vertical cleaning-up trends and hence go on to allow the interpretation of the lateral extent of the cycles in the subsurface. Gamma ray logs reflect the natural radioactivity in the formations, and are used to identify the clay content of the sedimentary lithologies, with highest values in fine-grained mudstones. A clean siliciclastic or carbonate rock will give a low gamma ray reading while fine-grained mudstones rich in clay minerals will give a high gamma ray reading. Generally, the gamma ray log is used to differentiate fine and coarse grain sediments (Rider, 2000 and Rider and Kenney, 2011).

The basic techniques for illustrating sequence stratigraphy from wireline logs are based on Rider (1996, 2000) and Rider and Kennedy (2011). Following their approaches, flooding surfaces are identified in the Early Miocene successions in the subsurface sections. Firstly, drilled wells with complete successions were examined, these being the HR2, HR12, JM37 and KM3 wells in Figure 5. Note that in the KM3 well, ~50m of relatively clean carbonate below a depth of 1620m is here re-interpreted (compared to the original well report and log interpretation) as being part of the relatively homogeneous Anah Formation due to its log character. In the PU7 well, some 35m of Jeribe Formation appears to have been logged above the thick Dhiban Formation interval, but the geophysical log records are incomplete above this, so it is likely that the log record has been truncated, losing the record for the uppermost part of the Jeribe Formation. Taking these uncertainties into account, lateral correlations have been made to try to represent and interpret consistent cycle variations of the Lower Miocene Formations. This sequence stratigraphic framework will then allow consideration of any reservoir heterogeneity from the North-East to the South-West part of the study area, within a framework of patterns of regressive and transgressive relative sea level changes. It is the variations in the gamma ray log patterns which are used to distinguish transgressive and regressive sea level changes. It is recognized, though, that these interpretations are not unique solutions. In particular, the presence of fine-grained mudstones in inner ramp lagoonal settings means that not all high gamma-ray values are likely to be deeper water facies. Where a progressive cleaning-up trend is evident, such as from 540-490m in HR12, this has been allowed to drive the interpretation of a regressive package. Where the upper part of a regressive, cleaning-up trend includes a gamma-ray kick, such as in the package above 1793m in JM37. This is assumed to be an inner ramp fine-grained mudstone or wackestone. The log correlations interpreted on this basis are remarkably consistent across the wells (Figure 5). In the subsurface, the Euphrates is best interpreted as consisting of two transgressive-regressive parasequences and the Jeribe Formation shows four to five transgressive- regressive parasequences. It is this consistency of log character that allows a reasonable level of confidence in the sequence stratigraphic interpretations.

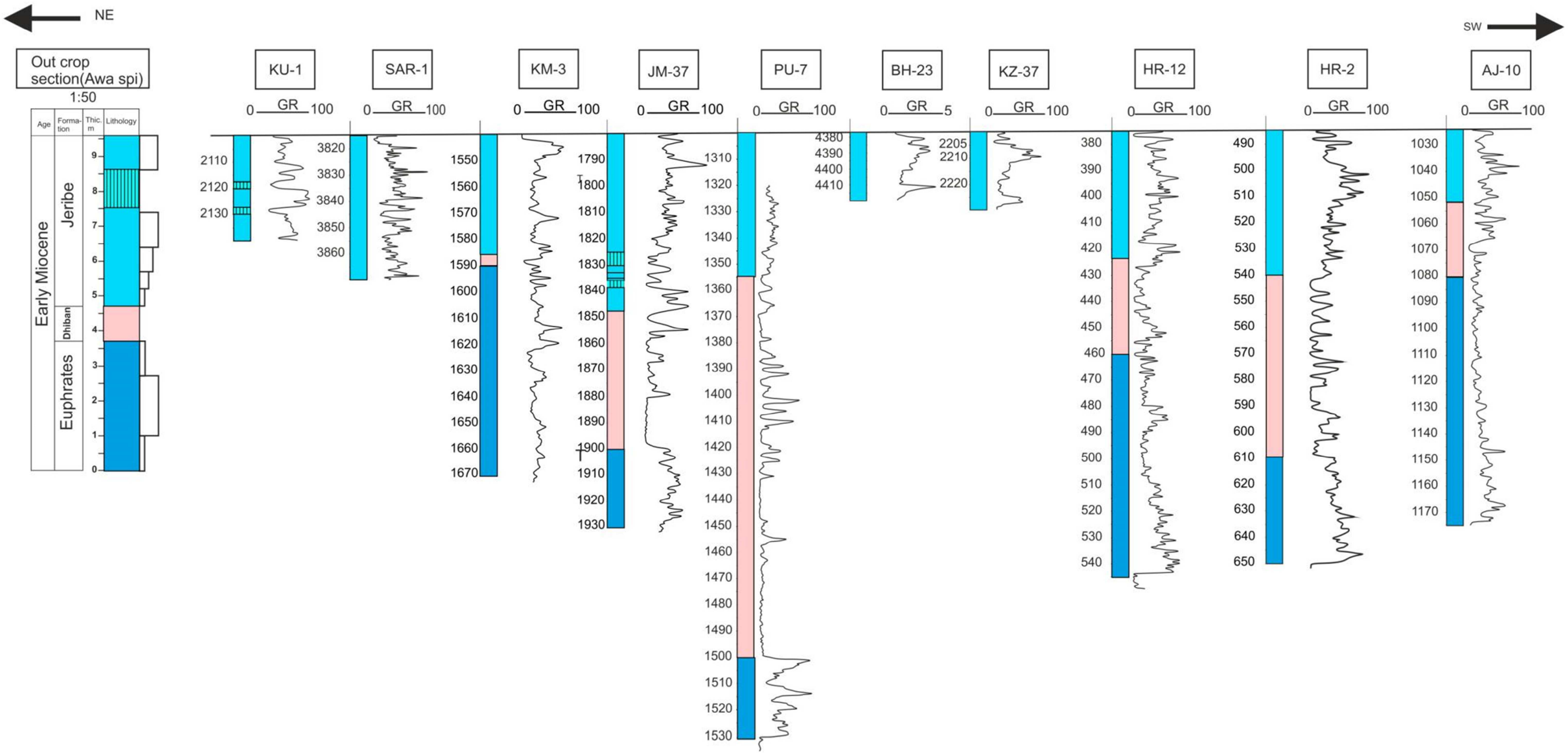


Figure 4 Gamma ray reflection of the Lower Miocene Formations in the outcrop and subsurface sections, for detailed key legend see figure 5.

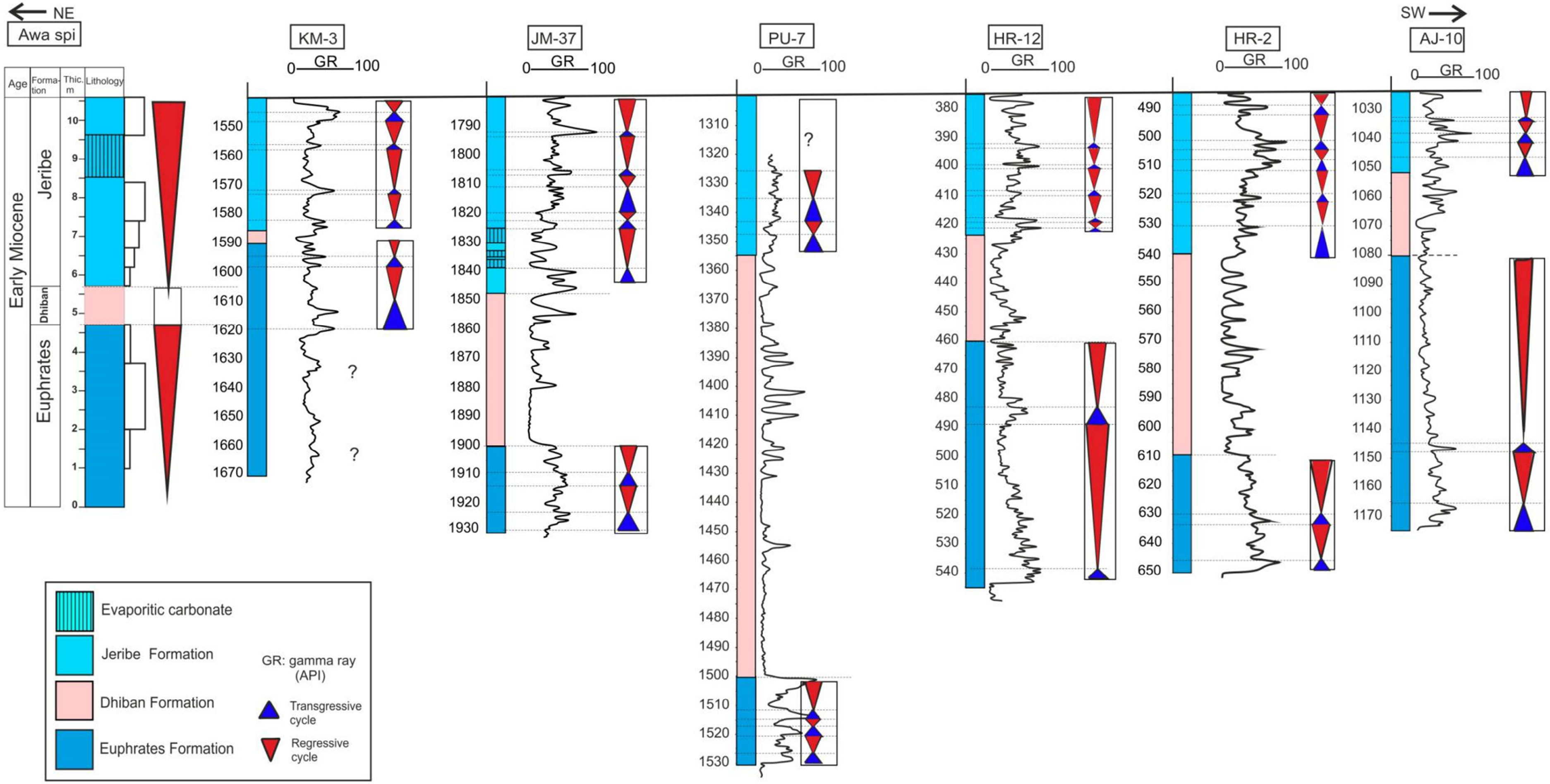


Figure 5 Detail sequence stratigraphic framework and transgressive, regressive cycles of the Lower Miocene Formations in the outcrop and subsurface sections, showing RPT and TPT parasequence pattern; and the transgressive surface at the base of Euphrates Formation is with the underlying Serikagni or Oligocene Formations.

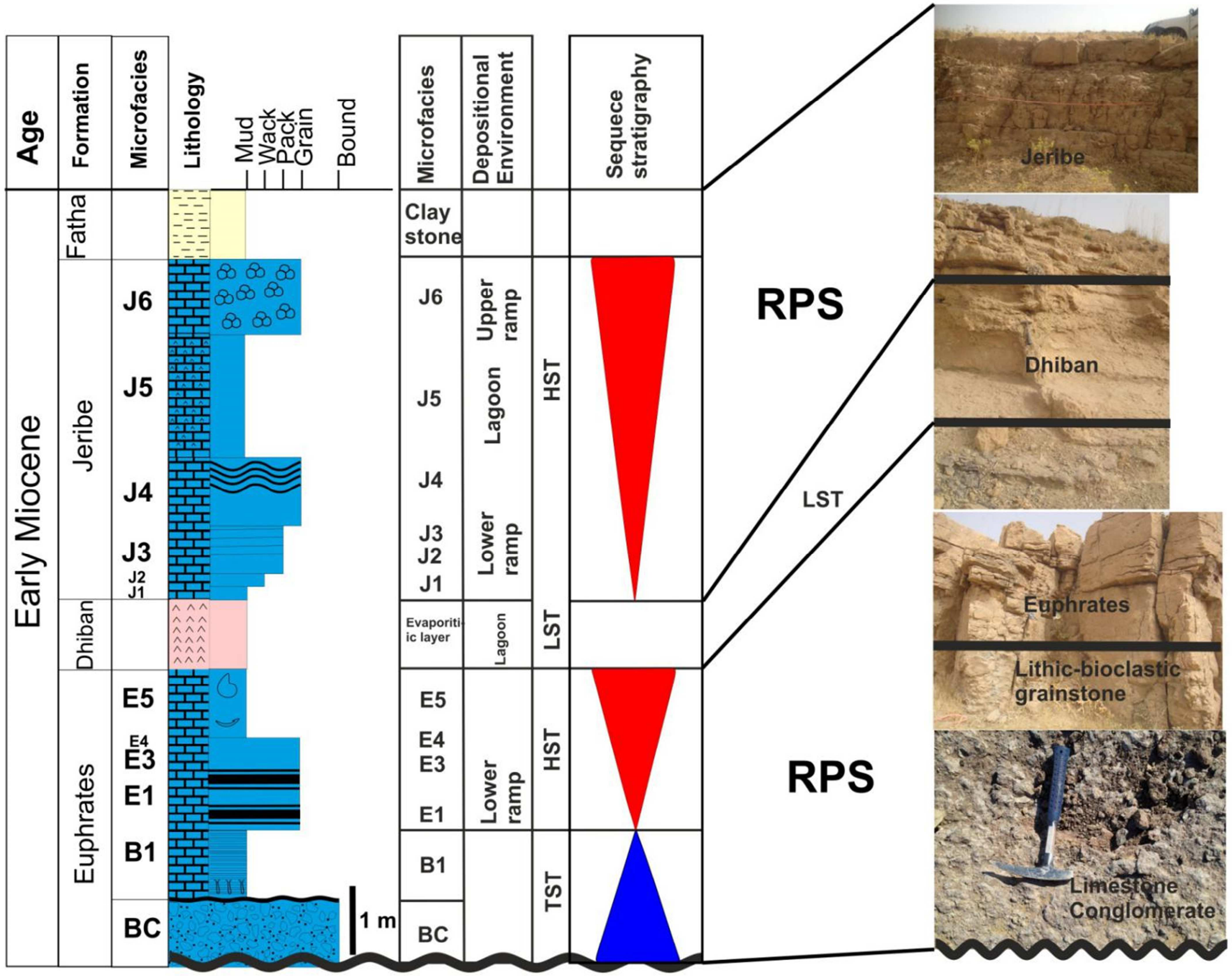


Figure 6 Stratigraphic sequence and Sea level change of the Lower Miocene Formations in the Awa Spi section, RPT, Regressive Parasequence Set.

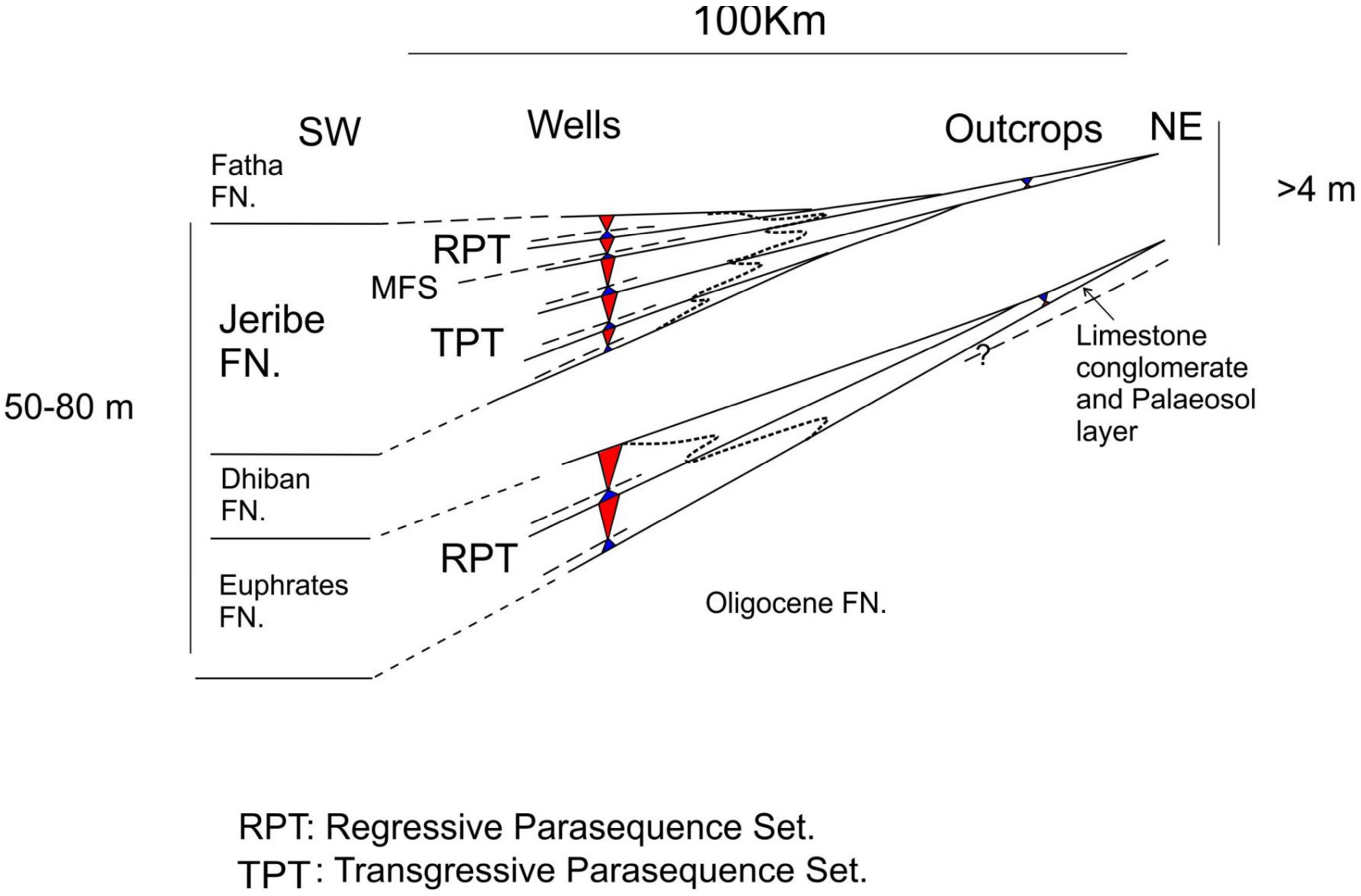


Figure 7 cross section of transgressive-regressive parasequence sets from south-western to north=eastern part of the study area in the Lower Miocene Formations. Two transgressive-regressive parasequence set are found in the Euphrates Formation with four to five transgressive-regressive parasequence set in the Jeribe Formation.

1.4.3 Transgressive and regressive cycles:

Based on the wireline log inflections across the Early Miocene successions the transgressive and regressive elements have been correlated across the study area (Figure 5). As described above, a transgressive package is inferred from a rapid increase in gamma log count, while, conversely, a decreasing gamma ray trend is interpreted as a regressive cycle. Where possible, the log signatures have been compared to other analyses such as core descriptions and thin sections.

The stacking of parasequences may be characterized to highlight overall progradational, aggradational or retrogradational trends across successive parasequences (after Van Wagner et al., 1990). Here, the same general approach in used, but to differentiate regressive from transgressive stacking patterns. This variation in application of the approach recognizes that it is not possible to differentiate a truly progradational relationship from a regressive relationship that might be developed on the falling limb of a sea level cycle. Hence, a regressive parasequence set (RPT) would represent a series of parasequences showing an overall cleaning-up, shallowing-up trend and so a basin-wards shift in facies belts, whilst a transgressive parasequence set (TPT) would show an overall dirtying-up, deepening-up series of parasequences and hence a landward shift in facies belts.

Two parasequences make up a regressive parasequence set in the Early Miocene Euphrates Formation. This is best illustrated in wells HR12, HR2 and AJ10. This implies that it is the lower of the two parasequences that extends most landwards and is therefore likely to be the single parasequence exposed at outcrop. Figure 6 represents this situation in the Euphrates Formation, the formation comprising this regressive parasequence set.

The Jeribe Formation in the subsurface is best interpreted from the wells JM37, HR12 and HR2, which show consistent gamma ray log trends. In each case, five transgressive-regressive parasequences are interpreted, the lower three forming a transgressive parasequence set (TPT) and the upper two forming a regressive parasequence set (RPT). The flooding surface at the boundary between the two parasequence sets may therefore be considered a maximum flooding surface (Figure 7). The parasequence above the maximum flooding surface (MFS) should then be interpreted as that which extends most landwards and is therefore the best candidate for correlation with the single parasequence seen at outcrop in the north-east. Log patterns are remarkably homogeneous in the lateral correlations from north-eastern to the south-western parts of the study area, although with differing thicknesses of transgressive and regressive elements to each cycle.

Transgressive-regressive parasequences and regressive or transgressive parasequence sets are thus established for the studied carbonate reservoirs based on the wireline well logs response and core analysis. However, it is recognized that there are uncertainties in the details of the sequence stratigraphic picks. In addition, there is uncertainty over formation thickness, especially in the Euphrates Formation in well KM3. But the consistency of interpretation results allows a good level of confidence in the new sequence stratigraphic model for the Euphrates and Jeribe Formations.

1.4.4 Sequence stratigraphic analysis of carbonate-evaporite basins

The lateral and vertical evolution of carbonate-evaporites facies is relevant to many hydrocarbon bearing sedimentary basins (Sarg, 2001). Carbonate depositional environments includes the main types of carbonate platforms (rimmed shelf and ramp), in addition to aggraded shelves and epeiric, isolated and drowned platforms. Evaporite depositional settings appear in a range of shallow to deep water environments in conditions of high aridity, and are generally precipitated in sabkhas and hypersaline lagoons (Tucker, 1991). In this study the sequence stratigraphic architectures of the Euphrates and Jeribe carbonate ramp depositional settings are described based on a a modification of established models of Tucker (1991), Sarg (2001) and Sadooni and Al-shahran (2004).

Analysis of sequence stratigraphic concepts as applied to carbonate-evaporite successions is important, especially in a region of varied chemical sedimentation settings. However, there is no widely applied model of mixed evaporite-carbonate successions for displaying fluctuations in brine inflow/outflow levels with the rate of evaporation (Becker and Bechstadt, 2006).

The Lower Miocene carbonates of the study area are separated by variable thicknesses of an anhydritic layer. A very thin layer of anhydrite (Dhiban Formation) is recorded at surface sections between the Euphrates and Jeribe Formations, whereas down towards the basin the thickness of this anhydritic layer (Dhiban Formation) increases. Increasing thickness of anhydritic layers of the Dhiban Formation alternate with carbonate layers in the sub-surface section, which can be identified from the log inflection patterns (low gamma with high density readings). Recently, in Sarqala and Taza wells that penetrate the Early Miocene successions (Jeribe-Dhiban-Euphrates), oils with gravity of (40-36 API) have been discovered (English et al., 2015).

In this study reservoir evaluation in the Dhiban Formation has not been conducted because of the lack of core samples and core description data; only log data are recorded. Based on outcrop descriptions and wireline log data the Dhiban Formation may be interpreted as a lowstand system tract (LST) of a third order sequence, lying between the Euphrates Formation regressive parasequence set that could represent a highstand systems tract (HST) of a third order sequence and the transgressive parasequence set (third order transgressive systems tract, TST) of the lower part of the Jeribe Formation. Several higher order transgressive and regressive cycles are evident within the Dhiban Formation in the subsurface sections (e.g., JM37 and PU7, in Figure 6). The transgressive cycles within the Dhiban formation are associated with the carbonate layers. Yellowish grey, friable anhydrite is recognized in the Dhiban Formation at outcrop, and thick anhydrite of low gamma ray and high density readings was identified in the subsurface sections. This a lowstand evaporite system filling the basin centre can be confirmed as the relevant model for the mixed carbonate-evaporite basin at the scale of a third order cycle (Figure 8).

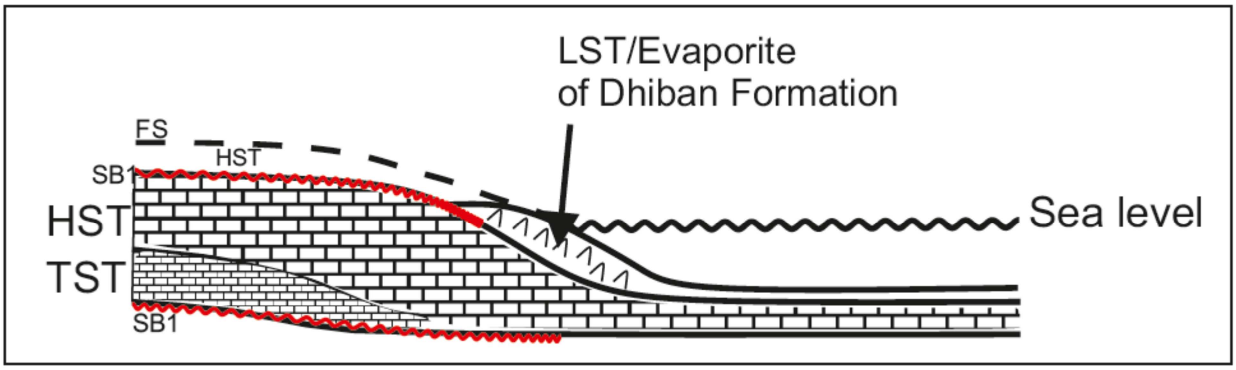


Figure 8 An established sequence stratigraphic model of mixed carbonate-evaporite of the Lower Miocene Formations, LST: lowstand evaporite of the Dhiban Formation surrounded by sequence boundary one (SB1) with underlying Euphrates Formation, overlain by flooding surface (FS), modified after (Tucker, 1991 and Sarg, 2001).

1.4.5 Sequence stratigraphic impacts on reservoir characterization

Reservoir characterization based on a sequence stratigraphic framework involves regional correlation of stratal units and well log records to evaluate seal, source and reservoir rocks with their locations in both time and space (Slatt, 2006). Furthermore, the reservoir's heterogeneity and potentiality, as controlled by the systems tract, can then be determined (e.g., Ambrose et al., 2009). Sequence stratigraphic settings of carbonate rocks are more commonly identified from electrical image logs and gamma ray logs, which in combination with other data (core, outcrop and seismic data) are used to generate a subsurface sequence stratigraphic framework. However, the complexity of the carbonate facies means that they cannot be fully characterized from single trace logs (Rider and Kennedy, 2011). Evaluating depositional sequence variations and their system tracts plays an important role in exploration and the development of potential reservoirs. Sequence stratigraphy in the carbonate reservoir is largely independent of continental influence, because of the intra-basinal origin of the carbonates and the fact they are mainly composed of in situ marine biogenic and chemical sediments formed by the carbonate factory, where the maximum rates of carbonate production are different on ramp and rimmed shelves and their sequence architectures also differ (Ahr, 2008).

Reservoir characterization includes evaluating quantitative and qualitative variations in petrophysical and sedimentological characteristics, and reservoir heterogeneity indicators are based on lateral and vertical changes in porosity, permeability and capillary pressure at various scales ranging from micrometres to hundreds of metres, which generally correspond to variations in depositional facies, diagenesis and structural features such as fractures and faults (Morad et al., 2010). In this study it has been shown that sedimentary facies belts and hence petrophysical properties vary over distances on tens of kilometres.

Carbonate reservoir heterogeneity may also result from subsequent diagenetic alteration which will vary with pore water chemistry and depositional porosity, permeability and with the amount of intra-basinal grains and extent of bioturbation, in addition to the rate of deposition and the burial history of the basin. Moreover, relative sea level change and sediment supply are important factors in controlling near surface eogenetic alterations, such as changes in the chemical composition of pore waters between marine and brackish pore waters, the residence time of the sediment alteration by geochemical processes, and the extent of bioturbation (Morad et al., 2010).

Diagenetic alterations associated with sequence boundaries are mostly affected by meteoric water, with common features including formation of palaeosols, dissolution and karstification. Diagenesis processes along the flooding, transgressive surfaces and in the transgressive system tract (TST) are generally controlled by low rates of sedimentation relative to rates of rising sea level, with common diagenetic alterations including dolomitization of mudstone, wackestone and packstone (Morad et al; 2010). Diagenetic process (HST &LST) system tracts mostly indicate rates of sedimentation that higher than rates of rise in sea level (Sarg, 2001) involved in the cementation process, especially along early HST, while the late HST presents upward coarsing sediments (Morad et al., 2010). The LST deposits are generally subjected to meteoric water circulation that results in the dissolution process (Morad et al., 2000).

In the study area, the carbonate formations have been characterized from five outcrop sections, and wireline well logs from ten subsurface sections. Reservoir heterogeneity of the Lower Miocene Euphrates and Jeribe Formations may be interpreted in terms of diagenetic variations related to sequence stratigraphic architecture (e.g. Ambrose et al., 2009; Ketzer, 2002; Morad et al., 2012; Morad et al., 2010; Slatt, 2006) in a few cases.

Diagenesis along flooding surface is characterized by poikolitic and blocky calcite cementation, and the formation of paleosols (for example Hussein et al., 2017). Vuggy pores and solution pores are recognized along the third order sequence boundary between the Euphrates and Dhiban Formation. There is no diagenetic alteration along the recognized thin layers of (TPS) at outcrop sections, while dolomitization of mudstone, wackestone and packstone is recognized in the Jeribe and Euphrates Formation in well (HR2). This variation of the dolomitization trend is expressed through the euastatic fluctuation of relative sea level changes.

Diagenesis of the regressive cycle (shoaling upward) in both Lower Miocene Euphrates and Jeribe Formations in the outcrop sections is determined by calcite cementation, dissolution of skeletal grains, formation of non-touching moldic pores, and fabric selective dolomitization. Calcite cementation is widely identified at outcrop sections, whereas the high dolomitization and dissolution of the skeletal grains that create interconnected pores are indicated in the south-western part of the study area, and cause high porosity and permeability. Reservoir characterization and heterogeneity in the Early Miocene successions of the Euphrates and Jeribe Formations are greatly controlled by distribution of the diagenetic evolutions. The diagenetic modifications are in turn controlled by depositional facies and sequence stratigraphic analysis, which create a lateral increase in dolomitization and dissolution processes.

1.5 Conclusion

Complete successions of the Lower Miocene Formations are deposited in most sections in the study area. Two depositional sequences are evaluated for the Lower Miocene Formations.

Determining sequence architecture in outcrop logs and wireline well logs (gamma ray and density logs), for all of the Lower Miocene formations, has generated a broad framework for understanding how sea level fluctuations impact on the observed diagenesis processes, which then enable us to understand how this influences the underlying geological and reservoir textures, as revealed by lithological, log derived petrophysical properties.

Based on this study, the Lower Miocene Euphrates Formation is showing shallowing upward cycles and Jeribe Formation is appearing as regressive cycles. Moreover, In Subsurface sections, regressive parasequence has established in the Euphrates Formation and two parasequence of regressive and transgressive patterns have found in the Jeribe Formation.

A proper model has build to the evaporitic layer of the Dhiban Formation between the above mentioned formations (Euphrates and Jeribe), it described as a lowstand system tract (LST) of a third order sequence, lying between the Euphrates Formation regressive parasequence set that could represent a highstand systems tract (HST) of a third order sequence and the transgressive parasequence set (third order transgressive systems tract, TST) of the lower part of the Jeribe Formation. Lastly, from sequence patterns and its surfaces reservoir characterization of both carbonate rocks have interpreted.

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