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ORIGINAL PAPER

Sequence stratigraphic analysis of the Lower Jurassic succession, Western Iraq

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Abstract The Lower Jurassic succession of Western Iraq reflects deposition within various depositional environments. These are fluvial, coastal plain, sabkha, shallow restricted marine, and shallow open marine environments. Several third- and fourth-order cycles were recognized within the studied succession. Facies stacking patterns, cycle thicknesses, and symmetries were the direct result of different effects of the major controlling factors (eustacy, subsidence, rate of carbonate production, and clastic supply) at different locations within the study area of Western Iraq. The different rates of subsidence between the Rutba uplift, Anah Graben, and the unstable shelf area produced different effects on the Lower Jurassic sequence development. In the Rutba uplift where the rate of subsidence was at its minimum, eustacy was the major controlling factor. Tectonic subsidence was the major controlling factor on sequence development of the other sections where high rates of subsidence characterized these areas. The development of the Lower Jurassic basin in Western Iraq was initiated during the early stages of the Neo-Tethys opening. The physiography of this passive margin basin was controlled by the Hail-Rutba Arch and the Anah Graben within the stable shelf area. Facies architecture was controlled mainly by the change in accommodation (eustacy+ subsidence). The resultant relative sea level greatly affected the nature of carbonate production and consequently facies stacking pattern.

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Introduction

The Lower Jurassic formations of Western Iraq are mainly exposed northeast of Rutba, particularly along Wadi Hauran, Wadi Hussiniya, and Wadi Amij. These formations are represented by the dominant carbonates of the Ubaid Formation and the siliciclastic-carbonate successions of Hussainiyat and Amij formations. Subsurface sections of these formations and their equivalents at wells KH5/9, Anah-2, and Melh El therthar-1 were also studied (Fig. 1). Many previous studies were conducted on the clastic unit due to their economic importance, especially the iron deposits within the Hussainiyat clastic unit. The Amij sandstones were also important for their Fe and Ti mineral concentrations.

The main aim of this study is to analyze the development of the Lower Jurassic succession in Western Iraq in order to interpret the tectonic framework of sedimentation of the basin. For this purpose, detailed description of petrography, lithofacies, and microfacies analysis was carried out for paleoenvironment interpretation, where detailed description of the available sections and study of more than 900 thin sections were carried out. This is one of the major steps of sequence stratigraphic analysis. In the next steps, the different lithofacies were related to system tracts and then the identification of key surfaces. Together with sediment volume partitioning, sequence stratigraphic subdivision and correlation followed where third- and fourth-order cycles can be determined. Base-level transfer cycles (BLTC) that affect the clastic sequence development were also defined. All these led to the interpretation of basin fill architecture.

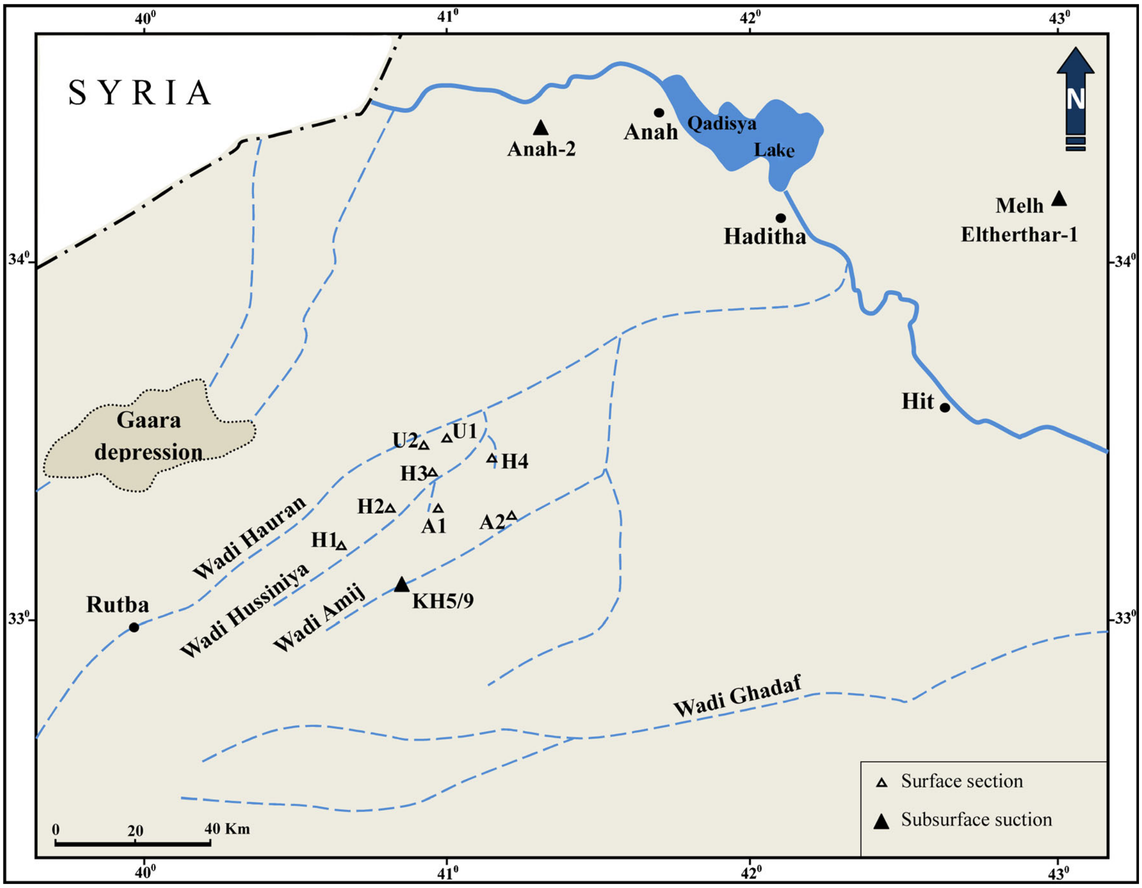

Fig. 1 Location map of the study area

Stratigraphy and tectonic setting

The main structural features in the study area include a NE-SW trending uplift along the Hail-Rutba Arch on the northeast margin of the Arabian Shield, Anah Graben, and Abu Jir fault zone; possible N-S suture trends; and NE-SW trending strike slip faults. The Early Mesozoic Neo-Tethys opening and the onset of the Mediterranean rifting initiated uplifts and grabens in the Arabian plate (Sharland et al. 2001). The activity of the Rutba uplift and Anah Graben during the Early Jurassic greatly affected the paleogeography of the basin in the study area (Buday and Jassim 1987). The pronounced northerly trend of the platform and the observed facies pattern reflect the tectonic control which probably corresponds to the Hercynian basement trend. These trends extend northward into Iraq and toward the plate margin (Ziegler 2001). The studied sequence was believed to be of Liassic–Dogger in age according to biostratigraphic investigations by Buday and Hak (1980) and Hassan (1984).

The stratigraphy of the Lower Jurassic succession of Iraq was studied by many geologists, and several subdivisions were made. It is represented in Western Iraq by the Ubaid Formation and the siliciclastic–carbonate of the Hussainiyat and Amij formations (Fig. 2). The Butmah, Adayah, Mus, and Alan formations are the Lower Jurassic equivalents to the north and northeast of the study area (Fig. 3). The Ubaid Formation consists of dark gray microcrystalline limestone interbedded with chalky limestone; overlain by light gray dolomitic limestone with some fossils, followed by compact bluish marl and reddish clay with marl; then overlain by sandstone, followed by marl with shell fragments and dolomitic limestone interbeds. This formation is underlain conformably by the Upper Triassic Zor Horan Formation.

The Hussinaiyat Formation starts with medium- to coarse-grained sandstone, followed by whitish to yellowish sandstone and reddish marl. It is overlain by reddish clay and light gray, friable sandstone, followed by yellowish to whitish sandy marl and sandstones interbedded with reddish marl and sandstone followed by gray karstified and silicified dolomitic limestone.

The Amij Formation consists of fine-grained sandstone and reddish sandy clay, followed by yellowish fossiliferous dolomite, overlain by gray to yellowish dolomitic limestone, followed by varicolored dolomite, fossiliferous in the upper part. This formation is overlain unconformably by the Middle Jurassic Muhawier Formation.

The greatest part of Butmah Formation in well Anah-2 consists of red clastics (shale, sand, silt, and macro conglomerates).

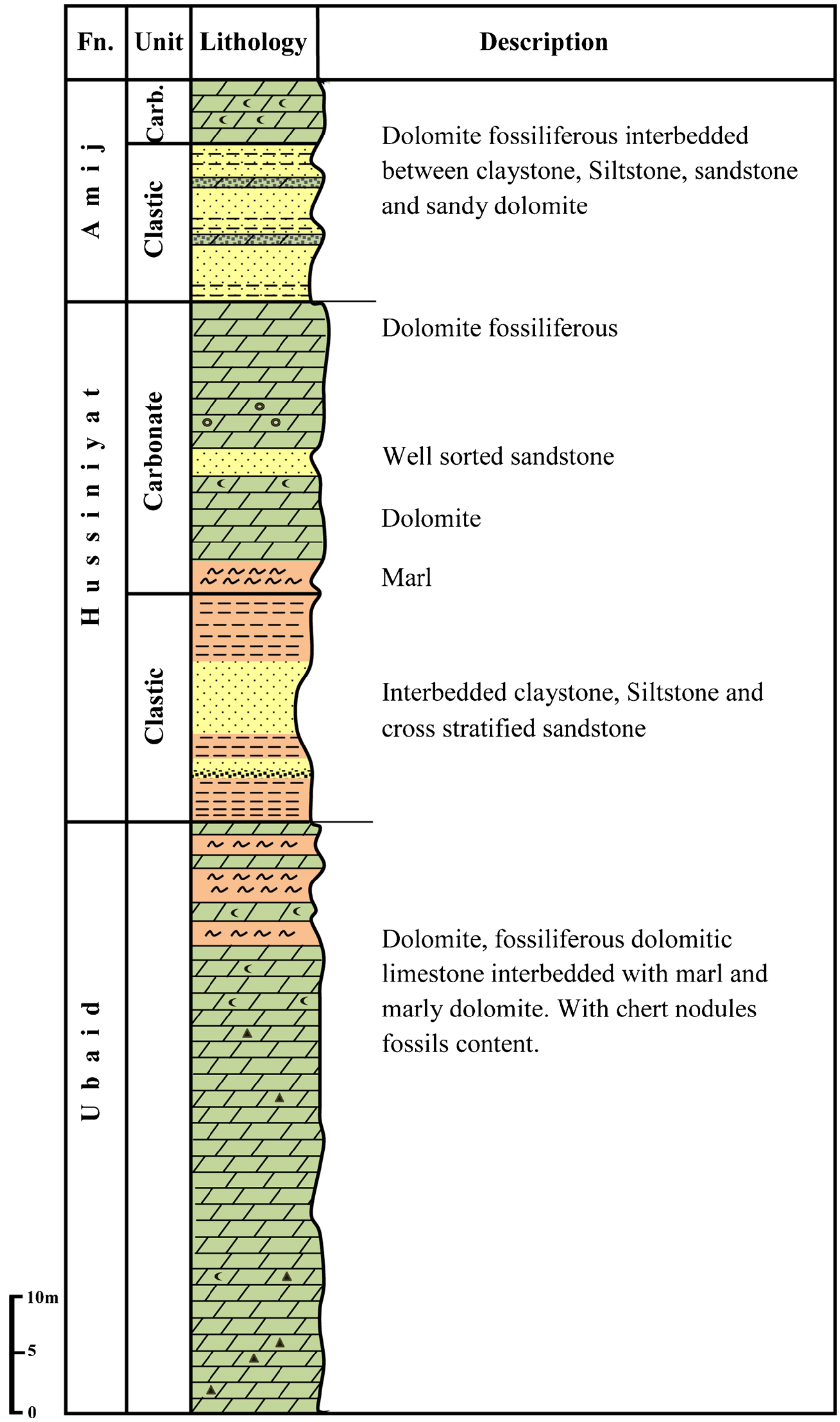

Fig. 2 Exposed Lower Jurassic succession in Western Iraq

The lower part of this formation consists of limestone, shale, sandstone, fossiliferous dolomitic limestone, and limestone (Hay and Hart 1959).

In well Melh El therthar-1, this formation begins with dolomitic limestone interbedded with anhydrite, followed by marl with siltstone and shale and overlain by limestone, dolomite, marl, and shale with some siltstones, then followed by alternation of limestone to dolomitic limestone and marl, shale with red hematitic siltstone and fine-grained sandstone follows. This is overlain by dolomite, marl, and limestone with fossils in part and anhydrite at the upper part (Hay and Algawi 1958). This formation is underlain unconformably by the Upper Triassic Kurra Chine Formation.

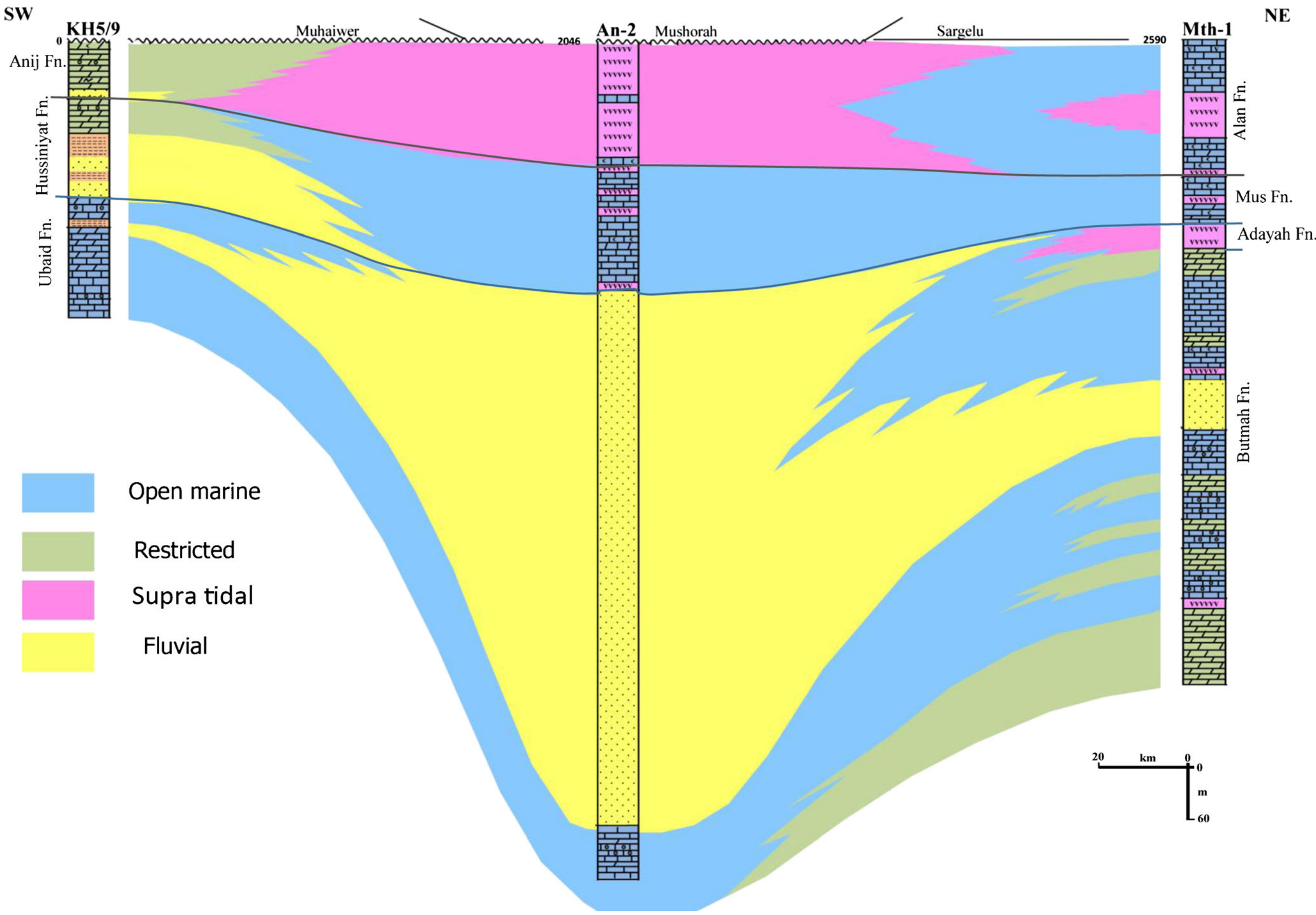

Fig. 3 Stratigraphic cross section of the subsurface Lower Jurassic succession in the west and its equivalents to the north and northwest

The Adayah Formation consists of anhydrite with beds of hard fossiliferous limestones with shale interbeds. The Mus Formation is composed of shales interbedded with anhydrite and fossiliferous limestone (Hay and Hart 1959).

The Alan Formation is represented by a sequence of bedded and nodular anhydrite, with marly limestone, partly pseudoolitic with red shale. This formation is overlain by the Upper Cretaceous Mushorah Formation in well Anah-2 and Sargelu Formation in well Melh Eltherthar-1 (Hay and Algawi 1958).

Paleoenvironments and sequence development

Sediment volume partitioning

One of the main fundamental attributes studied in the stratigraphic record is the differential sediment volume partitioning into different facies tracts formed during base-level cycles, also the changes in cycle symmetry in different paleogeographic and stratigraphic positions (Cross and Lessenger 1998). This will affect the sediment accumulation rates in different locations during these base-level cycles as well as the different rates of subsidence at different. As a result, the relation between accommodation and sediment supply which varies in time and space can be interpreted and sediment volume partitioning based on the above criteria can be used as basis for high-resolution stratigraphic correlation.

In concept, the base level is not a horizontal planar surface, it is equivalent to the sea level (Cross and Lessenger 1998). The base-level fall portion of the transit cycle is represented by the accumulation of gradual shallowing facies, and the base-level rise portion of the transit cycle on the other hand would represent a gradual deepening of marine and coastal plain facies and/or vertical aggradations or landward translation of facies tracts. The relative sea level change is the major controlling factor on the geographic shift of accommodation space. The base-level rise and fall as well as the balance and imbalance between accommodation space and sediment influx is reflected by the thickness and symmetry of each fourth-order cycle. The order of cyclicity was determined according to subdivisions suggested by Mitchum and Van Wagoner (1991), where the duration of the studied succession was according to the previous biostratigraphic studies by Buday and Hak (1980) and Hassan (1984).

Ubaid Formation

Microfacies analysis and facies stacking pattern of the Ubaid succession reflect deposition within a slowly subsiding carbonate platform. In the study area, this platform represents a ramp setting where deposition of the Ubaid took place. In such a setting, a relatively thick succession of inner ramp, restricted marine facies can develop (Ahr 1989). The restricted marine facies is represented by thick units of dolomitic and dolomitized mudstones; thin units of dolomitic bioclastic wackestone were also recognized, reflecting short episodes of open marine. Occasional thin unit of dolomitic peloidal packstone to grainstone indicates an inner barrier facies.

All the relative sea level fluctuations are reflected in the facies stacking pattern (Fig. 4), where sea level rises and still stands were represented by successive cycles of restricted and shallow open marine facies. This was also reflected by the effect of the shifting mixing zone on the sediments, where intense dolomitization characterizes the Ubaid section in this area. Thin reddish, brown mudstone and sand units can be observed within the upper part of the section at KH5/9. This may indicate progradation of the floodplain facies in the proximity of the shoreline.

The exposed section of the Ubaid Formation (Fig. 4) shows three asymmetrical third-order cycles, cycle A started in the upper part of Zor Hauran Formation and cycle B can be divided into two fourth-order cycles (b1 and b2); they are asymmetrical, reflecting short episodes of sea level rise followed by a relatively long still stands and resulting in the formation of thin units of open marine and inner barrier facies of the TST.

Hussainiyat Formation

The Hussainiyat Formation in the study area consists of a lower clastic unit and an upper carbonate unit. Lithofacies analysis of the clastic unit indicates deposition in a meandering river system where channel facies, point bar facies, and flood plain facies were recognized,

The channel facies is represented by pebbly pisolitic sandstones with planar and trough cross stratification. These sandstones are medium-grained and moderately sorted. They consist mainly of iron pisolites as the major component in addition to quartz. This facies was observed in all sections at Wadi Hussainiya. The point bar facies is represented by coarse- to fine-grained, subrounded to rounded sandstones with a clear fining upward trend. Planar and trough cross stratification characterizes this facies. This type was observed in the section at the northern part of Wadi Hussainiya. The floodplain facies on the other hand is characterized by gray- to red-colored laminated mudstones, rich with iron concretions especially in the southern part of Wadi Hussainiya. These mudstones consist mainly of kaolinite with abundant plant remains mostly in the lower part of the section. Thin sandstone and siltstone beds are also interbedded within this facies (Fig. 5). The succession of floodplain, channel deposited, and finning upward point bar facies reflects a low-gradient alluvial plain characterized by a very low rate of subsidence. This was indicated by the fact that the migrating channel deposits approximate to a one-channel thickness (up to 10 m), and this also reflects deposition in a proximal setting with the absence significant subsidence.

The stratigraphic cross section of the exposed Hussainiyat Formation in the study area shows that the bulk sediments of the clastic unit consist predominantly of fine floodplain deposits which predominate over the channel fill sandstones. This is typical of meandering river system where floodplain deposits make up the majority of the basin fill, and this may indicate a low rate of vertical aggradation leading to a pronounced channel migration and lateral stacking of channel deposits.

This is typical of very low gradient meandering or possibly anastomozing river system (Einsele 2000). In such a system, the channels has a relatively high width/depth ratio characterized by predominantly mixed load, where the bed load is generally low in this system whereas suspended load predominates.

The upper carbonate unit reflects deposition in various shallow marine subenvironments; these include the restricted marine, inner barrier, and shoal environments. Coastal plain facies was observed within the lower part of the Hussainiyat upper carbonate unit at the northern part of Wadi Hussainiya. It is represented by light gray, fine- to medium-grained, well-rounded, and well-sorted sandstones, characterized by planar cross stratification. It may reflect deposition within the upper shore face.

The exposed Hussainiyat succession is represented by a major third order (Fig. 5). Its lower boundary is erosional with the underlying Ubaid Formation and represents a type-one sequence boundary (SB1); its upper boundary with the Amij Formation is also erosional and represented by SB1. This succession in Wadi Hussainiya exposure can be divided into two third-order cycles (D1 and D2) and a number of fourth-order base-level transfer cycles (BLTC); these cycles reflect the effect of base-level fall and rise on cycle thickness, symmetry, and facies stacking pattern. These fourth-order cycles (d1, d2, d3, d4) are asymmetrical and show an upward increase in thickness (Fig. 5); this may reflect the imbalance between accommodation and sediment influx for the clastic unit, whereas the carbonate unit cyclicity shows a more or less balanced situation between the relative sea level rise, accommodation, and accumulation of sediment, reflecting a relatively low subsidence.

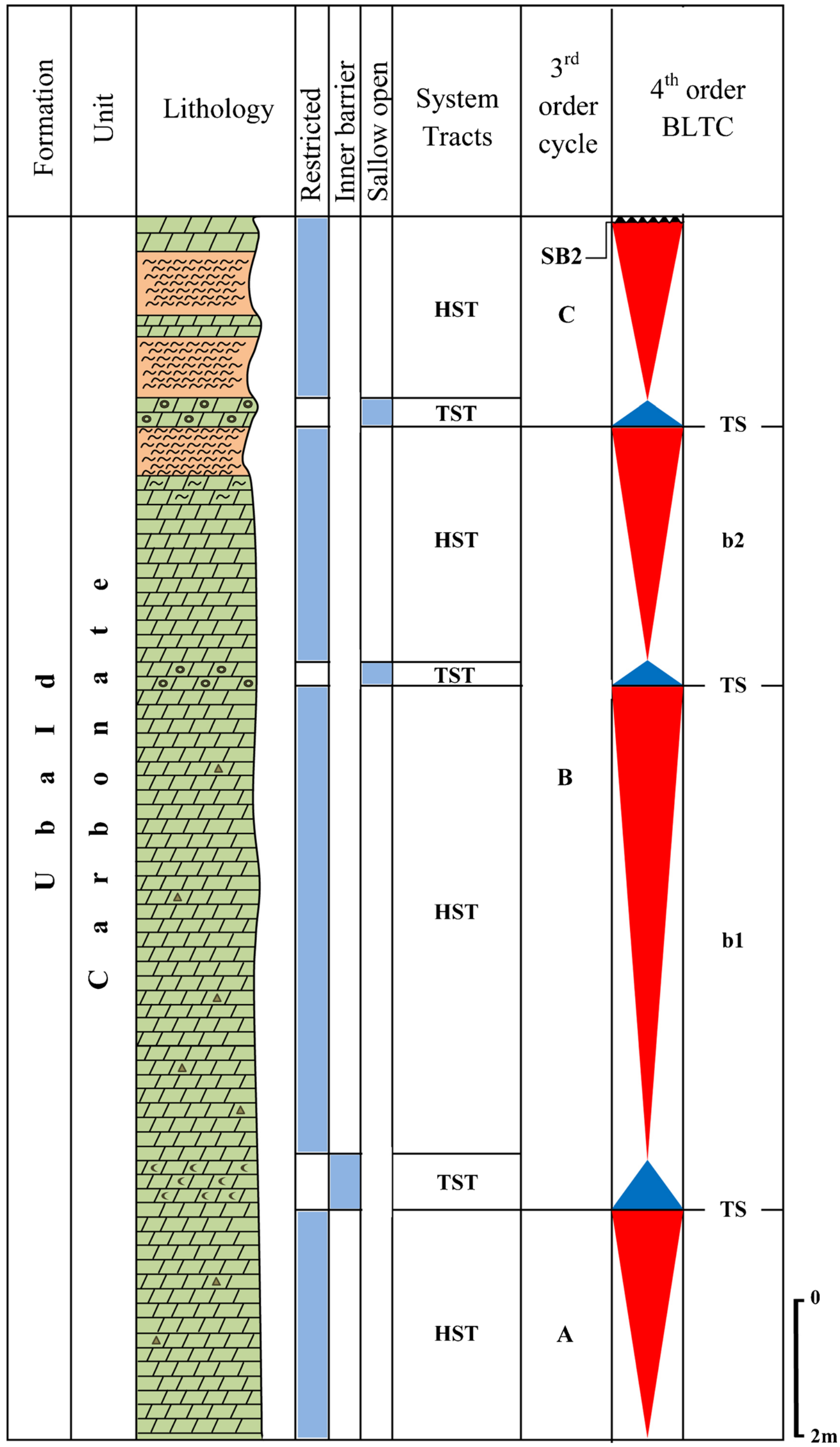

Fig. 4 Facies stacking pattern and sequence stratigraphic subdivisions of the Ubaid Formation

The correlation of the exposed sections (Fig. 5) shows the lateral variation in cycle thickness and symmetry which reflects the differences in accommodation and consequently the rate of subsidence as well as the paleogeography of the basin. The oldest exposed complete BLTC is cycle d2; this cycle is asymmetrical and shows a slight change in thickness laterally; this may reflect a more or less balanced situation in all sections. Cycle d3 on the other hand shows a considerable thickness at northern Wadi Hussiniya (section H4), where it shows a clear asymmetry becoming more symmetrical and thinner to the southwest. This may reflect the effect of differential subsidence resulting in the formation of variation in accommodation space.

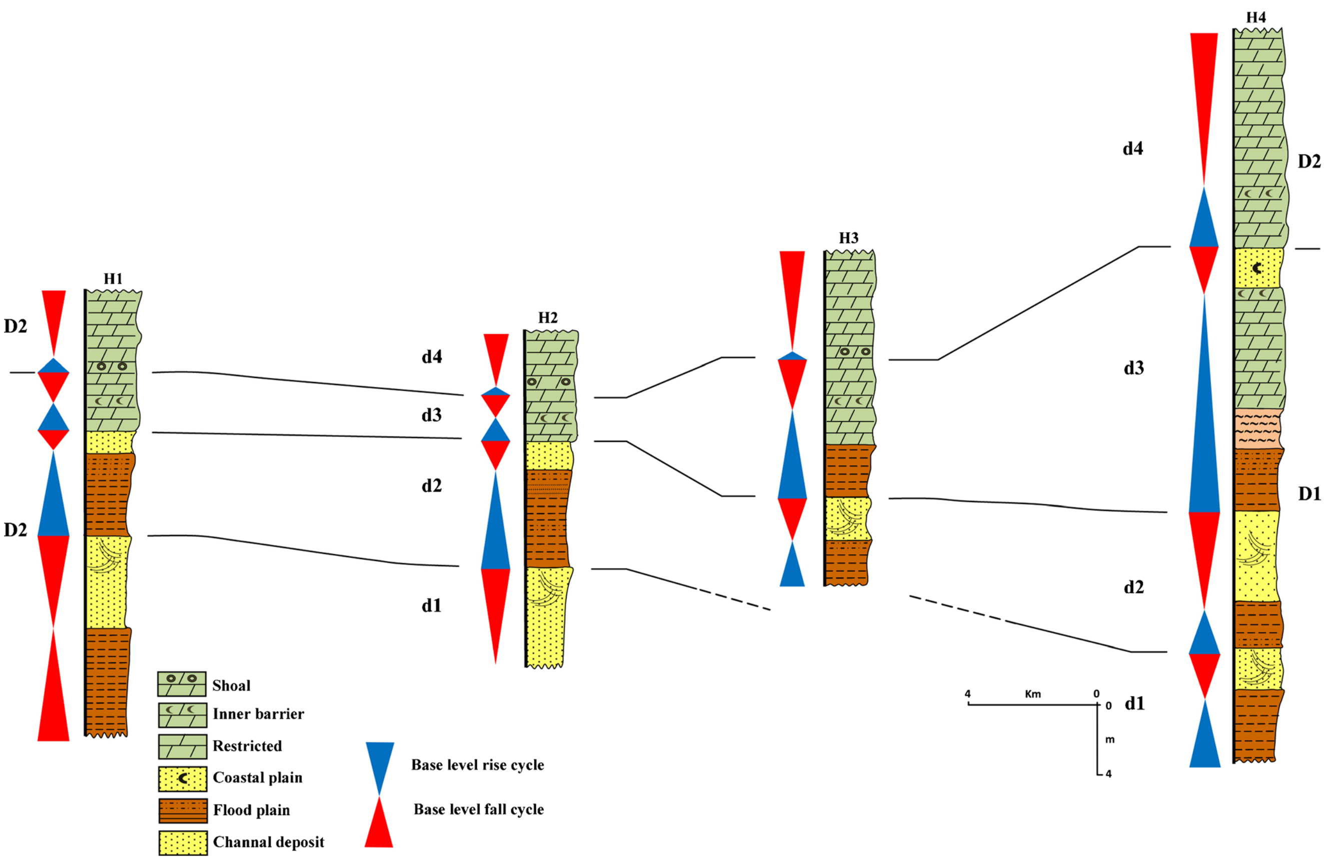

Fig. 5 Stratigraphic cross section at Wadi Hussainiya showing facies stacking pattern and sequence stratigraphic subdivisions of the Hussainiyat Formation

Amij Formation

The Amij succession of Western Iraq also consists of a lower clastic unit with few carbonate interbeds and an upper carbonate unit. This succession represents a wide range of lithofacies reflecting the different subenvironments of fluvial, transitional, and shallow marine condition.

The clastic unit shows a facies stacking pattern typical of fluvial facies in a proximal area. It also represents a meandering river system characterized by scattered channel deposits where fine floodplain deposits makes up the bulk of sediments in this area. The floodplain facies are interbedded with thin units of the beach barrier grain stones and coastal plain sandstones as well as the restricted marine facies. The coastal plain facies is characterized by white to light gray, fine- to medium-grained sandstones; they are well sorted and well rounded with parallel and cross stratification. Bands of heavy mineral concentrations are abundant, reflecting the effect of high wave energy of swash zone alternation on the upper shore face (Gayara and Al-Ubaidi 2000). The nature of facies stacking pattern of the clastic unit (Fig. 6) may reflect deposition on a low gradient alluvial plain subjected at times to the effect of high wave energy along the shoreline where the coastal plain facies were deposited in this area of low rate of subsidence and relatively low accommodation.

The beach barrier facies is represented by dolomitized oolitic grain stones which are composed of fine superficial oolites with dolomitized cement. Some shell fragments of molluscs were also observed. This microfacies was recognized in all surface sections, reflecting a wave-dominated environment along the shoreline. According to microfacies analysis of the upper carbonate unit, three main depositional environments were distinguished; these include restricted marine, shallow open marine, and shoal environments of the inner ramp setting.

The exposed Amij succession is represented by two third-order cycles (E and F); cycle E can be divided into four fourth-order BLTC cycles (Fig. 6), they are in general asymmetrical showing slightly lateral variation in thickness and symmetry. Cycle E is separated from cycle F by a wave ravinement surface. It can be divided into two fourth-order cycles (f1 and f2), and these cycles show a considerable variation in thickness. The clastic succession of the Amij Formation reflects deposition under the influence of fluvial and coastal plain environment processes. This reflects a facies stacking pattern consisting of relatively thick fluvial facies and thin

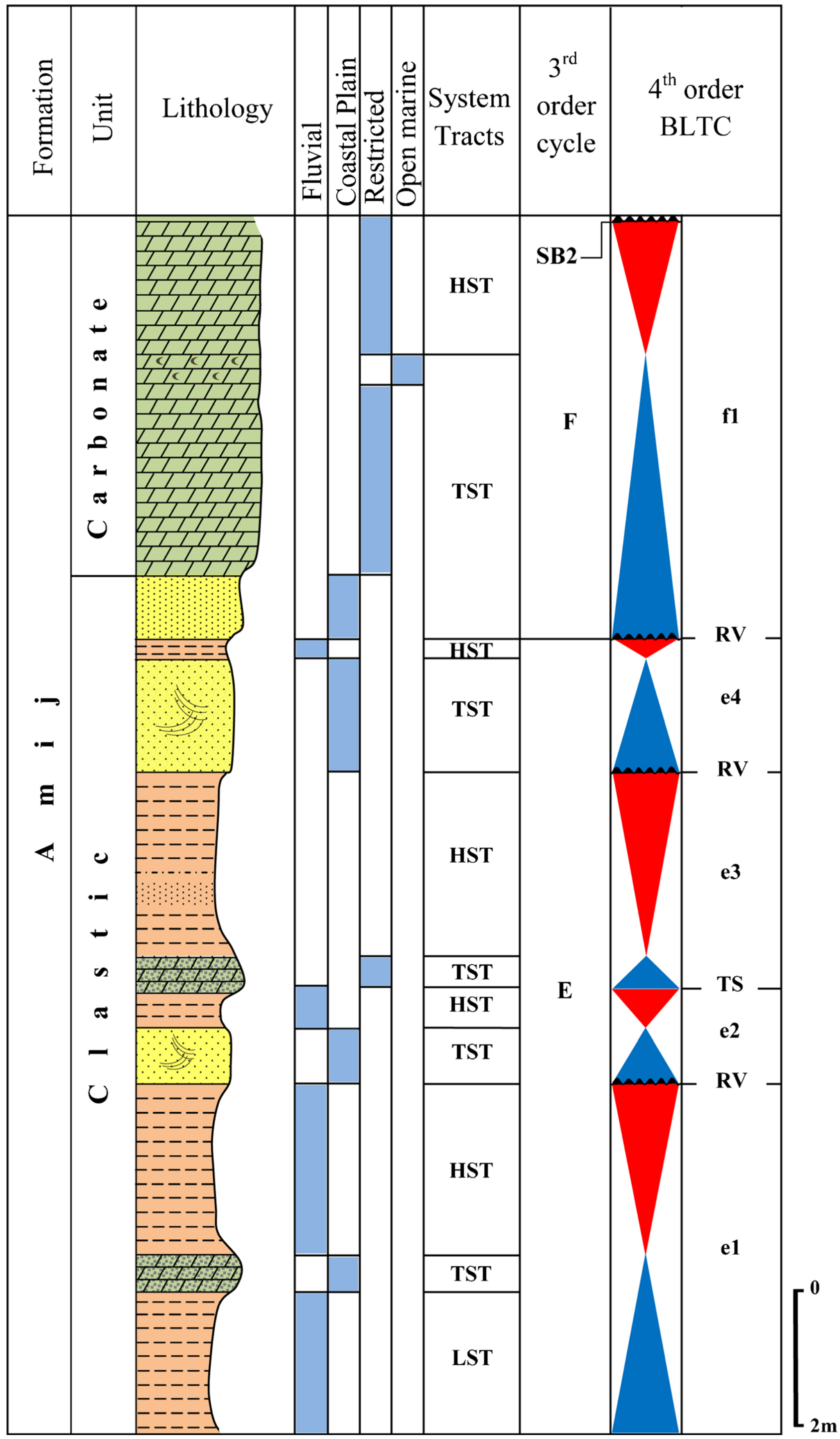

Fig. 6 Facies stacking pattern and sequence stratigraphic subdivisions of the Amij Formation

coastal plain sandstones as well as oolitic grain stones of the beach barrier facies; the differences in the rate of clastic supply as well as the rate of beach barrier accumulation resulted in the asymmetry of these cycles except cycle e2 which appears to be more or less symmetrical, because of the amount of the flood plain facies eroded by the wave action along the wave ravinement surface, separating the floodplain facies from overlying beach barrier. This is dependent on the physiography of the shoreline as well as the direction of long shore currents.

Butmah Formation

According to a detailed core and cutting description from wells Anah-2 and Melh Eltherthar-1, different microfacies and lithofacies types were recognized; they reflect different depositional environments, these are fluvial, restricted marine, shallow open marine, and shoal environments. The section at Anah-2 (Fig. 3) shows a thick clastic succession represented by red sandstones of the fluvial facies overlying a thin, predominantly restricted carbonate unit. This may reflect deposition in a relatively highly subsiding area where high accommodation rate/or high sediment supply contributed to the formation of thick fluvial facies. This is contrary to the situation at Melh-Eltherthar-1 where the Butmah Formation reflects a thick succession of predominantly restricted marine facies interbedded with supratidal and thin fluvial facies (Fig. 3). The observed relatively thin fluvial facies at Melh Eltherthar shows distinct dolomite interbeds, which is typical of deposition in a proximal area.

Adayah Formation

Evaporites are the main facies in the Adayah Formation. This facies consists of anhydrites and dolomitized mudstones (Fig. 3). Anhydrite is both nodular and layered as well as intergrown dolomitized mudstones and anhydrite with minor mudstone intercalations. These facies reflect typical supratidal environment.

Mus Formation

Detailed microfacies analysis of core and cutting samples of this formation reflects various types of environments, these include supratidal, restricted marine, and shallow open marine environments (Fig. 3).

Alan Formation

The Alan succession was deposited in a shallow inner platform, mainly within the supratidal and restricted marine environments as well as episodic open marine conditions (Fig. 3). This was based on microfacies analysis of core and cutting samples of this formation.

Basin evolution

The most important prerequisite for analyzing the development of a sedimentary basin is to identify the behavior of key parameters responsible for basin fill architecture. In the present study, these parameters include eustacy, tectonics, and sediment supply (Fig. 7). The interrelationship of these parameters and the resultant effect on the nature of relative sea level, physiography, and accommodation can be reflected on facies associations and stacking pattern as well as the nature of cyclicity. Sea level lowstand was reflected by the progradation of fluvial or supratidal facies basin ward.

Physiography is one of the main parameters affecting the stratigraphic architecture of the sedimentary basin; it is mainly the result of tectonics and sedimentary processes, and these processes are mainly the result of paleogeography and environmental energy.

The Early Jurassic basin of the Arabian Plate is typical of a passive margin basin formed during the early stage of the Neo-Tethys opening. This long-lived basin throughout the Mesozoic also includes the formation of numerous intrashelf basins in Iraq. The Early Jurassic (Hettangian) rifting in the central Mediterranean propagated eastwards the Arabian Plate, initiating uplifts and grabens (Sharland et al. 2001). The Butmah Formation started to deposit on an evaporitic shallow marine platform during the Hettangian lowstand, and this was followed by the Toarcian transgression which was widely recognized in a global scale. The Early Jurassic was culminated by the Sinemurian lowstand where Adayah, Mus, and Alan and their siliciclastic–carbonate equivalents (Hussiniya and Amij formations) in the Rutba area were deposited.

The study area lies on the eastern flank of the Hail-Rutba Arch and extends north and northeast to include the Anah Graben and the subsiding unstable shelf. The activity of the Rutba uplift and Anah Graben during the Early Jurassic greatly affected the basin physiography. That was reflected by the stratigraphic architecture and sequence development of the succession. Local block movements and/or thermal subsidence also affected the relatively stable Rutba area.

Eustacy is one of the main parameters effecting sequence development; it is the result of major climatic changes as well as the total subsidence which affect the global sea level changes, and the total subsidence resulted mainly from on-sequence development.

The relative sea level is a result of total subsidence and eustacy; these two factors produce the necessary accommodation for sediment accumulation. In the study area, the relative sea level curve and its amplitude is different from one location to another due to the difference in nature and intensity of subsidence at each location (Fig. 7).

The lower-Middle Jurassic succession at well KH5/9 is located within the most stable part of the study area (Rutba), and hence, the eustatic component is the major controlling factor on facies stacking pattern and together with different rate of supply affected the nature of the fourth-order cycles; the relative sea level curve in this area shows a relatively higher amplitude where episodes of sea level fall (forced regression) are represented by exposure of the inner platform, valley incision, and progradation of fluvial facies. This was reflected mainly by unconformable contact between the Ubaid and Hussiniyat formations and between the Hussiniyat and Amij formations.

The situation at the Anah-2 section to the north is quite different, where higher rates of subsidence in this area which lies within the Anah Graben produced the necessary accommodation space for a thick succession represented by the

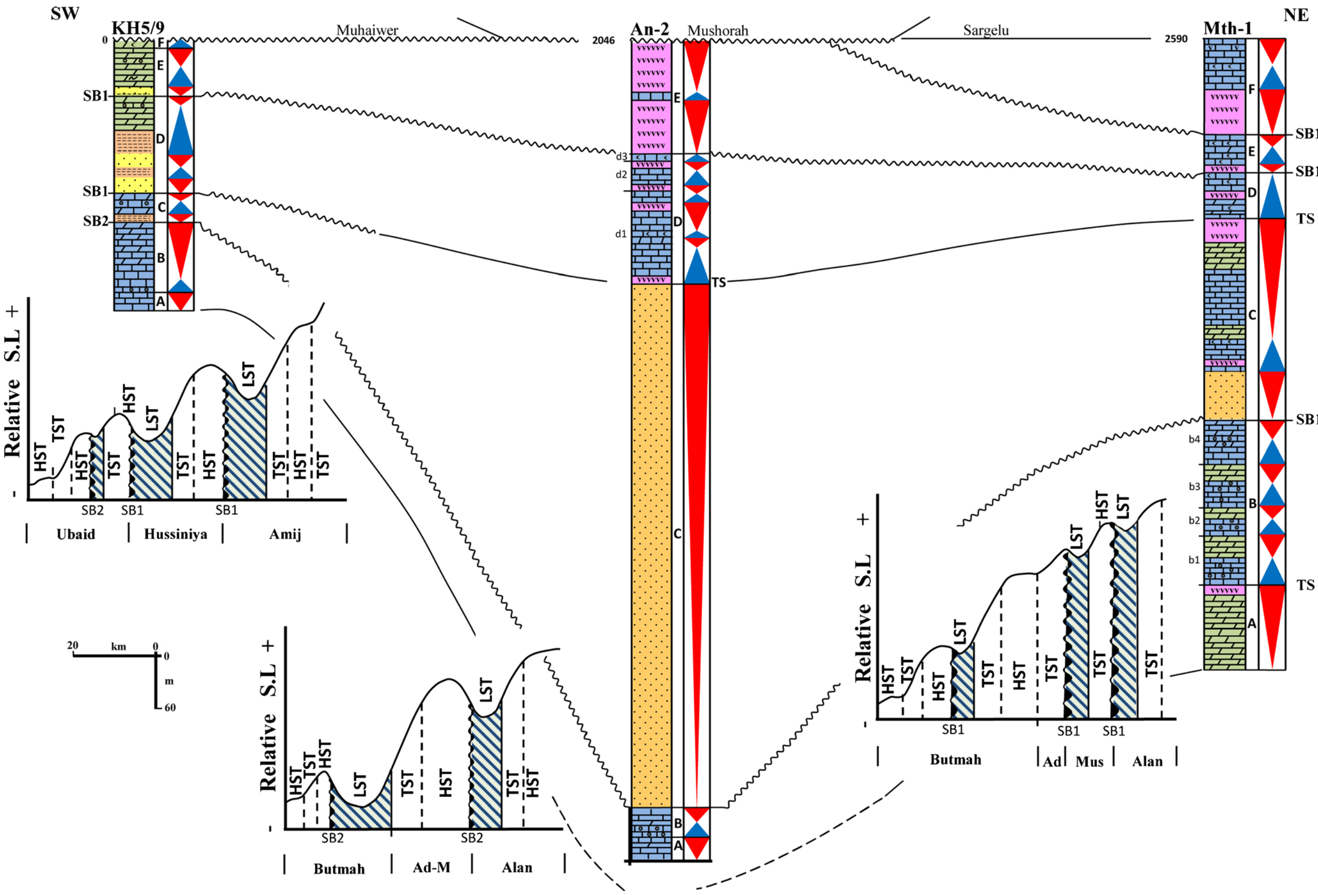

Fig. 7 Stratigraphic cross section of the Lower Jurassic succession at different settings showing variations in facies stacking pattern and cycle thicknesses and symmetries as well as the interpreted relative sea level

clastic succession of the Butmah Formation to be deposited; this was possible also due to the high rate of supply from nearby uplifted area; post Hettangian lower rates of subsidence at the Anah Graben was reflected by lower accommodation. As a result, Sabkha and restricted conditions predominate during the deposition of the Adayah, Mus, and Alan formations.

The succession at Melh Eltherthar-1 which lies within the unstable shelf shows different facies stacking pattern. The more or less steady subsidence during the Hettangian maintained the shallow marine conditions, where the predominantly carbonate succession of the Butmah was deposited; successive episodes of sea level rises and still stands during the Butmah deposition was interrupted by a major fall, causing valley incision and progradation of fluvial facies on the exposed inner platform. This event reflected by an SB1 can be correlated in all areas (Fig. 7). The erosion along this boundary was less intense in the Rutbah area, reflected by an SB2 within the upper part of Ubaid Formation at KH5/9. The post Butmah succession at Melh Eltherthar-1 where shallow marine conditions interrupted by Sabkha conditions within the Alan Formation reflects lower rates of subsidence during the deposition of the Adayah, Mus, and Alan formations.

The difference in relative sea level amplitude at different settings (Fig. 7) was a direct result of different rates of subsidence. To correlate the relative sea level curve of the studied succession with that of Haq et al. (1988), one must choose the most stable area, and in this case the section at KH5/9. This comparison shows marked differences in the short-term fluctuations due to local conditions. This proves that correlation with the global sea level curve can only be credible in a general sense. This is mainly due to the complexity of local tectonic development at each area.

The clastic supply seems to have changed from one area to another depending on the initiation of uplift in the source area and the consequent gradient change of river valleys, as well as the available accommodation space. Carbonate rates of accumulation on the other hand are mainly dependent on the balance between sea level rise and subsidence to produce the shallow marine conditions favorable for maximum carbonate production. Imbalance due to still stands or slow rises produced restricted and sabkha conditions.

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